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POPULATION ANALYSIS OF NORTHERN BOTTLENOSE WHALES IN THE GULLY, NOVA SCOTIA

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ABSTRACT

Northern bottlenose whales (*Hyperoodon ampullatus*) are consistently found through the year in the Gully, a prominent submarine canyon on the edge of the Scotian Shelf. Individuals were photographically identified during field studies between 1988 and 1995. About 70% of the population is identifiable, and 29% have markings which persist reliably over periods of years. A mark-recapture analysis of photographic individual identifications collected between 1988 and 1995 indicates that the population using the Gully numbers about 230 animals (approximate 95% confidence interval 160–360). The rate of mortality plus emigration plus mark change (in animals with reliable long-term marks) is about 12% per year, although this estimate has wide and uncertain confidence limits. Members of the Gully population, which includes calves and mature males, are shorter than animals caught off Labrador. The small size of the Gully population and its persistent use of a very small, bathymetrically unique ocean area make it vulnerable to human disturbance.

Key words: bottlenose whale, *Hyperoodon ampullatus,* photoidentification, mark-recapture, submarine canyon, length distribution, human disturbance.

The northern bottlenose whale (*Hyperoodon ampullatus*) is a 7–9-m beaked whale found only in the northern parts of the North Atlantic Ocean. The most southerly and westerly location where this species can be consistently sighted is the Gully, a prominent submarine canyon on the edge of the Scotian Shelf (Reeves *et al.* 1993; Fig. 1). Between 1962 and 1967, 87 bottlenose whales were taken by Canadian whalers, mainly in the region of the Gully (Reeves *et al.* 1993); and Winn *et al.* (1970) described the sounds recorded from bottle-

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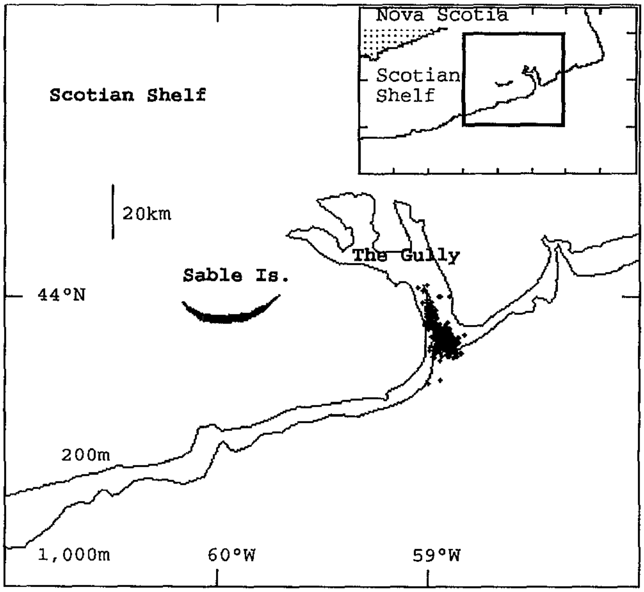

Figure 1. The Gully, showing positions in which identification photographs of northern bottlenose whales were taken (+) and the 200-m and 1,000-m contours.

nose whales during a visit to the Gully. However, little information is available for these animals during the period 1970–1988.

We have been studying the bottlenose whales of the Gully since 1988 using a number of techniques including the photographic identification of individual animals. In this paper we use these photographic identifications and other data to examine the size and structure of the population of bottlenose whales that uses the Gully. This information is important, as oil and gas exploitation is increasing in the waters surrounding the Gully, causing concern for this population (Amirault 1995, Faucher and Whitehead 1995). The research described in this paper is the first study of identified living individuals in any of the 20 or so species of beaked whale (family Ziphiidae).

Methods

Field Work

The majority of the field work in the Gully (44°N, 59°W; Fig. 1) was carried out using auxiliary sailing vessels, during the summers of 1988–1990 the 10-m *Elendil* and during 1993–1995 the 12-m *Balaena* (Table 1). Additional sightings and observations were available from shorter visits on other motorized vessels to the Gully (Table 1).

