Vol. 27: 87–94, 2015
doi: 10.3354/esr00658

ENDANGERED SPECIES RESEARCH
Endang Species Res

Published online February 11

Effects of bycatch on the population viability of the narrow-ridged finless porpoises in Ariake Sound and Tachibana Bay, Japan

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ABSTRACT: The narrow-ridged finless porpoise *Neophocaena asiaeorientalis* is a coastal cetacean that is threatened by various human activities. Bycatch mortality is a particular danger to the porpoise population in Ariake Sound and Tachibana Bay, Japan. To evaluate the impact of bycatch mortality on the viability of this population, we simulated changes in population size over the next 100 yr, using a Leslie matrix model. The simulation trials were repeated for 3 scenarios of possible bycatch mortality rates. If bycatch mortality remains at the reported level, the estimated annual rate of decrease is 0.671 to 3.87 %, and the estimated population size reduction over 3 generations is 29.6 to 86.3 %. A population size reduction of ≥30 % was predicted in almost half the simulation trials, even in the most optimistic scenario. The reported bycatch mortalities would pose a serious threat to the viability of this porpoise population; therefore, the population should be classified at least as 'Vulnerable' according to Criterion A4, as defined in the IUCN Red List. Our predictions were sensitive to annual bycatch mortality rate estimates. Hence, the collection of current abundance and bycatch data should be promoted in order to minimize uncertainty in risk assessments.

KEY WORDS: Bycatch · Extinction risk · Leslie matrix model · Narrow-ridged finless porpoise

INTRODUCTION

Narrow-ridged finless porpoises *Neophocaena asiaeorientalis* inhabit coastal waters and rivers in East Asia. The species is critically affected by a wide variety of human activities, such as bycatch (i.e. incidental capture during fishing), ship strikes, and the degradation and reduction of habitats due to dredging and pollution (Kasuya et al. 2002, IWC 2006). Bycatch in particular can have a serious impact on porpoise populations because it is lethal and, therefore, can threaten the viability of the populations (Reeves et al. 1997, IWC 2006). A rapid decline caused by human-induced mortality has been noted in some populations (Kasuya et al. 2002, Zhao et al. 2008, Mei et al. 2012, Hashimoto et al. 2013). Because of a suspected past decline in population size, this species is classified worldwide as 'Vulnerable' (VU) according to Criterion A2 of the IUCN Red List of Threatened Species (Wang & Reeves 2012). However, little work has been conducted on classification at the population level.

Predictions of population trends are useful in identifying the quantitative impact of human-induced mortality on cetacean populations (e.g. Burkhart & Slooten 2003, Currey et al. 2009, Huang et al. 2012, Mei et al. 2012, Hashimoto et al. 2013). Population predictions for the narrow-ridged finless porpoise have only been conducted for 2 populations, in which the declines in population size were detected by

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quantitative evaluations. Kasuya et al. (2002) demonstrated a heavy decline of the Inland Sea population, the largest population in Japanese waters. Density in 1999 and 2000 was about 4% of that in the late 1970s in the middle and eastern part and about 70% in the western part of the Inland Sea. Using the decline rate, Hashimoto et al. (2013) predicted that the population would decrease by approximately 90% over 50 yr. For the population in the Yangtze River in China, Mei et al. (2012) predicted that approximately 90% of the current population would be lost in the next 3 generations. Therefore, the subspecies inhabiting the river (*N. asiaeorientalis asiaeorientalis*) is classified as 'Critically Endangered' (CR), the most serious threat level, according to Criteria A3 and A4 of the IUCN Red List (Wang et al. 2013).

