Scar-Based Inference Into Gulf of Maine Humpback Whale Entanglement: 2009

Report to the
Northeast Fisheries Science Center
National Marine Fisheries Service
166 Water Street
Woods Hole, MA 02543

EA133F09CN0253
Item 0003AA, Task 3

January 5, 2011

Submitted by:

Jooke Robbins, Ph.D.
Provincetown Center for Coastal Studies
5 Holway Avenue
Provincetown, Massachusetts 02657

ABSTRACT

Entanglement in fishing gear is a known source of humpback whale, *Megaptera novaeangliae*, injury and mortality. However, reported events provide limited insight into entanglement frequency, risk factors and biological impacts. The caudal peduncle is commonly implicated in humpback whale entanglements and is consistently presented during the terminal dive. Since 1997, peduncle injuries have been studied annually as a relative index of entanglement frequency. Here we report on the analysis of injuries at the caudal peduncle and fluke insertion of 278 individual Gulf of Maine humpback whales in 2009. Preferred photographs were obtained while parallel to the whale and slightly ahead of its flukes during the terminal dive. Suitable images were examined for evidence of wrapping scars, notches and other injuries observed in documented entanglements. Of the individuals with comparable photographic coverage in 2008 (n=120), 12.5% ± 5.92% exhibited new scarring in 2009. Using another metric, 11.8% ± 3.80% of 278 individuals with suitable coverage exhibited unhealed injuries likely obtained within the prior year. Neither metric was significantly different from 2008, but it is likely too soon to detect the effects of recent mandatory changes in fishing practices aimed at reducing entanglement rates. Multi-state statistical models were also used to further study patterns and implications of entanglement injury acquisition. Modeling was based on individuals sampled Gulf of Maine-wide, 1997-2008. It included 1,688 annual encounters of 512 adults (272 females, 239 males) and 900 encounters of 643 known and suspected juveniles. The results to date support previous conclusions that 1) injuries are acquired more frequently by juveniles than by adults, 2) the sex of an individual does not consistently affect its likelihood of acquiring new injuries and 3) there has been little annual variation in scar acquisition rates over the past decade. However, modeling also revealed the possibility of lower juvenile survival after documented injuries as well as slight trends in annual entanglement rate (increasing for juveniles and decreasing for adults). We will further evaluate evidence for such effects when data from the 2009 and 2010 seasons are incorporated into this analysis.

INTRODUCTION

The humpback whale (*Megaptera novaeangliae*) is a migratory large whale that feeds at mid- to high latitudes and congregates at low latitudes to mate and calve. The Gulf of Maine is the southern-most humpback whale feeding stock in the North Atlantic. This region straddles U.S. and Canadian waters and humpback whales can be found there consistently from April through December. Animals aggregate at submerged banks and ledges, although they can be found in other areas and their spatial distribution varies with prey availability (Payne *et al.* 1990, Weinrich *et al.* 1997). In winter, the majority of the population is thought to migrate to the breeding range along the Atlantic margins of the Antilles, from Cuba to northern Venezuela (Winn et al. 1975, Balcomb & Nichols 1982, Whitehead & Moore 1982). A few Gulf of Maine whales remain in coastal U.S. waters in winter, whether in the Gulf of Maine itself (Robbins 2007) or off the U.S. mid-Atlantic states (Swingle *et al.* 1993). The latter is known to be a mixture of individuals from the Gulf of Maine, the Gulf of St. Lawrence and Newfoundland (Barco *et al.* 2002).

Humpback whales are listed as an endangered species in the U.S. and are vulnerable to a human sources of injury and mortality, including fisheries by-catch (NMFS 1991, Waring *et al.* 2007). Gear recovered from humpback whales has been tracked to sites from the Bay of Fundy to North Carolina (J.F. Kenney, pers. comm.). Between 2004-2008, there were 81 confirmed humpback whale entanglement events reported along the U.S. east coast and portions of the Canadian maritimes, and 16 were either mortalities or considered likely to result in imminent death (Glass et al. 2010). These observed impacts exceed what is considered sustainable for this population, and additional cases likely go un-witnessed (Glass et al. 2010). Furthermore, the data available from each reported case can be limited. Thus, other sources of information on the frequency of entanglement events, risk factors, and biological impacts can potentially aid mitigation efforts.

Entanglements produce injuries that can be detected even after gear is removed or shed. Since 1997, scar analysis has provided an additional source of information on the nature and frequency of entanglements on Gulf of Maine humpback whales (Robbins & Mattila 2000, 2001, 2004, Robbins 2008, Robbins 2009, Robbins 2010). This report describes the results of this study for the 2009 humpback whale feeding season in the Gulf of Maine.

METHODS

Data collection

Reported entanglements

Data from documented entanglement events were obtained from the Provincetown Center for Coastal Studies (PCCS, Massachusetts, USA) and other Atlantic Large Whale Disentanglement Network (ALWDN) members operating under the authority of the U.S. National Marine Fisheries Service (NMFS) and the Department of Fisheries and Oceans, Canada. The ALWDN has provided formal reporting, disentanglement response and awareness training along the eastern seaboard of the United States since 1997. Members attempt to obtain documentation of each entanglement, including the configuration of gear on the animal. Identifying features of the entangled whale are also obtained whenever possible so that the individual can be re-identified with or without entangling gear. The PCCS Humpback Whale Studies Program uses that documentation to identify and study Gulf of Maine humpback whales involved in reported events. Here, that information was used to identify sampled animals with confirmed entanglements, to study the injuries produced by those events and as a baseline for tracking the healing process. Entanglement reporting data were also used in conjunction with scar study data to evaluate the effectiveness of eyewitness reporting (see below).

Free-ranging animals

Entanglements may involve any body part, but are typically anchored at the mouth, flippers and/or the tail (Johnson *et al.* 2005). On the U.S. East Coast, the tail was an anchoring site for at least 53% reported entanglements (Johnson et al. 2005), and raw injuries suggested that this under-estimated tail involvement. Unlike other attachment sites, the tail can be systematically sampled when it is raised above water each time the whale takes a terminal dive. We therefore used scarring in this area as an index of the entanglement history of the individual.

This study focused on several body areas, including the posterior caudal peduncle, the insertion point of the flukes and their leading edges. Photographs were obtained in the Gulf of Maine, primarily by PCCS research vessels conducting photo-identification (photo-ID) surveys. These cruises targeted known humpback whale aggregation sites and, with the exception of the Stellwagen Bank area, sampling effort was expended roughly proportional to observed whale density. Images were generally obtained while alongside an animal and ahead of its flukes when it began its terminal dive. Photographers were instructed to photograph this part of the body whenever it was presented, without regard for injuries or scars observed in the field. Photographs were also taken when these features were exposed during rolling or lob tailing behaviors. The latter was particularly important for calves, which are less likely than older animals to systematically raise their tails upon diving. Images were obtained using digital SLR cameras equipped with a 300-mm telephoto or a 100-300mm zoom lens and shot in 24-bit color at a minimum resolution of 2160 x 1440 pixels. Supplemental photographs were also obtained from whalewatch based data collection programs operated by the Dolphin Fleet (Provincetown, MA) and the Blue Ocean Society for Marine Conservation (Portsmouth, NH).