While in the Gully, we surveyed the area where the bottlenose whales are found (Fig. 1) in a manner neither systematic nor random: we visited areas where we or others had seen bottlenose whales. On sighting bottlenose whales,

Table 1. Field studies in the Gully, with the number of individual whales identified from high-quality photographs from the left and right sides, and the number with reliable long-term marks (in parentheses).

		Photoidentified individuals	
Dates	Vessel	Left side	Right side
8 July–6 August 1988	*Elendil*	9 (5)	9 (4)
16 July–14 August 1989	*Elendil*	58 (32)	58 (30)
1 October 1989	*Lady Hammond*	1 (1)	1 (1)
10–11 February 1990	*Alfred Needler*	1 (1)	0
14 June–11 August 1990	*Elendil*	117 (43)	102 (47)
24–25 July 1991	*All Seven*	0	0
26–27 July 1992	*Divecom III*	0	0
12–22 July 1993	*Balaena*	38 (11)	45 (15)
2–17 August 1994	*Balaena*	39 (11)	29 (8)
23–30 August 1995	*Balaena*	7 (3)	16 (6)

either the research vessel was stopped so that the whales could approach it, or, if the whales were not curious, they were approached cautiously.

When conditions permitted, we attempted to photograph the dorsal fin and surrounding region of any bottlenose whale less than about 30 m from the research vessel. Whales were photographed irrespective of whether there were obvious markings on or near the fin. Most photographs were taken with Canon AE1 and AT1 35-mm cameras equipped with 300-mm f4 lenses, using Ilford HP5 400 ASA black-and-white film.

Photographs were taken of the whales parallel to the horizon from 9 to 10 m up the mast of the research vessel, using Canon AE1 cameras with 50-mm lenses (focus taped to infinity) and Kodak Kodachrome 200 ASA color film. Measurements taken from these photographs allow the lengths of the whales to be estimated (Gordon 1990, Waters and Whitehead 1990). As individual whales cannot usually be identified from measurement photographs, our sample must be considered as one obtained with replacement.

Analysis of Identification Photographs

Photographs showing the dorsal fins of bottlenose whales were given a 'Q' quality value based on the image size, focus, lighting, angle of the fin, and exposure of the photograph. Q values ranged from $Q = 0$ (fin barely visible) to $Q = 6$ (excellent photograph with a well-lit, well-exposed, in-focus fin filling much of the frame) (see Arnbom 1987). The Q value does not depend on how well marked the animal is.

Photographs with adequate marks were compared with a catalog containing the best photograph of each previously identified whale. If matched, the photograph was linked to the whale identification number. If not matched, it was given a new number and added to the catalog. Separate catalogs were maintained for photographs taken of the left and right sides of the dorsal fin.

Identified individuals were assigned an 'M' quality value (1–6), for both the left and right sides of their fins, based on the number of marks present and their distinctiveness. Photographs with $Q \geq 4$ of individuals with $M \geq 4$ could be reliably matched to one another.

The proportion of animals that can be photographically identified was estimated from the number of photographs in which $M \geq 4$ in a random sample of 237 photographs with $Q \geq 4$.

Although high-quality photographs ($Q \geq 4$) of well-marked individuals ($M \geq 4$) could be matched reliably against one another if taken at the same time, substantial mark change could cause the same individual photographed at different times to be considered different whales. In a study of 50 animals identified in more than one year, A. Faucher (personal communication) estimated rates at which different types of marks were gained and lost. Of the marks found on a substantial proportion of individuals, only 'notches' on the edge of the dorsal fin had sufficiently low rates of loss and gain (<0.04/animal/yr) so that the great majority of animals possessing these marks could be reliably identified over periods of years.

We calculated, for each major survey, the proportion of identified ($M \geq 4$) animals possessing notches (summing left- and right-side identifications). The mean and standard error of the annual estimates of this proportion were calculated, as were the mean and standard error of the ratio of identified individuals to notched individuals (inverse of proportion of individuals with notches).