The porpoise population in Ariake Sound and Tachibana Bay (32° 34′ N, 130° 10′ E) is the southernmost of 5 populations in Japan, identified by mitochondrial DNA variability (Yoshida et al. 2001, Yoshida 2002). These waters are located in western Kyushu, and most of them have topographical features that are favorable for the porpoises: 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 porpoise population in these waters is one of the most abundant, and has one of the highest population densities in Japanese waters (Yoshida et al. 1997, Yoshida 2002, Amano et al. 2003, Shirakihara et al. 2007). Moreover, the population shows a distinct haplotype cluster (Aizu et al. 2013); therefore, it is a valuable resource for discovering the origin of Japanese narrow-ridged finless porpoises. The commercial capture of this species is banned in Japan. However, an interview-based survey of gill netters in 2007 and 2008 found that 250 porpoises were bycaught annually during gill net fishing (Shirakihara & Shirakihara 2013). Therefore, bycatch mortality is a major threat to this population.

Potential biological removal (PBR) has been commonly used as an index for evaluating the effects of bycatch 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 & Shirakihara 2012, 2013). The PBR level is defined as the maximum number of individuals that can be removed from a population without the depletion of that population (Wade 1998). The PBR level for the porpoise population in Ariake Sound and Tachibana Bay was estimated as 27 ind. (Shirakihara & Shirakihara 2013). This approach is useful for assessing cetacean populations with few biological data because only 3 parameters, minimum population size, maximum rate of increase, and recovery factor, are needed to calculate the PBR level. However, if the reported number of bycaught cetaceans significantly exceeds the PBR level, as is the case with this population, then a further evaluation would be necessary to assess the potential effects of bycatch, in order to devise appropriate conservation measures.

The purpose of this study was to evaluate the impact of bycatch mortality on the viability of the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay. To achieve this, we conducted a quantitative analysis of population-size predictions using the possible bycatch mortality rate estimated from available information. Moreover, we conducted a risk assessment following the IUCN Red List criteria to show the current status of this population.

METHODS

The age-structured model

The Leslie matrix model (Leslie 1945, Caswell 1989) was used to express annual changes in the number of individuals of each age class, as follows:

$$\mathbf{n}_{(t+1)} = \mathbf{A}\,\mathbf{n}_{(t)} \quad (1)$$

where $\mathbf{n}_{(t)}$ is the vector of an age-structured population in year t. The population size in year t was given by summing $\mathbf{n}_{(t)}$ over ages. The Leslie matrix ($\mathbf{A}$) is expressed as:

$$\mathbf{A} = \begin{pmatrix} F_0 & F_1 & \dots & F_{k-1} & F_k \\ P_0 & 0 & \dots & 0 & 0 \\ 0 & P_1 & \dots & 0 & 0 \\ & & \vdots & & \\ 0 & 0 & \dots & P_{k-1} & 0 \end{pmatrix} \quad (2)$$

where F_x is the per capita fertility rate, P_x is the survival rate of age class x (age x to $x + 1$), and k is the maximum age class. When the values of these demographic parameters are invariant on a yearly basis, the annual rate of increase (λ) is calculated as the maximum eigenvalue of the Leslie matrix ($\mathbf{A}$).

Demographic parameters

Life-history parameters, such as longevity, age at first reproduction (AFR), fertility rate, and survival rate, are essential for the matrix model. The value of each parameter for narrow-ridged finless porpoises was obtained from the literature. Values for females only were incorporated, because the sex ratio at any given age was assumed to be 1:1.

k was given as 29, because the longevity of the porpoises is approximately 30 yr (Shirakihara et al. 1993, Kasuya 1999, Jefferson et al. 2002b), and the estimate of λ would not be sensitive to k (Bradford et al. 2008).

The AFR was calculated by adding the gestation period to the age at sexual maturity. The gestation period of the porpoises is 10.6 to 11.2 mo (Kasuya et al. 1986). Jefferson et al. (2002b) reported that the age at sexual maturity for females is approximately 5 yr, and there are no significant differences between porpoise populations. Therefore, the AFR was set at 6 yr.

The age-specific fertility of individuals at AFR and older was calculated as:

$$F_x = 0.5 \times 1/\mathrm{CI} \times P_x \tag{3}$$

where CI denotes the calving interval and 1/CI represents the annual pregnancy rate (Dans et al. 2003). Here, we assumed that the CI was 2 yr based on the most common pregnancy cycle of this species (Kasuya & Kureha 1979).

