Scar-Based Inference Into Gulf of Maine Humpback Whale Entanglement:
2010

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

EA133F09CN0253
Item 0003AB, Task 3

January 2012

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 an index of entanglement frequency. Here we report on the analysis of injuries at the caudal peduncle and fluke insertion of 335 individual Gulf of Maine humpback whales in 2010 and compare those results to previous years. We focus particularly on evidence for change since the 2009 federal sinking ground line rule, which was intended to reduce the amount of line in the water column. 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 in 2010 with comparable photographic coverage in 2009 (n=130), 16.9% ± 6.45% exhibited new scarring. Similarly, 13.5% ± 3.8% of 319 individuals with adequate coverage in 2010 exhibited unhealed injuries likely obtained within the prior year. In both metrics, juveniles exhibited a higher frequency of new injuries than adults. Multi-state statistical models were further used to study patterns and implications of entanglement injury acquisition. Modeling was based on individuals sampled Gulf of Maine-wide, 1997-2010. It included 2,012 annual encounters of 527 adults (279 females, 248 males) and 1063 encounters of 713 known or suspected juveniles. Modeling results through 2010 continue to indicate that juveniles have a higher annual probability of acquiring new injuries than adults. The model averaged probability of an individual acquiring new injuries between 2009 and 2010 was 0.302 (95%CI: 0.200-0.429) for juveniles, 0.103 (95%CI: 0.076-0.139) for adult females and 0.105 (95%CI: 0.076-0.141) for adult males. Results to date do not indicate a decline in entanglement rate immediately following the coast-wide federal requirement for sinking ground line, but they also do not exclude possible effects. Available data were limited to one full feeding season after the ground line rule and so additional work will be needed to fully assess the effects of mandatory changes in fishing practices aimed at reducing entanglement rates.

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 also encountered off the southeast U.S. (Georgia/Florida), but the stock identity of these individuals is less well-understood.

Humpback whales are currently listed as an endangered species in the U.S. and are vulnerable to a number of human sources of injury and mortality, including fisheries by-catch (NMFS 1991, Waring *et al.* 2007). Between 2005 and 2009, there were 94 confirmed humpback whale entanglement events witnessed along the U.S. east coast, Gulf of Mexico and portions of the Canadian maritimes (Glass et al. 2011). Of those that were adequately documented, 18 were either confirmed mortalities or considered likely to result in imminent death; together they exceed what is considered sustainable for this population (Glass et al. 2011). In April 2009, NOAA Fisheries implemented a regulation requiring the use of sinking (rather than floating or neutrally buoyant) ground line in fisheries along the East Coast of the United States. This action was intended to reduce large whale entanglement rate by reducing the amount of line arching into the water column. The effect of this action on entanglement rate and population impacts is under investigation and those results will help to determine the direction of further mitigation.

Not all events are witnessed in progress and some cases are not adequately documented to determine their biological significance. Therefore, other sources of information on the frequency of entanglement events, risk factors, and biological impacts can potentially aid monitoring efforts. Entanglements produce injuries that can be detected even after gear is removed or shed. Since 1997, injuries and scars have been studied as 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, Robbins 2011). This report describes the results of this research for the 2010 humpback whale feeding season in the Gulf of Maine, in relation to prior years.

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 whale watch based data collection programs in various coastal Gulf of Maine areas.

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 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), irregular edges 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. Patterns of scarring at any given time 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. This approach is informative of change over short time frames for resighted individuals. However, some humpback whales are 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 recent events. 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. 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 2010, 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 adequate coverage was first obtained for assessment. An encounter history was then constructed for each indicating its annual documentation status (sampled or not) and inferred entanglement state (new entanglement injury documented or not) when sampled. 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 adequately sampled for this study, then that sighting was not included. Reported entanglement events were also not included unless the event detected by 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). This modeling was performed as described by Robbins (2011) and below. To minimize model complexity, juvenile encounter histories were analyzed separately from adults. Each year that a juvenile was sampled, it had the potential to move between two entanglement states (recently entangled or not) or to make a one-way transition to an absorbing third adult state. Subsequent scar acquisition rates were estimated in a second, adult-only 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. A list of notations used to describe model structure is shown in Table 1. 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. We assumed that only detection probability and the transition from non-entangled to entangled states had the potential to vary with time (and temporal constraints). Otherwise, all reduced forms of the global model were examined.

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.

Of particular interest was evidence for a change in entanglement rate since the April 2009 sinking ground line rule. Several models were fit to scar acquisition data to reflect hypotheses of no change over time, unconstrained annual variation and linear trends across the study period. We also examined the possibility that entanglement scar acquisition after the ground line rule (modeled as transitions after 2009 and/or 2010) differed categorically from prior years.