We combined our estimates of the proportion of identified individuals in the population and the ratio of identified individuals to notched individuals to obtain an estimate of the ratio of the total population size to the number of animals with notches.

Population Analysis

Mark-recapture analyses were applied to the individual photographic identifications to examine the size and structure of the population of bottlenose whales using the Gully. This is now a common procedure with studies of populations of individually identifiable cetaceans, and a number of specific techniques are available (Hammond 1986). In the population analyses presented in this paper, only high-quality photographs ($Q \geq 4$) of whales with reliable long-term marks ($M \geq 4$ and at least one notch in the dorsal fin) were used in mark-recapture analyses.

All analyses were carried out separately for photographs from the left and right sides, although these analyses are not independent; individuals were often identified from both the left and right sides during encounters lasting a few minutes.

The mark-recapture models used maximum-likelihood methods to estimate population parameters (*e.g.*, Jolly 1979), conditioning on first identification to simplify the assumptions and modeling (Seber 1992). From the original data set (consisting of when each individual was photographed) an 'identification history' was compiled for each animal. For each population model and any set of parameters, a likelihood could be calculated for each identification history (the probability that an individual would have that identification history given the model and parameters). The likelihoods of each animal's identification history were multiplied to give a total likelihood (L) for the data set. Population parameters were estimated by finding (iteratively on a computer using the package MATLAB) that set which maximized the likelihood.

Likelihood methods can also be used to compare different models, using the likelihood ratio test, and to construct confidence intervals for estimates. Suppose a null model, H_0, is a restricted version of a more general model, H_1. If H_0 is true, then twice the natural logarithm of the ratio of the likelihood under H_1 over the likelihood under H_0, $2 \cdot \text{Log}_e(L(H_1)/L(H_0))$, is asymptotically distributed as $\chi^2(s)$, where s is the increased number of parameters in H_1. Thus, the utility of adding an additional parameter to a model can be assessed. Approximate confidence intervals for parameter estimates can be obtained from the support function (Edwards 1972): the log-likelihood for a given set of parameters minus the log of the maximum likelihood. For any parameter, the range of values for which the support function has values less than 2.0 gives an approximate 95% confidence interval (as the 0.05 percentile of $\chi^2(1)$ is about 4.0).

Likelihood mark-recapture analyses of the bottlenose whale data were carried out with calendar years as units. We also attempted analyses with calendar months as units, allowing for both emigration from the core area in the Gully to a surrounding population, as well as re-immigration back into the core area (see Whitehead 1990). However, data in consecutive months were not sufficient for these to add much of use to the results from the analyses using years as units.

The analyses assumed (1) The whales were identified independently of one another; (2) Identification took place in small time periods, with negligible death, emigration, or mark change taking place within periods; (3) Identification rates were equal for all members of the population; (4) The probability of an animal dying, emigrating from the population, or experiencing a change in marks during a time unit was the same for all animals and did not change with time; and (5) Identification in one year was independent of identification in previous years.

Estimates of the size of the population of bottlenose whales that use the Gully (N'), and upper and lower bounds (*u.b., l.b.*) of approximate 95% confidence intervals were calculated, using the population estimates for the number of whales with reliable long-term marks (notches) derived from these analyses (N), with estimates and approximate confidence intervals adjusted for the ratio of the total population size to the number of animals with reliable long-term marks (c):

$$N' = N \cdot c \tag{1}$$

$$l.b.(N') = N \cdot c \cdot (1 - 2 \cdot \sqrt{(((N - l.b.(N))/(2 \cdot N))^2 + \text{CV}^2(c)))} \tag{2}$$

$$u.b.(N') = N \cdot c \cdot (1 + 2 \cdot \sqrt{(((u.b.(N - N)/(2 \cdot N))^2 + \text{CV}^2(c)))} \tag{3}$$