Survival data are often lacking, because direct observations of survival in cetaceans, including the narrow-ridged finless porpoise, are usually difficult or impossible. The use of relatively accurate observations of other species, with similar life histories, is a useful approach for constructing a survivorship curve for a species with limited data (Caswell et al. 1998, Dans et al. 2003, Hashimoto et al. 2013). Here, the previous approach employed by Hashimoto et al. (2013) was used to estimate the 'natural' survival rate (S_x), without human-induced mortality. The uncertainty in S_x was produced by randomly sampling the survival rate estimates of 4 other cetaceans. Presuming that only bycatch was the cause of human-induced mortality, the age-specific 'total' survival rate of age class x was given as:

$$P_x = S_x(1 - M) \tag{4}$$

where M denotes the age-specific bycatch mortality rate. M may be age-dependent, but we did not consider this because the age composition of bycaught porpoises has not been established. The values of λ were estimated from this 'total' survival rate.

The value of M is calculated from the estimates of abundance and the total number of bycaught porpoises. For the Ariake Sound and Tachibana Bay population, the most recent abundance estimate is 3093 ind. (coefficient of variation [CV] = 15.7%) in 1993 and 1994 (Yoshida et al. 1997); 250 ind. (CV = 22.3%) were estimated to be bycaught annually during gill net fishing (Shirakihara & Shirakihara 2013). Assuming all bycaught individuals to be dead, the default value of M for this population is 8.1% (= 250/3093). Shirakihara & Shirakihara (2013) suggested that this value might be an overestimation. The abundance estimate of 3093 ind. was calculated under the assumption that the detection probability on the track line in an 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 decreases to 5.3% (=250/[3093/0.65]).

Population viability analysis

The population viability analysis study flow is shown in Fig. 1. Demographic parameters and the current population structure were initially used as input for Step (i). The details of the demographic parameters were described in the previous section.

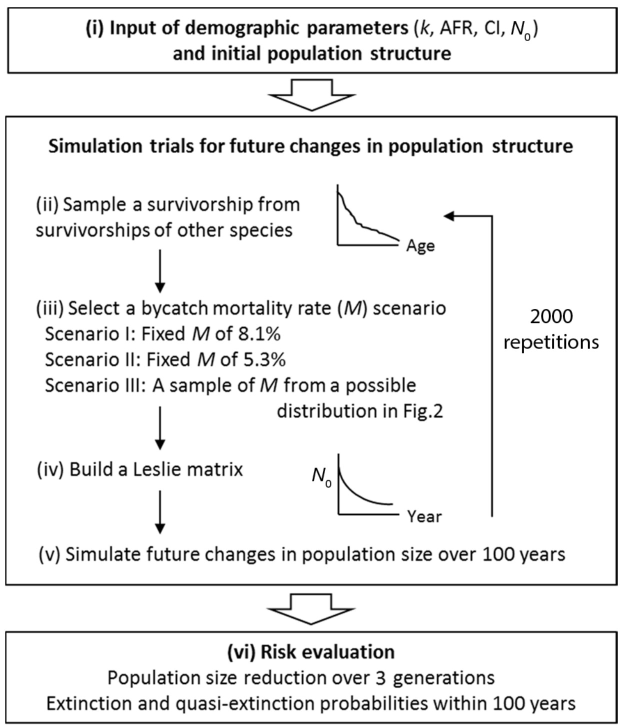

Fig. 1. Study flow of a population viability analysis of the narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) population in Ariake Sound and Tachibana Bay, Japan. k: longevity; AFR: age at first reproduction; CI: calving interval; N_0: current population size

The population size in the first year (N_0) for all the simulation trials was set to be 3093 ind., derived from the latest abundance estimate for the porpoise population (Yoshida et al. 1997). 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 age dependence in bycatch was not incorporated into the present study, so there was little change in the age structure.