Individual humpback whales can be identified from their natural markings, especially the ventral pigmentation of the flukes and the shape and size of the dorsal fin (Katona & Whitehead 1981). Identifying shots of each individual were matched to a photo-identification catalog of Gulf of Maine humpback whales maintained by PCCS since the 1970s. Sexes of Gulf of Maine humpback whales in this catalog were determined by genetic analysis of a tissue sample (Palsbøll et al. 1992, Bérubé & Palsbøll 1996a, b), a photograph of the genital slit (Glockner 1983) or, in the case of females, at least one documented calf. Age was known for individuals that were dependent calves at first encounter. Calves were classified in the field based on their physical size, stereotypical behaviors and close, consistent association with a mature female. They were assumed to range from 3 to 9 months old when first observed and typically remained dependent until at least October of their first year (Clapham & Mayo 1987, Baraff & Weinrich 1993). For animals without a known year of birth, a minimum age was assigned by assuming that the whale was at least 1 year old the first year it was sighted. Female humpback whales in the Gulf of Maine have been shown capable of producing a calf as early as age five (Clapham 1992), although the average age at first reproduction was closer to nine years during the study period (Robbins 2007). Animals first cataloged as calves and less than five years old in the year that they were sampled were considered juveniles. Whales were considered adult if they were known to be at least five years old or were first sampled as an independent whale at least four years prior to being sampled. A maturational class could not be confidently assigned to whales without a known year of birth and first cataloged less than four years prior to sampling. However, these were assumed to be predominantly juvenile animals (Robbins 2007).

Entanglement scar analysis and interpretation

A single individual (JR) examined evidence of a previous entanglement across six body areas: the right and left posterior flank, the right and left leading edge of the flukes, the dorsal peduncle and the ventral peduncle. High probability injuries consisted of healed scars or unhealed wounds that were consistent with wrapping around the feature. Healed injuries could be raised or indented, but tended to be smooth and either white or black in color. Unhealed injuries were identified based on their color (often grey, pink or red) and angularity. When multiple images were available from the same individual, we selected the best image per feature per day for analysis. The quality of the images was also evaluated prior to coding, taking into consideration factors such as distance to the subject, angle and focus. Images taken of the right and left sides of the animal, when available, were initially evaluated independently. Data on documented entanglements and other known sources of injury were not factored into the initial coding process.

When a new individual was added to the study, it was assigned to an entanglement history category based on its composite scar patterns. Animals with high probability scarring in at least two body areas were assigned a 'high' probability of a prior entanglement. Those with no diagnostic injuries or scars were considered to have a 'low' probability of prior entanglement. When injuries were detected in only one body area, entanglement was neither strongly supported nor ruled out. In those cases, the whale was assigned an 'uncertain' probability of previous entanglement. However, patterns of scarring in any given image represent a composite of events over the lifetime of the whale. Some injuries may have been acquired long ago, while others may have healed beyond recognition. Once we obtained at least one image of a feature, we focused our attention on scarring and injuries that were not present in that baseline coverage. From one sampling period to the next, an individual's scarring pattern could remain the same, decrease as a result of healing or increase as new events occurred. Unhealed injuries were also flagged to better estimate the timing of injury acquisition and to identify recent events for whales without prior baseline images. New injuries were assumed not to have resulted from entanglement if they did not meet the above criteria for high probability of prior entanglement.

Scar-based inference was evaluated using data from documented entanglement events. We calculated the frequency with which previously entangled individuals in our sample were successfully coded as having a high probability of entanglement. We also tracked the persistence of unhealed entanglement injuries from the time that the gear was successfully shed or removed by disentanglement. The latter was done to further assess the value and limitations of unhealed injuries for tracking entanglements from one year to the next. Finally, we estimated the entanglement reporting rate for the study period by cross-referencing animals exhibiting new entanglement injuries in this study with those that were reported entangled during the same period. Scar-based cases that could not be linked to a documented event based on the identity of the individual and the timing of its injuries were considered unreported events.

Entanglement frequency and impact

Proportional indices

Two proportional indices were used to evaluate recent trends in entanglement frequency. The first was an inter-annual metric based on the frequency of new entanglement injuries among individuals with comparable photographic coverage the prior year. However, some individuals were more likely than others to be re-sighted, others were not previously available for sampling (such as calves) and photographic coverage was not always comparable when inter-annual re-sightings did occur. We therefore also calculated the frequency of unhealed entanglement injuries for all sampled individuals with high quality coverage of one or both sides. Unhealed injuries were assumed to have been acquired recently and therefore informative without a baseline sample. The results of these two approaches were later cross-referenced to produce a minimum count of events that likely occurred from one year to the next. The 95% confidence interval (*CI*) of percentages were calculated based on the standard error, as follows:

$$CI = 1.96\sqrt{\frac{p*(100-p)}{n}}$$

Where: p = the percentage of interest and n = total number of animals examined. Indices were calculated in a similar manner to compare the incidence of raw injuries among age classes and across geographic areas. Categorical differences between samples were evaluated using a G-test with a William's correction (Sokal & Rohlf 1981).

Mark-recapture statistics

Mark-recapture statistical techniques were also used to estimate injury acquisition rates from 1997 through 2008, in light of the fact that individuals are not equally likely to survive and be seen in all years. Multi-state mark-recapture models estimate transitions between states after accounting for detection probabilities and apparent survival (Arnason 1972, 1973, Hestbeck et al. 1991, Brownie et al. 1993, Schwarz et al. 1993, Lebreton & Pradel 2002). The technique is a generalisation of the Cormack-Jolly-Seber (CJS) model (Cormack 1964, Jolly 1965, Seber 1965) and was implemented in program MARK. Individuals were considered "marked" in the year that they entered this study. An encounter history was then constructed for each indicating its annual sighting status (seen or not) and inferred entanglement state (new entanglement injury documented or not) when observed. New injuries included any wound or scar that was consistent with entanglement and was either photographically confirmed to be new since the last sighting or was unhealed. If an individual was seen in a given year but not appropriately sampled for this study, then that sighting was not included. Reported entanglement events were also not included unless the event was reported by us during our survey effort.

Analysis was based on the Arnason-Schwartz (AS) multi-state model which assumes that the probability of making a state transition does not depend on prior states (Arnason 1972, 1973, Schwarz et al. 1993). To minimize model complexity, juvenile encounter histories were analyzed separately from adults. Juveniles were modelled as a single group potentially moving between two entanglement states. Additionally, they could make a one-way transition to an absorbing third adult state, although entanglement transitions within that state were evaluated in the adult model. Adults were only permitted to move among two entanglement states, but were further grouped by sex. We did not incorporate the sex of juveniles into the models because genetic analysis results were not yet available for many individuals and the added model complexity did not seem warranted in light of the results for adults. A list of notations used to describe model structure is shown in Table 1. Note that in light of the results of prior studies, we did not consider models in which detection probability did not vary with time. We also did not model time variation in survival or in return transitions from entangled states. Otherwise, all relevant combinations were included. We evaluated the goodness of fit (GOF) of the most parameterized (global) models to the data (see below) and then examined support for reduced models.