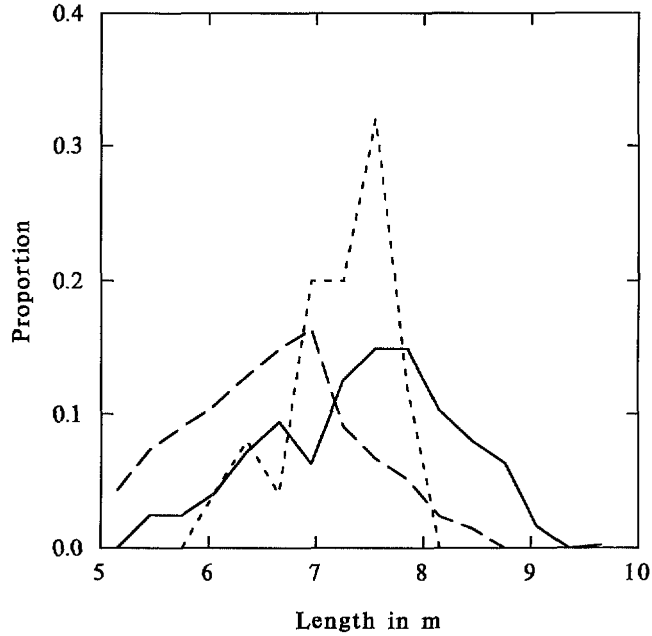

Figure 2. Length distribution of northern bottlenose whales caught in the Gully (- - -, n = 25), photographically measured in the Gully (— —, n = 451—some animals were measured several times), and off Labrador (———, n = 127).

Equations (2) and (3) are derived from the following standard statistical relationships:

$$l.b.(N') = N' \cdot (1 - 2 \cdot CV(N'))$$
$$u.b.(N') = N' \cdot (1 + 2 \cdot CV(N'))$$
$$CV^2(N') = CV^2(N) + CV^2(c)$$

Results

Composition of the Population

The length distribution of the bottlenose whales measured in the Gully is quite similar to that recorded from 25 recorded catches in the area between 1964 and 1967 (Reeves *et al.* 1993), although the whalers may have been selecting the larger animals (Fig. 2). However the Gully animals that we measured were considerably (*ca.* 0.7 m) shorter than those caught off Labrador in 1971 (data from Christensen 1975; Fig. 2).

Mature males, distinguished because of their flattened white foreheads (Mead 1989), were observed in the Gully during all survey months (February, June, July, August, and October) with, overall, approximately 35% of individuals photographed being mature or maturing males. Calves measured at 3.0–3.3 m, roughly the size at birth (Mead 1989), were observed in the Gully during August.

Seasonality

Bottlenose whales were sighted in the Gully during all the surveys listed in Table 1, as well as during an aerial survey of the Gully in November 1994 (Parsons 1995). Thus, bottlenose whales have been found in the Gully in 6 of the 12 months: February, June, July, August, October, and November. They have been found in the deep waters of the Gully (see Fig. 1) whenever they have been searched for.

As there were few identifications from high-quality photographs ($Q \geq 4$) in autumn and winter surveys (Table 1), certain identifications from photographs of moderate quality ($Q = 3$) were also used when examining seasonal residence patterns. Seven individuals were identified from right-side photographs with $Q \geq 3$ in October 1989, six of which were also identified during one or more summer surveys. For the left-side $Q \geq 3$ photographs, five individuals were identified during this survey, three of which were sighted during one or more summer surveys. Similarly, three of the four individuals identified in the February 1990 survey were also sighted during one or more summer surveys.

Proportion of Identifiable Individuals

Our analysis of a random sample of 237 high-quality ($Q \geq 4$) photographs indicated that 70% (approximate SE 3%, using binomial theory) of the population can be photographically identified. The proportion of identified individuals with notches was 41% (SE 4.1%), and the number of identifiable individuals was 2.60 times the number of animals with nicks in their fins (SE 0.273).

Putting the estimate of the proportion of identifiable individuals (70%) together with the estimate of the proportion of identifiable individuals with reliable long-term marks (41%), we estimate that about 29% (SE 2.9%) of the population were identifiable from reliable long-term marks. Alternatively, we estimate that the total population size was 3.72 times the number of individuals with reliable long-term marks (SE 0.39) (*i.e.,* the correction factor for population estimates $c = 3.72$).