RESULTS

Over 3,000 caudal peduncle images collected from Gulf of Maine humpback whales in 2010 were evaluated for potential use for scar-based inference. We evaluated entanglement status based on over 700 images that made up the best daily photographic coverage of 335 individual animals. Images selected for analysis were obtained on 101 days between March 10 and November 16, 2010, with individuals documented on an average of 1.3 days (max=6 days). Juveniles and adults were equally likely to be documented on multiple days. 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 (75.5%, n=253) of the individuals evaluated had prior baseline coverage of one or more parts of the peduncle, but these were predominantly adults. Most of the individuals entering the study for the first time were calves (n=26), independent juveniles (n=8) or other animals with short prior sighting histories (n=39). Only eight 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 (61.0%, n=133). Sampling was performed in US and Canadian Gulf of Maine waters, but more whales were encountered and sampled 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.

For individuals with comparable photographic coverage in 2009 (n=130), 16.9% ± 6.5% exhibited new high probability scarring in 2010 (Figure 1). As in previous years, a greater proportion of juveniles in this sample were confirmed to have acquired new injuries (36.6%, n=15) versus adults (7.9%, n=7). Looking only at unhealed injuries that appeared to be entanglement related, 13.5% ± 3.8% of the individuals with adequate coverage in 2010 (n=319) exhibited unhealed injuries that were likely received within the previous year. There was a higher incidence of unhealed injuries among known and suspected juveniles as compared to adults (G=4.72, p=0.03, df=1), consistent with previous years (Figure 2). Like most eye-witnessed entanglements, the majority of unhealed injuries appeared to involve skin lacerations and abrasions. Some penetrated the dermis completely, but few appeared to penetrate into deeper tissues (Figure 3).

In total, there were 48 new events detected, of which 42 were known or inferred to have occurred within the prior year and 6 were known to have occurred sometime since 2003. Three were matched to individuals involved in documented entanglement events in 2009 or 2010 (Figure 4). This suggests that only 7% of the individuals that obtained new injuries were successfully witnessed while entangled.

Scar acquisition modeling

Modeling was based on individuals sampled Gulf of Maine-wide, 1997-2010. It included 2,012 annual encounters of 527 adults (279 females, 248 males) and 1063 encounters of 713 known and suspected juveniles. Goodness of fit testing indicated a significant transient effect for both juveniles and adults, although it was minimal among adult females (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 the modeling process are shown in Table 3 for juveniles and Table 4 for adults. The parameters of primary interest were the probability of entanglement over time and the probability of survival relative to entanglement state. Models in which detection probability varied with time and 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 data limitations and excluded those configurations from further analysis.

For adults, two models were equally plausible given the data. In these, males and females exhibited parallel, time-varying detection probabilities and survival that was either constant or depended on sex. The latter differences were limited to the first interval only and so interpreted as a greater tendency of males toward transience. In both models, entanglement scar acquisition was constant over time. A number of additional models were less supported by the data and suggested minor changes in scar acquisition rates, whether categorical (a change in 2009 or 2010) or as part of a linear trend. Model averaged parameter estimates for adult survival are shown in Table 4 and entanglement probabilities are depicted in Figure 5. Taken together, there was little evidence of change in entanglement rates or in survival after injuries were received. The estimates for scar acquisition rates between 2009 and 2010 were 0.103 (95%CI: 0.076-0.139) for adult females and 0.105 (95%CI: 0.076-0.141) for adult males.

For juveniles, all of the models with some degree of support (AICc <10) included annually varying detection probabilities (Table 3). Several models were equally plausible given the data (AICc<2). One of the top two models included support for a survival effect after scar acquisition, but other models that were equally plausible did not include it. With regard to scar acquisition rates, the most parsimonious models suggested scar acquisition to be on a continuing linear trend. However, there was considerable model selection uncertainty, and hypotheses of change around the time of the 2009 ground line rule also had some support from the data. Model averaged apparent survival estimates are shown in Table 5 and annual probabilities of entanglement are depicted on Figure 5. As expected from model selection, the point estimate of juvenile survival was lower for newly injured individuals, but with confidence intervals overlapping the estimates for juveniles without entanglement injuries. Point estimates of model averaged entanglement scar acquisition rates suggest a possible change in recent years, but with considerable overlap among confidence intervals (Figure 5). The estimate for scar acquisition rates between 2009 and 2010 was 0.302 (95%CI: 0.200-0.429).

DISCUSSION

Large whale entanglements on the U.S. East Coast are difficult to study because most are observed only after whales have moved away from the site where the interaction occurred. Whereas the owner of the gear might detect a whale that remained anchored at that site, whales that carry the gear away may or may not overlap knowledgeable observers and may or may not behave in a manner that is similar to other whales. Humpback whale entanglement reports in this region come from a wide range of marine users, including commercial whale watchers, researchers, recreational boaters/beachgoers, members of the fishing industry and others. Because we do not know how many people could have potentially witnessed events in a given year, there is no measure of effort with which to standardize the reports. Unfortunately, it is not plausible to assume that opportunistic observer coverage is constant over time and space. It is also unrealistic to assume that observed events are complete counts of the events that have occurred. Therefore, patterns observed in the frequency of humpback whale entanglement reports may reflect entanglement rates, variation in event detection or both.