Mark-recapture models produce valid estimates only when the data meet model assumptions. Program U-CARE (version 2.2.5, Choquet et al. 2005) was used to detect and diagnose heterogeneity in apparent survival (Test3G.Sr and Test3G.Sm) and detection probabilities (Test M.ITEC and Test M.LTEC). We first attempted to account for significant GOF test results by adjusting the structure of the starting model (Choquet et al. 2009). A variance inflation factor (c-hat) was then calculated by dividing the Pearson statistic of the sum of each U-CARE test component by its degrees of freedom, after removing any test components that were addressed structurally (Choquet et al. 2009). An estimate of c-hat was also produced based on the global model using the median c-hat function in program MARK. We used the larger of the two values to address residual over dispersion during the model selection process.

Model selection was performed in program MARK (version 6.1), based on Akaike's Information Criterion (Burnham & Anderson 2002). Akaike's Information Criterion (AIC) evaluates the relative fit of each candidate model in light of the number of parameters necessary to achieve that fit. We used QAICc, a form that accounted both for small sample sizes and the inclusion of a variance inflation factor. The model with the lowest QAICc value was considered the most parsimonious, and other models were evaluated based on their distance from the preferred model (ΔQAICc). Those within 2 units were considered equally likely given the data, whereas a model that differed by 10 units or more was inferred to have no support (Burnham & Anderson 2002). In most cases, model selection sought the most parsimonious fit for re-sighting, apparent survival and transition parameters, in that order. Parsimony was attempted by reducing model parameters, starting with interactions (*), additive effects (+) and finally main effects. Multi-state models sometimes fail to reach global optima and we addressed this known problem in MARK by optimizing with simulated annealing and re-running the model as necessary using prior results as starting values. Given model selection uncertainty, parameter estimates were generated by model averaging in program MARK.

RESULTS

Over 1,800 caudal peduncle images collected from Gulf of Maine humpback whales in 2009 were ultimately screened for potential use for scar-based inference. Images had been obtained on 98 days between March 15 and December 15, 2009, with individuals documented on an average of 2.00 days (max=12 days). We evaluated entanglement status based on the best daily photographic coverage from 278 individual animals. While not all images were considered to be of equal or adequate quality for determining entanglement status through blind coding techniques, they were deemed potentially valuable for monitoring the same individual over time.

The majority (72.7%, n=202) of the individuals evaluated had prior baseline coverage, but these were predominantly adults. Most of the individuals entering the study for the first time (n=76) were calves (n=14), independent juveniles (n=11) or other animals with short prior sighting histories (n=41). Only 10 new individuals were known to be adults. Sexes have not yet been determined for many of the individuals newly entering the study; however, more than half of the sexed whales in the overall sample were female (62.8%, n=120). Sampling was performed in nine aggregation sites in US and Canadian Gulf of Maine waters, but more whales were encountered in southern New England (coastal waters from Stellwagen Bank to the Great South Channel) than elsewhere. The overall demography of the sample was generally consistent with prior years.

Among the individuals with comparable photographic coverage in 2008 (n=120), 12.5% ± 5.92% exhibited new high probability scarring in 2009 (Figure 1). Using an alternate metric, 11.8% ± 3.80% of the individuals with adequate coverage in 2009 (n=278) exhibited unhealed injuries that were likely received within the previous year. Neither result was significantly different from 2008. There was a higher incidence of unhealed injuries among known and suspected juveniles as compared to adults ($G=15.71$, $p<0.001$, $df=1$), consistent with previous years (Figure 2). The vast majority appeared to involve skin lacerations and abrasions (87.9%, n=29), with only a few penetrating more deeply into the flukes or caudal peduncle. In total, there were 47 new events detected based on scarring, of which 35 were known or inferred to have occurred within the prior year and 12 were known to have occurred sometime between 2001 and 2007. Focusing on unhealed injuries, eight were confirmed to have happened before the end of April 2009, whereas at least seven individuals received new injuries after that time (see Figure 3). The specific timing of the remaining cases could not be determined at that level of temporal detail. Unhealed injuries were more prevalent in sightings made off northern New England (33.3%, n=4) than either southern New England (12.1%, n=28) or the Canadian Gulf of Maine (5.4%, n=2). However, these apparent spatial differences were not statistically significant ($G=3.08$, $p=0.214$, $df=2$).

Seven of the individuals in our study were sampled after reported entanglement events in 2008 or 2009. Five of those reports involved hook/monofilament line interactions, and none of those produced persistent raw injuries at the peduncle. Individuals involved in the other two entanglement cases (Ravine 08 calf and Pepper) both exhibited raw injuries at the caudal peduncle. Given that these were the only new injuries in our study that corresponded to non hook/monofilament entanglement reports, the entanglement detection and reporting rate was estimated to be 5.7%.

Scar acquisition modeling

Modeling was based on individuals sampled Gulf of Maine-wide, 1997-2008. It included 1,688 annual encounters of 512 adults (272 females, 239 males) and 900 encounters of 643 known and suspected juveniles. Sex was not known for 16 adults (17 encounters) and so these data were excluded from analysis. Goodness of fit testing indicated a significant transient effect for juveniles and adult males (Table 2). This was addressed structurally in the models by allowing survival in the entry interval to differ from all subsequent intervals (i.e., TSM models, Pradel et al. 1997). The median c-hat procedure estimated slightly higher values of c-hat than indicated by U-CARE test statistics (Table 2) and so we applied the former during model selection. The results of this process are shown in Table 3 for juveniles and Table 4 for adults. The parameters of primary interest were the probability of entanglement, whether constant, annually variable or trending over time) and the probability of survival relative to entanglement state. Models in which detection probability varied with entanglement state either failed to estimate desired parameters or produced implausibly high entanglement probabilities for both juveniles and adults. We interpreted this to be due to inadequacies in the data or constraints and excluded those configurations from further analysis.

Of the 18 models considered for juveniles, two were equally plausible and four shared virtually all of the support from the data (Table 3). In all of these, juveniles exhibited time-varying detection probabilities. In the top ranking model, juvenile survival did not vary with entanglement state and entanglement probabilities were constant over time. However, there was also support for models in which juveniles had lower survival after new injuries, as well those in which there was a slight increasing trend in the probability of entanglement over time. Given model selection uncertainty, parameter estimates were obtained model averaging. Apparent survival estimates are shown in Table 5 and annual probabilities of entanglement are depicted on

Figure 4. As expected from model selection, the resulting point estimate of juvenile survival was lower after entanglement, but with confidence intervals overlapping the non-entangled survival estimate. A similar result was observed for annual estimates of entanglement probability (Figure 4).