Population Size, Mortality, and Migration

Three population models were used in the mark-recapture analysis: (1) A closed population, with no immigration, emigration, birth, death, or mark change (the 'Schnabel' model); (2) A population with a constant rate of emigration + death + mark change (δ), which is balanced by a similar rate of immigration + recruitment + mark change; and (3) A population with a constant rate of emigration + death + mark change (δ), which is changing in size at a constant multiplicative rate (r) per year.

Table 2. Estimates of population parameters for bottlenose whales with reliable long-term marks using three models.

Model type	Data	Parameter estimates			Log (likelihood)
		N	δ	r	
(a)	Left fin	71	—	—	−83.51
(b)	Left fin	60	0.10	—	−81.93
(c)	Left fin	64	0.13	0.96	−81.86
(a)	Right fin	90	—	—	−87.07
(b)	Right fin	65	0.15	—	−84.50
(c)	Right fin	77	0.21	0.90	−83.90

Note: N = population size; δ = mortality + emigration + mark change rate/yr; r = rate of change of population size/yr.

The results of fitting these models to the data for left- and right-fin identifications are shown in Table 2. Likelihood ratio tests indicate that model (3) fits the data no better than model (2) ($P = 0.7$ for left fins; $P = 0.3$ for right). Approximate 95% confidence intervals for r were estimated from the support surface for model (3): r = 0.78–1.23 (left fins); r = 0.76–1.10 (right fins). Thus there is no indication of significant trend in population size, although the data are not sufficient to permit testing this with any power.

Model (2) fits the data better than model (1) ($P = 0.08$ for left fins; $P = 0.025$ for right), indicating the presence of mortality, emigration, and/or mark change at about 12% per year in a population numbering about 62 individuals with reliable long-term marks.

The support surfaces for the parameter estimation in model (2) are shown in Figure 3. These suggest 95% confidence intervals for the population of individuals with reliable long-term marks, N, of 51–79 (left side) and 52–94 (right side), and for the emigration + death + mark change rate, δ, of 0.00–0.22 (left side) and 0.02–0.27 (right side).

Using the estimate of the ratio of the total population size to the number of animals with reliable long-term marks and equations [1–3], these estimates were converted into estimates of the total size of the population:

From left fin identifications—223 (95% CI: 166–308)

From right fin identifications—242 (95% CI: 172–361)

Reliability of Assumptions

The population analyses make five principal assumptions:

1. *Independence*—There are a few apparent instances of long-term companionships between pairs of bottlenose whales in the Gully (Faucher and Whitehead 1991). These violate the assumption of independence. Lack of independence will not generally bias population estimates, but will cause estimated confidence intervals to be too narrow.

2. *Short survey periods*—Except in 1990, survey periods were less than 1 mo, and it is likely that relatively little mortality, emigration, or mark change took place within them.