A simulation trial from Step (ii) to (v) (Fig. 1) was conducted for the future change in population structure, and was repeated 2000 times. For Step (ii), a new survivorship curve was sampled from survivorships of other species. The details of the sampling approach are described in Hashimoto et al. (2013). For Step (iii), we selected 3 scenarios that were based on plausible values of the annual bycatch mortality rate (M): Scenario I, the value of M was fixed at 8.1% as the baseline for population predictions; Scenario II, the value of M was fixed at 5.3%; and Scenario III, a new value of M was randomly sampled from a distribution, given the uncertainty in the estimate of M. A possible distribution of M can be shown (Fig. 2) when the ranges of the abundance estimates are selected from a log-normal distribution, defined with a mean of 3093 and a CV of 15.7%. For Step (iv), a Leslie matrix was built with a combination of demographic parameters. For Step (v), the future change in population size was simulated over a 100 yr period, starting from the current year, with the same survivorship curve and a fixed value of M. The yearly variations in these parameters were not incorporated, because no useful data were available. The simulation period was chosen as the longest time period defined by the IUCN (2001).

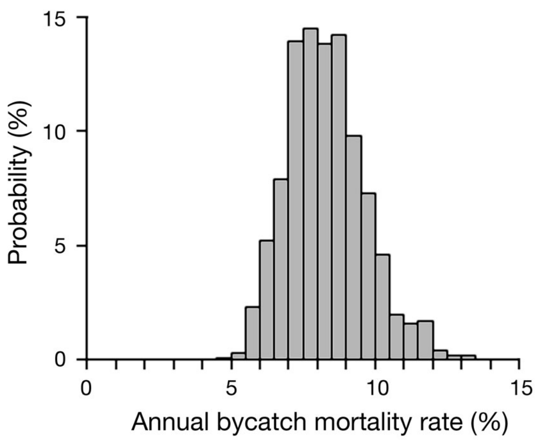

Fig. 2. Possible distribution of annual bycatch mortality rates of the narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) population in Ariake Sound and Tachibana Bay, Japan

For Step (vi), the risks due to bycatch were quantitatively assessed from 2 perspectives: the population size reduction over 3 generations and the extinction probability within 100 yr, both of which are associated with Criteria A4 and E as defined by the IUCN (2001). The generation period for the narrow-ridged finless porpoise is estimated to be 16.5 yr (Taylor et al. 2007); therefore, 50 yr was given as the 3-generation period. The extinction probability was defined as the percentage of trials (out of 2000) in which the population declined to <2 ind. The quasi-extinction probabilities, which were defined as the percentage of trials where the population declined to <100 ind. from 2000 trials, were also estimated. The value of 100 ind. was chosen, as it is the threshold value for the CR category according to Criterion D (IUCN 2001).

RESULTS

Future population trend

The median of the annual rate of increase estimate $\hat{\lambda}$ was 1.048 (2.5–97.5 percentiles: 1.022–1.063) in the absence of bycatch. If bycatch mortality remained at the reported level, the medians of $\hat{\lambda}$ would be <1 (Table 1), and the population size would continue to decrease over the next 100 yr in all scenarios (Fig. 3). As an index of population decline, estimates of the annual rate of decrease $\hat{d}$ $(1 - \hat{\lambda})$ were introduced. The estimates were 3.64% (2.5–97.5 percentiles: 2.33–6.09) in Scenario I, 0.671% (−0.677–3.20) in Scenario II, and 3.87% (1.08–7.72) in Scenario III (Table 1). In most simulation trials, including those in the most optimistic case (Scenario II), $\hat{d}$ exceeded zero.