In the case of adults, the models with the most support from the data were those in which males and females exhibited parallel, time-varying detection probabilities. Three models were equally plausible given the data. In the top ranking model, survival was slightly lower for adult females but was not affected by entanglement state, nor did the probability of entanglement vary with time. However, there was also support for models without a gender effect on survival and in which entanglement probability decreased slightly over time. Model averaged parameter estimates for survival are shown in Table 4 and entanglement probabilities are depicted in Figure 4. As expected, these produced estimates with overlapping confidence for sex-stratified adult survival (Table 4) and for annual probabilities of entanglement (Figure 4).

DISCUSSION

Scar monitoring has provided an annual index of Gulf of Maine humpback whale entanglement rates since 1997. It studies one common entanglement injury site (the caudal peduncle/flukes) on free-ranging individuals and so is not expected to detect all events. Nevertheless, it is an effort-based alternative to eyewitness entanglement reporting data, for which the number and distribution of potential observers is rarely known. It is also a component of the longitudinal research on this population and therefore linked to other useful data, such as the age and sighting histories of individuals. Because estimates are effort based, they do not include or depend directly on reported entanglements. This is important given that scar-based inference continues to indicate a low frequency of successful entanglement reporting in the Gulf of Maine, despite a well-developed reporting and response network. Furthermore, our results are independent from other measures of entanglement rate and/or mitigation success.

As in previous years, we used two proportional indices to estimate the frequency of recent entanglements. Both suggested scar acquisition rates for adults and juveniles that were consistent with previous years. It is tempting to interpret these results in the context of the April 2009 federally-mandated switch to sinking ground line coast-wide. However, it is too soon to reliably evaluate possible effects of that action from scar-based inference. We were fortunate to have been able to sample humpback whale aggregations in early to mid-March in 2009, and this early spring baseline coverage allowed us to definitively identify some injuries that occurred either before or after this critical date. However, injuries can take months to heal and so it was not to possible to evaluate the remaining cases on such a fine temporal scale. Similar uncertainty exists with regard to reported events, given that the prior duration of an observed entanglement can only be determined from individual sighting histories or gear set information. In 2009, PCCS sighting history data demonstrates that at least two of four reported entanglements involving identified Gulf of Maine humpbacks occurred after April. Overall, results from 2009 confirm that the ground line rule did not eliminate entanglement, but this was also not expected. The degree to which this management action may have reduced the frequency of entanglement will be further evaluated as data accumulate.

One tool for evaluating changes in entanglement rate will be the newly implemented mark-recapture statistical analysis described here. Mark-recapture statistics use more of the available data and estimate other parameters of biological interest, such as the survival of individuals in relation to scar acquisition. They also provide a unified framework for evaluating the relative support for various working hypotheses, given the available data. The modeling results reported here focused on the data collected through 2008, to better understand the baseline period prior to the ground line rule. The parameters of primary interest were the probability of entanglement (whether constant, annually variable or trending over time) and the probability of survival relative to entanglement state. Multi-state models estimate probabilities of state changes (in this case, acquiring new entanglement injuries) from one occasion to the next. As such, the specific values estimated are not directly comparable to annual proportional indices from prior years. Nevertheless, modeling results supported several of the conclusions previously drawn from proportional indices: 1) injuries are acquired more frequently by juveniles than by adults, 2) the sex of an adult does not appear to play an important role in the acquisition of new injuries and 3) there has been little annual variation in acquisition rates over the past decade. Nevertheless, model selection can only evaluate support for the suite of model structures identified for analysis. We chose these models based on our *a priori* understanding of biology, as well as known or expected limitations of the data. However, we will continue to further evaluate and refine candidate models as the results from 2009 and 2010 seasons are incorporated into this analysis. This work may also be facilitated by the use of other mark-recapture modeling software, such as programs M-Surge or E-Surge.

Multi-state modeling produced age and sex stratified apparent survival estimates within the ranges previously reported for this population (Rosenbaum et al. 2002, Robbins 2007). They confirmed expectations that juvenile survival rates would be lower than adults (regardless of entanglement status), thereby highlighting the importance of age-stratification when evaluating biological effects. The results also suggested that recently entangled juveniles (but not adults) may have a lower probability of survival than those with no new injuries. Previously, it has been assumed that scar-based studies monitor non-lethal events, but this had not formally been tested. If there is reduced survival among formally-entangled, free-swimming individuals then such an effect would need to be accounted for in estimates of entanglement mortality (such as in the approach described by Robbins et al. 2009). Support for this effect was ambivalent in the models that were run and so future modeling will explore this question further with the aid of covariate data, such as the apparent severity of observed injuries. We also plan to re-examine our quality coding and screening practices to determine whether more data are being excluded than necessary to make reliable assessments of entanglement state. If so, then it may be possible to increase the sample sizes available to answer this question, as well as when evaluating future trends in entanglement rate.

Finally, scar studies on free-ranging whales have typically not been informative regarding the specific type of gear involved in the interaction. However, it is worth noting that most of the documented humpback whale interactions with hook/monofilament fisheries have not produced injuries at the caudal peduncle. This is likely because of the different way in which whales encounter and carry this gear. Although we do not believe that our estimates capture these types of interactions, this will be further evaluated as more documented cases become available for study.

Acknowledgements

Thanks to Scott Landry, Jenn Tackaberry and Christie McMillan for their assistance with this study, and to Richard Pace for originally suggesting a mark-recapture statistical approach. Supplemental data were provided by the Dolphin Fleet and Blue Ocean Society. Per Palsbøll and Martine Bérubé undertook the molecular genetic sexing of Gulf of Maine humpback whales.

Special thanks to the PCCS Marine Animal Entanglement Response Program, the Atlantic Large Whale Disentanglement Network and the National Marine Fisheries Service for information on documented entanglement events. When required in U.S. waters, photographic sampling was performed under NOAA ESA/MMPA permit 633-1778. In Canadian waters, sampling was conducted with the authorization of the U.S. Department of State and the Department of Fisheries and Oceans Canada. Additional support for data collection was provided by the Beneficia Foundation and other donors.