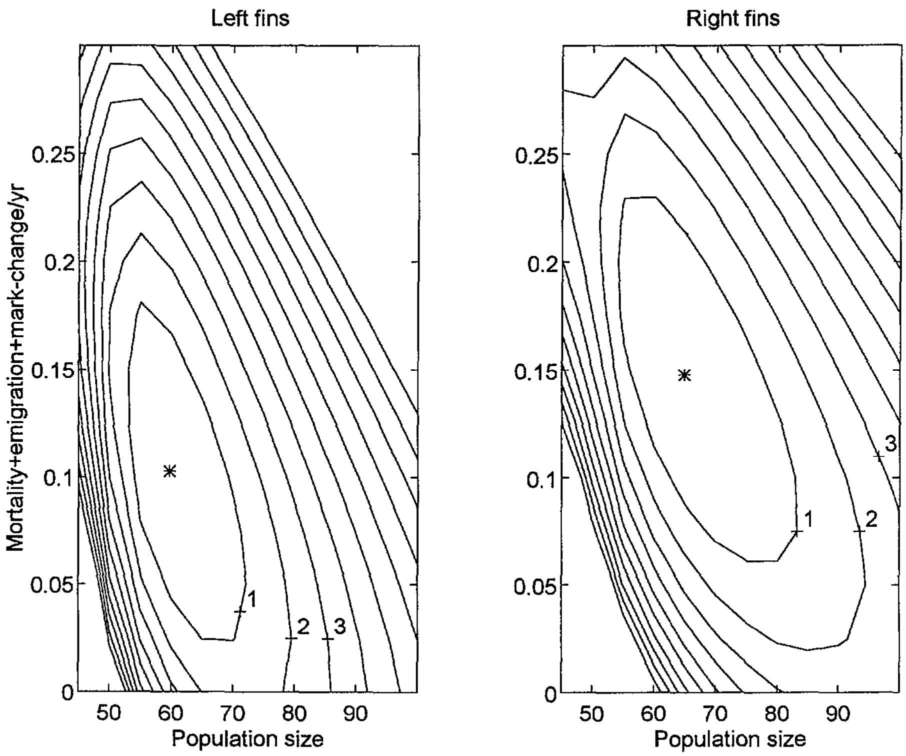

Figure 3. Contours of support function for estimates of the number of northern bottlenose whales with reliable long-term marks using the Gully, and their rate of mortality + emigration + mark change/yr. For any parameter, the range of values for which the support function has values less than 2.0 gives an approximate 95% confidence interval. Maximum likelihood estimates are indicated by (*).

3. *Homogeneity of identification probability*—Heterogeneity in identification rates can lead to substantial negative bias in mark-recapture population estimates (*e.g.*, Hammond 1990). In our study, heterogeneity of identification could be caused by consistent differences in the ways that animals use the Gully or behave when near our research vessel. Cormack (1985) suggests checking for such heterogeneity by examining the residual differences between the observed and the expected (using the fitted model) number of individuals with each identification history. Heterogeneity is indicated if these residuals are high for identification histories with large and small numbers of identifications, showing that more individuals than expected were identified many times and few times. There is no sign of this 'U'-shaped pattern which is characteristic of heterogeneity in plots of the standardized residuals [after fitting model (2)] in the number of individuals with each identification history against the number of years identified (Fig. 4).

4. *Equality of mortality + emigration + mark change probabilities*—Like heterogeneity of identification, severe differences in mortality + emigration + mark change rates would give a 'U'-shape to the residuals plots in Fig-