Table 1. Estimated medians of the annual rate of increase (λ) and the annual rate of decrease (d) (% of $1 - \lambda$) of the narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) population in Ariake Sound and Tachibana Bay, Japan. Values in parentheses represent the 2.5–97.5 percentiles. For the 3 scenarios, see Fig. 1

	Scenario I	Scenario II	Scenario III
$\hat{\lambda}$	0.964	0.993	0.961
	(0.939–0.977)	(0.968–1.01)	(0.923–0.989)
$\hat{d}$	3.64	0.671	3.87
	(2.33–6.09)	(−0.677–3.20)	(1.08–7.72)

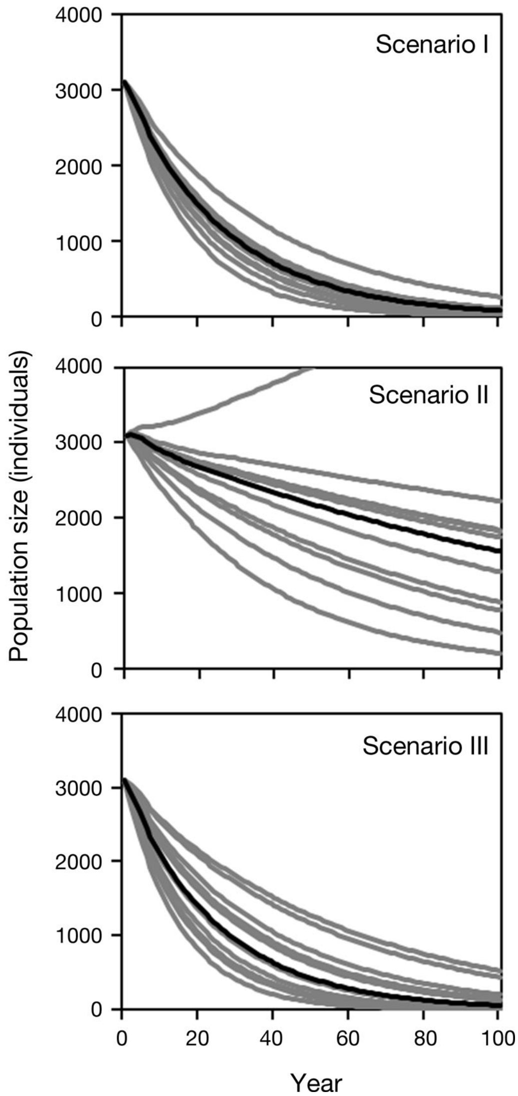

Fig. 3. Future changes in population size over a 100 yr period of the narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) population in Ariake Sound and Tachibana Bay, Japan. Black and gray lines indicate the medians and 10 examples from 2000 simulation trials, respectively. For the 3 scenarios, see Fig. 1

Table 2. Future risk evaluations (medians) of the narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) population in Ariake Sound and Tachibana Bay, Japan. Values in parentheses represent the 2.5–97.5 percentiles. For the 3 scenarios, see Fig. 1

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

Evaluating the risks

If bycatch mortality remains at the reported level, the median of the population size reduction estimates over 3 generations (i.e. 50 yr) is 84.5% (2.5–97.5 percentiles: 69.9–95.7) in Scenario I, 29.6% (–37.2–80.3) in Scenario II, and 86.3% (42.6–98.2) in Scenario III (Table 2). A population size reduction of ≥80% over 3 generations, which qualifies for the CR category according to Criterion A4 (Table 3), occurred in almost 70% of the simulation trials in Scenarios I and III (Fig. 4). Moreover, in almost all of the trials in Scenarios I and III, and in almost 50% of the trials in Scenario II, the population size was predicted to decline by ≥30% over 3 generations.

The predicted extinction probabilities within 100 yr were <10% in all the scenarios (Table 2). This suggests that the population does not fulfill Criterion E, even for the VU category (Table 3). However, with regard to the quasi-extinction probabilities, much worse estimates were given (64.6 and 61.8% for Scenarios I and III, respectively).

DISCUSSION

Bycatch mortality poses a serious threat to the viability of the narrow-ridged finless porpoise population in Ariake Sound and Tachibana Bay. A trend in population size was not clearly detected, due to the deficiency of abundance estimates from sightings. Therefore, assessments of the population size reduction over the last 3 generations (Criterion A2 in IUCN [2001]) could not be made. 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 3-generation period, including both the past and the future, which meets the requirements of the CR category according to Criterion A4 (Fig. 4). 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 in the VU category (Table 3).