References cited

Arnason AN (1972) Parameter estimates from mark-recapture experiments on two populations subject to migration and death. Researches on population ecology 13:97-113

Arnason AN (1973) The estimation of population size, migration rates and survival in a stratified population. Researches on population ecology 15:1-8

Balcomb KC, Nichols G (1982) Humpback whale censuses in the West Indies. Rep int Whal Commn 32:401-406

Baraff LS, Weinrich MT (1993) Separation of humpback whale mothers and calves on a feeding ground in early autumn. Mar Mamm Sci 9:431-434

Barco SG, McLellan WA, Allen JM, Asmutis-Silvia RA, Mallon-Day R, Meagher EM, Pabst DA, Robbins J, Seton RE, Swingle WM, Weinrich MT, Clapham PJ (2002) Population identity of humpback whales (*Megaptera novaeangliae*) in the waters of the US mid-Atlantic states. J Cetacean Res Manage 4:135-141

Bérubé M, Palsbøll PJ (1996a) Identification of sex in cetaceans by multiplexing with three ZFX and ZFY specific primers. Molecular Ecology 5:283-287

Bérubé M, Palsbøll PJ (1996b) Identification of sex in cetaceans by multiplexing with three ZFX and ZFY specific primers: erratum. Molecular Ecology 5:602

Brownie C, Hines JE, Nichols JD, Pollock KH, Hestbeck JB (1993) Capture-recapture studies for multiple strata including non-Markovian transitions. Biometrics 49:1173-1187

Burnham KP, Anderson DR (2002) Model selection and multimodel inference: a practical information-theoretic approach, Vol. Springer-Verlag, New York

Choquet R, Lebreton J-D, Gimenez O, Reboulet A-M, Pradel R (2009) U-CARE: Utilities for performing goodness of fit tests and manipulating CApture-REcapture data. Ecography 32:1071-1074 (Version 1072.1073)

Choquet R, Reboulet A-M, Lebreton J-D, Gimenez O, Pradel R (2005) U-CARE 2.2 User's Manual., CEFE, Monpellier, France.

Clapham PJ (1992) Age at attainment of sexual maturity in humpback whales, *Megaptera novaeangliae*. Can J Zool 70:1470-1472

Clapham PJ, Mayo CA (1987) Reproduction and recruitment of individually identified humpback whales, *Megaptera novaeangliae*, observed in Massachusetts Bay, 1979-1985. Can J Zool 65:2853-2863

Cormack RM (1964) Estimates of survival from the sighting of marked animals. Biometrika 51:429-438

Glass AH, Cole TVN, Garron M (2010) Mortality and serious injury determinations for baleen whale stocks along the United States Eastern Seaboard and Adjacent Canadian Maritimes, 2004-2008 (Second Edition). Report No. U.S. Dep. Commer., *NOAA Technical Memorandum NMFS-NE-214.*

Glockner DA (1983) Determining the sex of humpback whales in their natural environment. In: Payne R (ed) Communication and Behavior of Whales. AAAS Selected Symposium 76. Westview Press, Colorado, p 447-464

Hestbeck JB, Nichols JD, Malecki RA (1991) Estimates of movement and site fidelity using mark resight data of wintering Canada geese. Ecology 72:523-533

Johnson A, Salvador G, Kenney J, Robbins J, Kraus S, Landry S, Clapham P (2005) Analysis of fishing gear involved in entanglements of right and humpback whales. Mar Mamm Sci 21:635-645

Jolly GM (1965) Explicit estimates from capture-recapture data with both death and immigration stochastic model. Biometrika 52:225-247

Katona SK, Whitehead HP (1981) Identifying humpback whales using their natural markings. Polar Rec 20:439-444

Lebreton JD, Pradel R (2002) Multistate recapture models: modelling incomplete individual histories. Journal of Applied Statistics 29:353-369

National Marine Fisheries Service (1991). Recovery plan for the humpback whale (Megaptera novaeangliae). Prepared by the Humpback Whale Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland. 105pp.

Palsbøll PJ, Vader A, Bakke I, El-Gewely MR (1992) Determination of gender in cetaceans by the polymerase chain reaction. Can J Zool 70:2166-2170

Payne PM, Wiley DN, Young SB, Pittman S, Clapham PJ, Jossi JW (1990) Recent fluctuations in the abundance of baleen whales in the southern Gulf of Maine in relation to changes in selective prey. Fish B-NOAA 88:687-696

Pradel R, Hines JE, Lebreton JD, Nichols JD (1997) Capture-recapture survival models taking account of transients. Biometrics 53:60-72

Robbins J (2007) Structure and dynamics of the Gulf of Maine humpback whale population. Ph.D. thesis, University of St. Andrews. http://hdl.handle.net/10023/328

Robbins J (2008) Scar-Based inference into Gulf of Maine humpback whale entanglement: 2007. Report to the National Marine Fisheries Service. Order Number EA133F07SE2932.

Robbins J (2009) Scar-Based inference into Gulf of Maine humpback whale entanglement: 2003-2006. , Report to the National Marine Fisheries Service. Order Number EA133F04SE0998.

Robbins J (2010) Scar-based inference into Gulf of Maine humpback whale entanglement: 2008, Report to the National Marine Fisheries Service. Order number EA133F09CN0253

Robbins J, Mattila DK (2000) Monitoring entanglement scars on the caudal peduncle of Gulf of Maine humpback whales: 1997-1999. Report to the National Marine Fisheries Service. Order number 40ENNF900253.

Robbins J, Mattila DK (2001) Monitoring entanglements of humpback whales (*Megaptera novaeangliae*) in the Gulf of Maine on the basis of caudal peduncle scarring. Unpublished report to the Scientific Committee of the International Whaling Commission: SC/53/NAH25.

Robbins J, Mattila DK (2004) Estimating humpback whale (Megaptera novaeangliae) entanglement rates on the basis of scar evidence. Report to the National Marine Fisheries Service. Order number 43ENNF030121.

Rosenbaum HC, Weinrich MT, Stoleson SA, Gibbs JP, Baker CS, DeSalle R (2002) The effect of differential reproductive success on population genetic structure: Correlations of life history with matrilines in humpback whales of the Gulf of Maine. J Hered 93:389-399

Schwarz CJ, Schweigert JF, Arnason AN (1993) Estimating migration rates using tag-recovery data. Biometrics 49:177-193

Seber GAF (1965) A note on the multiple recapture census. Biometrika 52:249-259

Sokal RR, Rohlf FJ (1981) Biometry, Vol. W.H. Freeman and Company, New York

Swingle WM, Barco SG, Pitchford TD, McLellan WA, Pabst DA (1993) Appearance of juvenile humpback whales feeding in the nearshore waters of Virginia. Mar Mamm Sci 9:309-315

Waring GT, Josephson E, Fairfield-Walsh CP, Maze-Foley K (2007) U.S. Atlantic and Gulf of Mexico marine mammal stock assessments - 2007

Weinrich MT, Martin M, Griffiths R, Bove J, Schilling M (1997) A shift in distribution of humpback whales, *Megaptera novaeangliae*, in response to prey in the southern Gulf of Maine. Fish B-NOAA 95:826-836

Whitehead H, Moore MJ (1982) Distribution and movements of West Indian humpback whales in winter. Can J Zool 60:2203-2211

Winn HE, Edel RK, Taruski AG (1975) Population estimate of the humpback whale (*Megaptera novaeangliae*) in the West Indies by visual and acoustic techniques. J Fish Res Board Can 32:499-506

Figure 1: Inter-annual acquisition of entanglement scars, 1997-2009. These represent the percentage of individuals confirmed to have acquired new injuries between years. The 95% confidence interval of percentages were calculated based on the standard error. Data from previous sampling periods are reproduced from previous reports (Robbins and Mattila 2004, Robbins 2008; 2009; 2010).