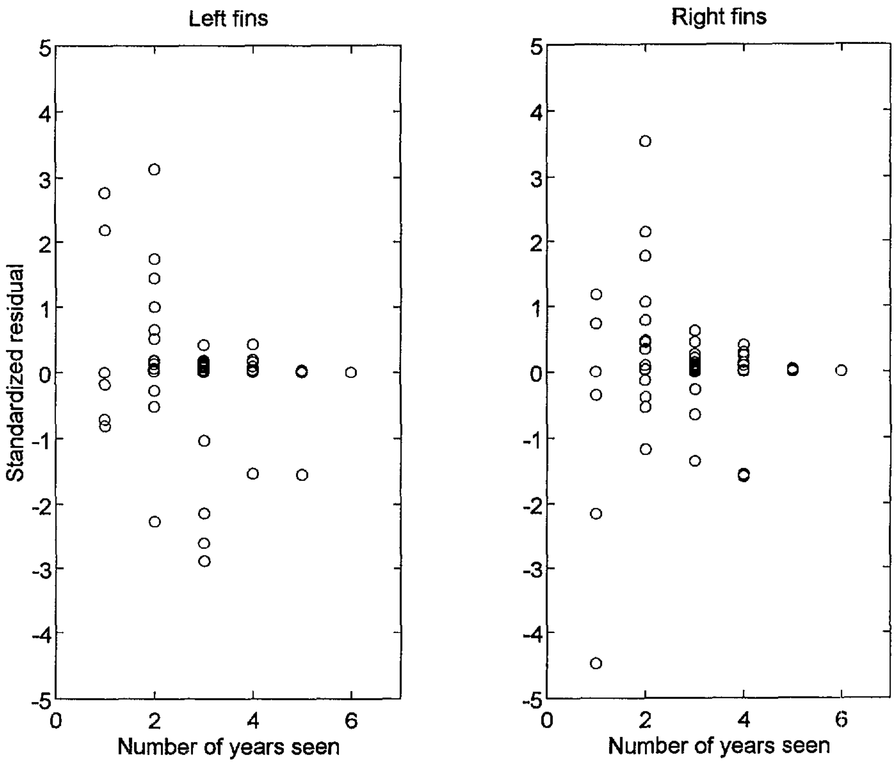

Figure 4. Residual difference between actual and predicted number of animals with each identification history plotted against the number of years identified for that identification history.

ure 4; some individuals would die quickly and be identified for short periods of time, others would live long and be identified often. There is no sign of this in our data (Fig. 4).

5. *Effect of identification*—It is hard to see how identification in one year can affect identification in subsequent years, unless animals became progressively wary of, or attracted to, boats. Such behavior would be indicated by 'U'- or 'inverted-U'-shaped patterns in the heterogeneity of identification plots shown in Figure 4, but no such patterns are apparent.

When extrapolating our estimates for the number of individuals with reliable long-term marks to the total population, we assume that the probability of photographing individuals is independent of the presence of such marks. This assumption cannot be checked, but, as the marks are generally small and not likely to be correlated with ship-seeking behavior, we think that it is reasonable.

Discussion

Although there are some probable departures from the assumptions of the mark-recapture model, these do not appear to be substantial, and they principally affect the estimates of confidence, rather than biassing the point estimates. Thus, it seems that there are about 230 northern bottlenose whales that use the Gully, and that the true number very probably lies in the range 160–360.

The precision of the estimate of mortality + emigration + mark change, about 12%/yr, is poor and uncertain (see above). Therefore, this estimate is of little value, and attempts to allocate the 12% between mortality, emigration, and mark change are not profitable.

Not only do bottlenose whales appear to use the Gully year-round, but it is largely or entirely the same individuals that are present. The animals using the Gully seem to be substantially smaller than those caught off northern Labrador (Fig. 2), 1,400 km to the north. This is the nearest other region where the species is consistently sighted (Reeves *et al.* 1993). Some of the difference could be due to different selection methods by the Labrador whalers and to our photographic measurement methods. However, this cannot account for all the difference: about 10% of the Labrador population were longer than 8.5 m, but animals this large were virtually absent from those measured during our studies or caught in the Gully (Fig. 2). As the measurements from catches in the Gully (between 1964 and 1967) took place before those off Labrador (1971) the discrepancy cannot be due to the Labrador whalers having previously removed larger animals from a single population. It is possible that only young animals visit the Gully. However, we do see distinctive mature males as well as females with calves, and a 6.15-m male with five growth layers in its teeth which stranded in the Bay of Fundy, and was thus likely from the Gully population, lay below the growth curve for animals caught in Labrador (Mitchell and Kozicki 1975).

Our results, then, suggest that the population of northern bottlenose whales using the Gully is largely distinct from the animals in more northern waters. However, additional photoidentification or genetic studies are needed to determine the extent of interchange.

Our field observations, and mark-recapture analyses using months as units, suggest that not all the animals that use the Gully are in the Gully at any one time (Whitehead *et al.,* in press). Northern bottlenose whales are occasionally sighted near the edge of the continental shelf to the east and west of the Gully (Whitehead *et al.,* in press). However the Gully seems to be the focus of their distribution.

With their small population size, location at the extreme southwestern limit of the species' range, and heavy use of a small, bathymetrically unique ocean area, this population is vulnerable to disturbance (Faucher and Whitehead 1995; Whitehead *et al.,* in press). The oil and gas fields on the Scotian Shelf are currently being developed. Exploitation of those fields nearest the Gully, with associated acoustic and chemical pollution, could have considerable impact on the population of bottlenose whales that uses the Gully.

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