Uncertainty in the value for M is influenced by the accuracy in the esti-

Table 3. Risk assessments for the narrow-ridged finless porpoise (*Neophocaena asiaeorientalis*) population in Ariake Sound (AS) and Tachibana Bay (TB), Japan, based on 3 'threatened' categories according to Criteria A4 and E defined by the IUCN (2001)

Criterion	Category: Vulnerable (VU)	Category: Endangered (EN)	Category: Critically endangered (CR)	Evaluated status of the AS/TB population
A4: population size reduction over 3 generations	≥30 %	≥50 %	≥80 %	At least VU
E: quantitative analysis showing the probability of extinction	≥10 % within 100 yr	≥20 % within 5 generations	≥50 % within 3 generations	Not applicable

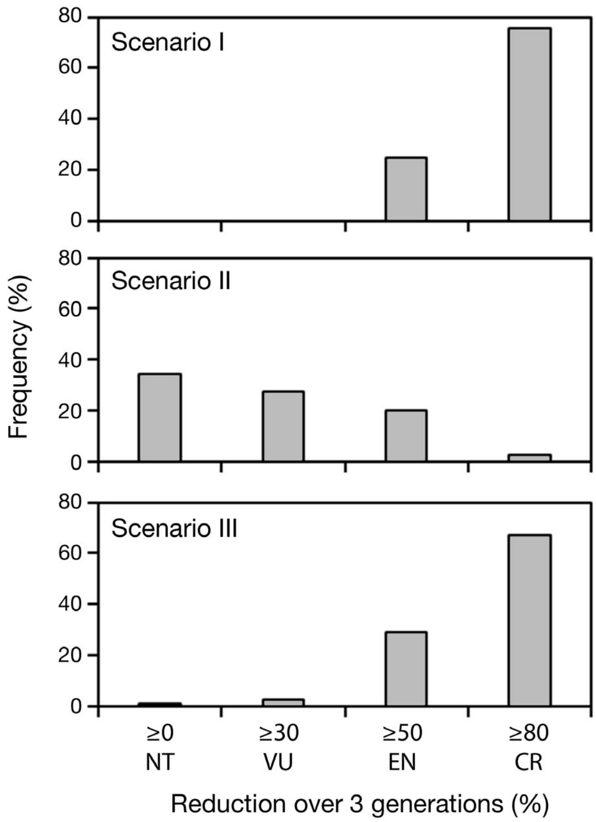

Fig. 4. Frequency distributions of the predicted population size reduction over 3 generations of the narrow-ridged finless porpoise *Neophocaena asiaeorientalis* in Ariake Sound and Tachibana Bay, Japan, from 2000 trials based on risk categories according to Criterion A4 defined by the IUCN (2001): Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). For the 3 scenarios, see Fig. 1

mated number of bycaught porpoises and the abundance estimate. The sampling bias in the interview-based survey to estimate the number of bycaught porpoises was not incorporated into 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. Our results suggest that predictions are sensitive to the estimate of *M* (Table 2; Scenarios I and II). In this study, we made additional predictions associated with a continuous range of *M*, from 5 to 15% (Fig. 5). Both the population size reduction and the quasi-extinction probability were more sensitive to estimates of *M* that were between 5 and 9%. 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 yr old and 2 yr, respectively, they may be lower in a depleted species. Shirakihara & Shirakihara (2013) showed that there are yearly variations in the number of porpoises bycaught during gill net fishing (238 and 270 ind. 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.

Age dependence in bycatch may exist, although it was not incorporated into this study. Indeed, Shirakihara & Shirakihara (2013) indicated that immature individuals (<1 yr old) accounted for approximately half the specimens collected around Ariake Sound and Tachibana Bay. They also showed that the accidental capture of the porpoises in bottom-set gill nets mainly occurred between fall and winter, i.e. 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 annual rate of population increase is most sensitive to the calving interval and the adult survival rate (Reilly & Barlow 1986, Brault & Caswell 1993).