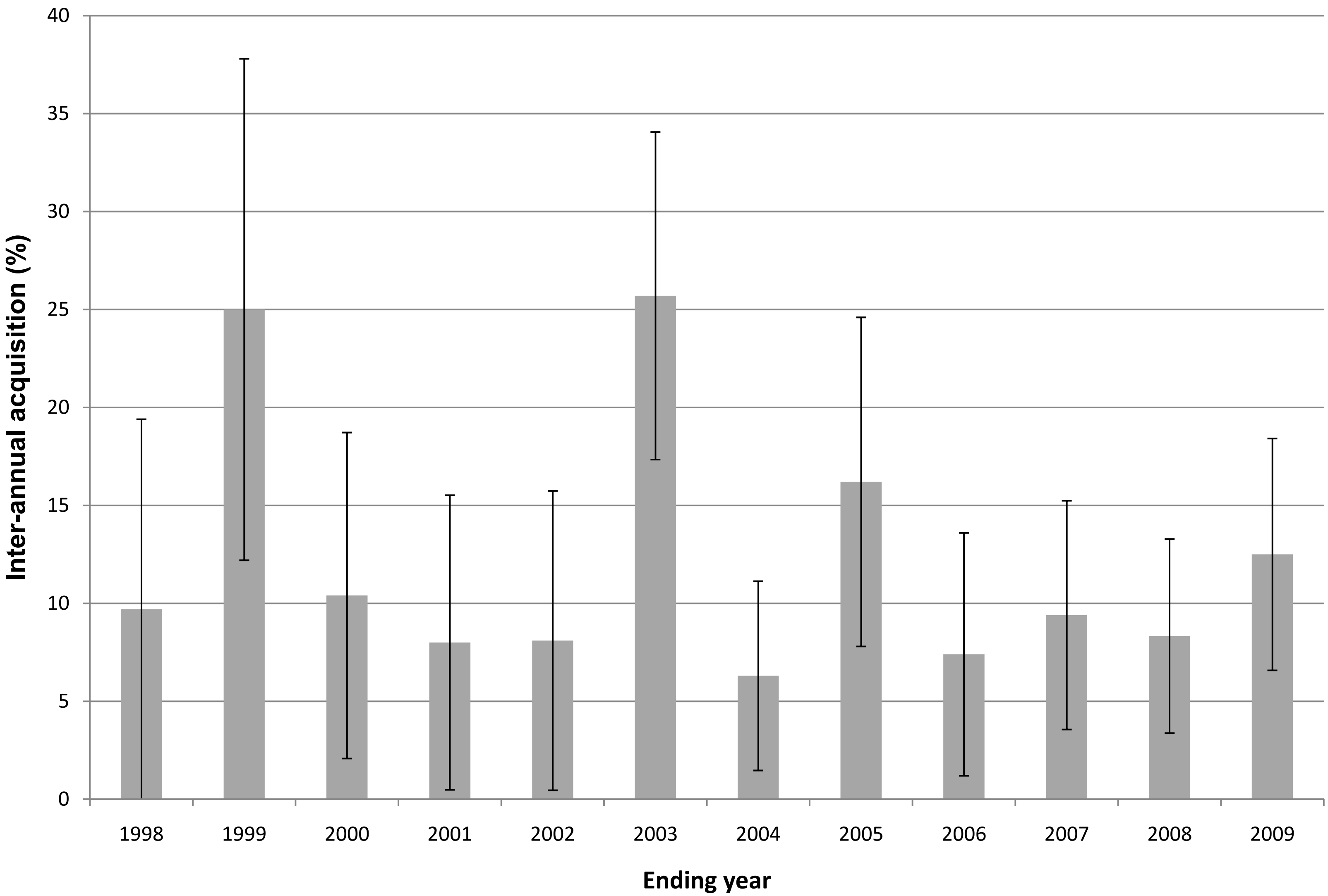

Figure 2: Frequency of unhealed injuries by year and age class, 2003-2009. The 95% confidence interval of percentages were calculated based on the standard error. Data from previous sampling periods are reproduced from Robbins (2010).

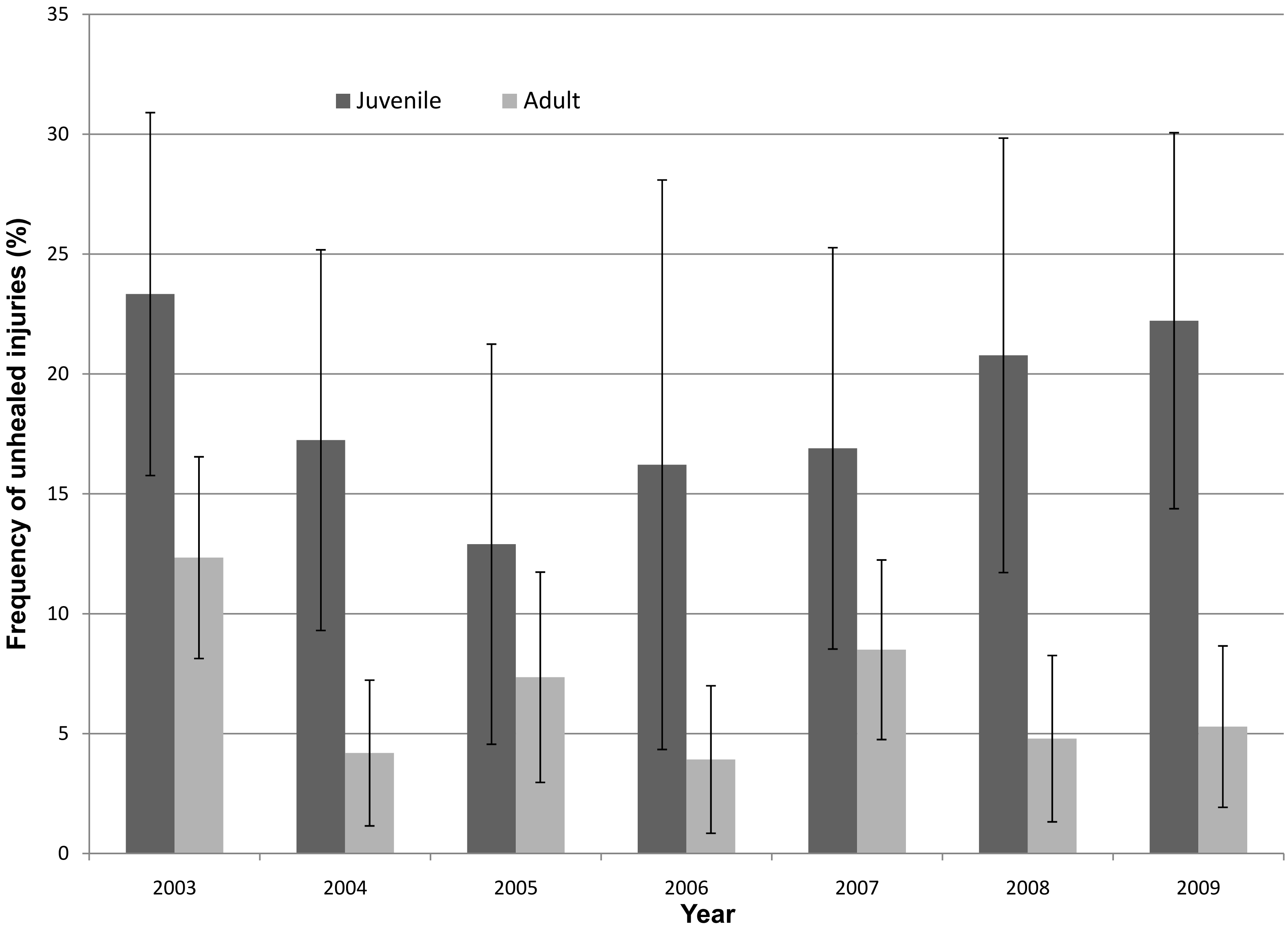

Figure 3: Examples of scar interpretation in 2009. Note that there are wrapping scars, notches and other injuries in at least two areas in all documented and inferred entanglement cases.

a) No scarring indicative of entanglement.

b) Unhealed injuries indicative of a recent entanglement. This event occurred before April 10, 2009 and does not correspond to any reported event.

c) Unhealed injuries obtained between obtained between July 6 and August 14, 2009. This case does not correspond to any reported event.

d) Unhealed entanglement-related injuries first obtained between August 20, 2007 and August 28, 2009. No other sightings were made between those dates.

Figure 4: Model averaged estimates of Gulf of Maine humpback whale entanglement scar acquisition, 1997-2008. Estimates reflect the probability of obtaining new injuries from one year to the next, conditional on survival. The 95% confidence intervals are not shown for adult females for the sake of clarity, but were comparable to adult males. Model selection results are shown in Tables 3 (juveniles) and 4 (adults).

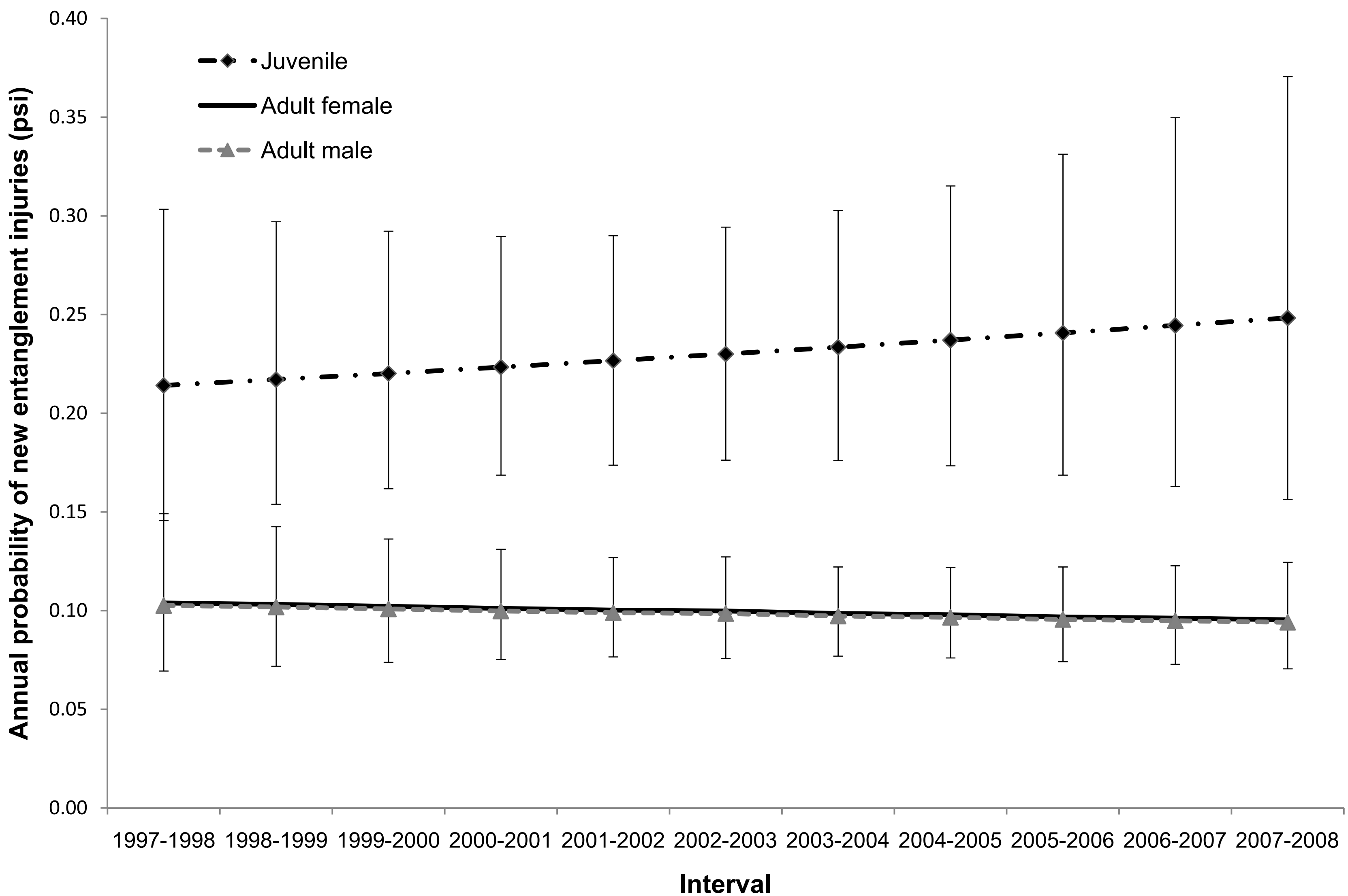

Table 1: Notations used to describe multi-state models of entanglement scar acquisition in Gulf of Maine humpback whales.

Type	Notation	Description
Parameters	phi	Apparent survival probability
	p	Detection probability
	psi	Probability of state transition. All individuals could move between two states ("new entanglement injuries" or "no new entanglement injuries") from one year to the next. Juveniles could also make a one-way (absorbing) transition to an adult state. Model notation refers only to transitions from no new injuries to new injuries.
Factors/ constraints	m/	Time since marking (Pradel et al. 1997) is a 2-age structure imposed on the apparent survival of juveniles and adult males to address heterogeneity (transience) identified during goodness of fit testing.
	.	Parameter held constant
	a	Differences between juveniles and adults
	g	Differences between adult males and adult females
	e	Differences between individuals with and without new entanglement injuries
	t	Differences across years.
	T	Increasing or decreasing trend in the probability of acquiring new injuries.
	*	Interactive effect
	+	Additive effect

Table 2: Goodness of fit testing results. Tests were implemented in program U-CARE to evaluate different aspects of possible heterogeneity in the data. WBWA tests for a memory effect. Two test 3G components test for evidence of transience. Two test M components (ITEC and LTEC) test for trap-dependence. Significant results are highlighted in grey and addressed by structural modification to the global model. A variance inflation factor (c-hat) was estimated by dividing the sum of the X^2 values by the sum of the degrees of freedom (df) across tests, excluding components that were structurally adjusted. Also shown is the value of c-hat estimated for the revised global model by the median c-hat routine in program MARK. The higher of the two c-hat values was used to address residual over dispersion during model selection.