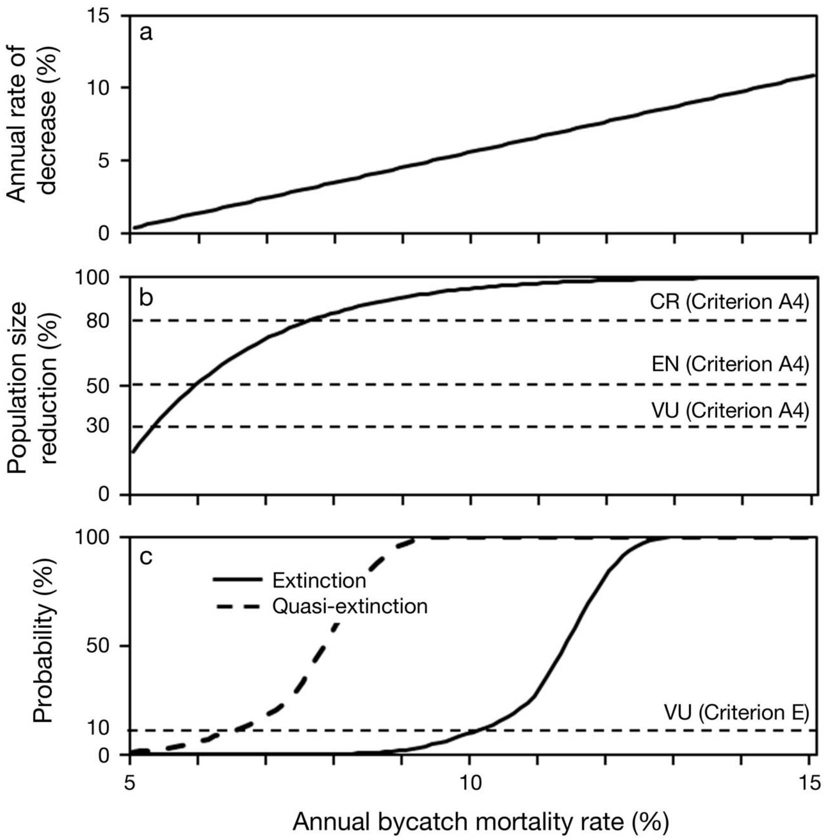

Fig. 5. Changes in prediction associated with the annual bycatch mortality rate of the narrow-ridged finless porpoise *Neophocaena asiaeorientalis* in Ariake Sound and Tachibana Bay, Japan. (a) Median of the annual rate of decrease, from 2000 simulation trials. (b) Median of the population size reduction over 3 generations, and thresholds (short dashed lines) for risk categories according to Criterion A4 as defined by the IUCN (2001): Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). (c) Extinction and quasi-extinction probabilities within 100 yr and the threshold (short dashed line) for the VU category according to Criterion E

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.

Finally, we should point out that the incorporation of other factors may result in more pessimistic predictions. In this study, we investigated the effects of bycatch mortality caused by gill nets. Because bycatch 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 conservation of the porpoise population. Our predictions can be applied to evaluate the impact of all human-induced mortality in place of gill net bycatch mortality. We recommend an annual human-induced mortality rate of <5% in order to ensure that the threat to this population remains below that defined in the IUCN Red List criteria (see Fig. 5).

Acknowledgements. This study was supported by Grant-in-Aid for Scientific Research (B) 21380120 and Grant-in-Aid for JSPS Fellows 268326. We thank 2 anonymous reviewers for their valuable comments, which improved our manuscript. We also thank the members of the Fish Population Dynamics Laboratory, Atmosphere and Ocean Research Institute, Japan.

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Editorial responsibility: Eric Gilman, Honululu, Hawaii, USA

Submitted: June 23, 2014; Accepted: November 13, 2014
Proofs received from author(s): January 27, 2015