Test	**Juveniles**	**Adult Females**	**Adult Males**
WBWA p-value (X^2, df)	0.966 (2.395, 8)	0.802 (6.962, 11)	0.902 (4.138, 9)
3G.sr p-value (X^2, df)	0.034 (33.000, 20)	0.338 (18.843, 17)	0.003 (32.756, 14)
3G.sm p-value (X^2, df)	0.914 (57.994, 74)	0.994 (28.240, 50)	0.922 (30.617, 43)
M.ITEC p-value (X^2, df)	0.245 (12.637, 10)	0.062* (16.259, 9)	0.567 (7.676, 9)
M.LTEC p-value (X^2, df)	0.026* (17.453,8)	0.258 (10.101, 8)	0.577 (5.681, 7)
C-hat ($\Sigma X^2/\Sigma df$)	0.905	0.846	0.986
Median c-hat	1.1701	1.1200	

*The significant effect was limited to one or two occasions and so no structural change was made to the model.

Table 3: Model selection results for juvenile humpback whale entanglement scar acquisition, 1997-2008. QAICc refers to Akaike's Information Criterion corrected for small sample sizes. Delta QAICc is the difference from the minimum QAICc model. The QAICc weight is a measure of the relative support for each model. See Table 1 for a description of model notations.

Model	**Delta QAICc**	**AICc Weight**	**QAICc**	**Parameter count**
phi(m/a) p(a*t) psi(.)	0.00	0.47227	2882.01	29
phi(m/a) p(a*t) psi(T)	1.29	0.24776	2883.30	30
phi(m/a*e) p(a*t) psi(.)	2.09	0.16575	2884.10	31
phi(m/a*e) p(a*t) psi(T)	2.85	0.11369	2884.86	32
phi(m/a) p(a*e*t) psi(.)	15.64	0.00019	2897.65	40
phi(m/a) p(a*t) psi(t)	16.52	0.00012	2898.53	39
phi(m/ a*e) p(a*e*t) psi(T)	17.52	0.00007	2899.53	43
phi(m/ a*e) p(a*e*t) psi(.)	18.26	0.00005	2900.27	42
phi(m/a) p(a*e*t) psi(T)	18.32	0.00005	2900.33	41
phi(m/ a*e) p(a*t) psi(t)	18.88	0.00004	2900.89	41
Global: phi(m/ a*e) p(a*e*t) psi(t)	22.48	0.00001	2904.49	52
phi(m/a) p(a*e*t) psi(t)	30.40	0	2912.41	50
phi(m/a) p(t) psi(.)	44.57	0	2926.58	18
phi(m/a) p(t) psi(T)	45.90	0	2927.91	19
phi(m/ a*e) p(t) psi(.)	46.43	0	2928.44	20
phi(m/ a*e) p(t) psi(T)	46.98	0	2928.99	21
phi(m/a) p(t) psi(t)	60.70	0	2942.71	28
phi(m/ a*e) p(t) psi(t)	62.89	0	2944.90	30

Table 4: Top model selection results for adult humpback whale entanglement scar acquisition, 1997-2008. Models with no support from the data are not shown. QAICc refers to Akaike's Information Criterion corrected for small sample sizes. Delta QAICc is the difference from the minimum QAICc model. The QAICc weight is a measure of the relative support for each model. See Table 1 for a description of model notations.

Model	**Delta QAICc**	**AICc Weight**	**QAICc**	**Parameter count**
phi(m/g) p(g+t) psi(.)	0.00	0.3396	4414.49	17
phi(m/.) p(g+t) psi(.)	0.91	0.2156	4415.40	16
phi(m/g) p(g+t) psi(T)	1.40	0.1686	4415.89	18
phi(m/.) p(g+t) psi(T)	2.31	0.1072	4416.80	17
phi(m/g) p(g+t) psi(g)	3.63	0.0554	4418.12	19
phi(m/.) p(g+t) psi(g)	4.53	0.0353	4419.02	18
phi(m/e) p(g+t) psi(.)	4.99	0.0280	4419.48	18
phi(m/e) p(g*t) psi(T)	6.36	0.0141	4420.86	19
phi(m/e) p(g+t) psi(T)	6.36	0.0141	4420.86	19
phi(m/e) p(g+t) psi(g)	8.63	0.0045	4423.12	20
phi(m/.) p(t) psi(.)	9.24	0.0033	4423.73	15
phi(m/g) p(g+t) psi(t)	9.28	0.0033	4423.77	27
phi(m/.) p(g+t) psi(t)	10.16	0.0021	4424.66	26
phi(m/.) p(t) psi(T)	10.64	0.0017	4425.13	16
phi(m/g) p(t) psi(.)	10.82	0.0015	4425.31	16
phi(m/g) p(g*t) psi(.)	11.15	0.0013	4425.64	27
phi(m/g) p(t) psi(T)	12.22	0.0008	4426.71	17
phi(m/g) p(g*t) psi(T)	12.58	0.0006	4427.07	28
phi(m/.) p(g*t) psi(.)	12.62	0.0006	4427.11	26
phi(m/.) p(t) psi(g)	12.86	0.0006	4427.35	17
phi(m/e) p(t) psi(.)	13.28	0.0004	4427.77	17
phi(m/.) p(g*t) psi(T)	14.04	0.0003	4428.53	27
phi(m/e) p(g+t) psi(t)	14.28	0.0003	4428.77	28
phi(m/g) p(t) psi(g)	14.44	0.0003	4428.93	18
phi(m/g) p(g*t) psi(g)	14.83	0.0002	4429.32	29
phi(m/.) p(g*t) psi(g)	16.29	0.0001	4430.78	28
phi(m/e) p(g*t) psi(.)	16.76	0.0001	4431.25	28
phi(m/e) p(t) psi(g)	16.92	0.0001	4431.41	19
phi(m/.) p(t) psi(t)	18.47	0.0000	4432.96	25
Other reduced forms of the global model with less support from the data are not shown.				
Global: phi(m/e*g) p(g*t) psi(g*t)	46.28	0.0000	4460.77	52

Table 5: Model averaged estimates of apparent survival of Gulf of Maine humpback whales, by age class, sex and scar-based entanglement status.

Class	New entanglement injuries	Apparent survival*	SE	95% Confidence interval	
				Lower	Upper
Juveniles	No	0.848	0.0380	0.7581	0.9087
	Yes	0.805	0.0707	0.6309	0.9090
Adult females	No	0.961	0.0080	0.9418	0.9741
	Yes	0.961	0.0118	0.9303	0.9790
Adult males	No	0.974	0.0117	0.9381	0.9889
	Yes	0.974	0.0142	0.9258	0.9911

*The estimates shown for juveniles and mature males exclude the first interval after entry.