Scar based studies of entanglement have been implemented annually since 1997 in order to provide an alternate, standardized index of entanglement rate. The data are obtained and analyzed independently from reports of whales carrying gear and calculated based on a known number of examined individuals. This work focuses on a later stage of entanglement than eye-witness reports. Whereas entanglement events themselves are of finite and variable duration, the injuries that they produce persist and extend the period over which an event can ultimately be detected. They do not represent the full range of entanglement events, such as those events that result in death before a whale can be sampled. Nevertheless, scar studies provide a consistent metric for evaluating non-lethal entanglement interactions over time. Any management efforts that attempt to reduce the frequency of interactions can therefore be monitored by this approach. The 2009 federal sinking ground line rule is an example of a management initiative that was expected to reduce entanglement rate (and thereby also the number of deaths) rather than severity directly. If successful, reducing the amount of gear from the water column should result in fewer whales observed carrying gear and fewer free-ranging individuals with new entanglement injuries. Unfortunately, there is no *a priori* information with which to determine the level of reduction to expect.

Robbins (2011) used data obtained through 2008 to evaluate trends in entanglement rate and impact prior to the implementation of the sinking ground line rule. The results indicated that injuries were acquired more frequently by juveniles than by adults, that the sex of an adult does not appear to play an important role in the acquisition of new injuries and that there has been little annual variation in acquisition rates. There was an indication of lower juvenile survival after new injuries, but an interpretation of no survival effect was also plausible given the data. Here, we report the first attempt to use multi-state mark-recapture modeling to evaluate the effect of a discrete management action on entanglement rate. We used several modeling approaches to evaluate possible changes in entanglement rate since the implementation of federal sinking ground line rule. Although the rule was in force in April 2009, we considered it possible that a significant change might not have occurred until 2010 because some humpback whales could have been entangled in 2009 before the rule was implemented. Prior to the sinking ground line rule, adult scar acquisition rates appeared to be constant and subsequent modeling does not suggest a change corresponding to the sinking ground line rule. We continued to group adults by sex in the current analysis because of recent evidence that calving females are more likely to acquire jaw scuffing thought to result from feeding at the bottom (Robbins and Tackaberry 2011). It was therefore conceivable that adult males and females might have a different likelihood of encountering ground lines and that might result in a detectable difference in scar acquisition rates after the ground line rule was in place. However, results to date continue to suggest that adults of both sexes have similar scar acquisition rates.

Juveniles appeared to be on a constant or increasing scar acquisition trend during the baseline period. Since the ground line rule, model selection results continue to support that pattern, although the possibility of a change around the time of the ground line rule cannot be excluded. Given that only one full year of data are currently available, the possibility of change must be evaluated with additional years of data. Robbins (2011) reported that recently entangled juveniles (but not adults) might have a lower probability of survival than those with no new injuries. Support for that finding was ambivalent in analyses of data through 2008 and remains uncertain here. We will continue to explore this issue in future modeling of scarification data, as it has implications for federal serious injury determinations (Henry et al. 2011) as well as efforts to estimate entanglement mortality rate from scarring data (Robbins et al. 2009). One approach for clarifying these results may be to incorporate apparent injury severity as a covariate in the analysis.

One important consideration when evaluating changes over time is the consistency of the sampling effort relative to prior years. In 2010, our sample size was larger than all prior years except 2003, but the data appeared to be consistent in terms of demographic composition, spatial distribution and temporal span. One exception is that we observed individuals on fewer days in 2010, which we interpret to be due to a lower contribution of opportunistic images from whale watching vessels. The most likely effect of seeing individuals only once is that within-season events are more likely to have been missed. If so, then such events still have the potential to be detected in the next sampling interval and those results may change the inference here.

Of the three entanglement metrics presented here, we consider the best to be the mark-recapture model estimates of injury acquisition rates (Figure 5), although proportional indices shown in Figures 1 and 2 are still useful for comparison to other scarification studies. Nevertheless, model selection can only evaluate support for the suite of model structures selected for analysis. We chose these models based on the results of prior modeling (Robbins 2011), our hypotheses regarding entanglement, as well as known or expected limitations of the data. However, we will continue to further evaluate and refine candidate models in future modeling efforts. It is also important to note that the scarification data used in this study still inherently under-estimate total entanglement rate. They measure only the frequency of entanglements at the caudal peduncle and miss injuries that lead to death before the whale can be sampled. Although this approach does not directly sample the portion of entanglements of greatest interest to managers (i.e., serious injury and mortality), scarification studies are nevertheless useful for monitoring the effectiveness of the specific mitigation measures that have been put into place. To date, this work has not detected a strong, immediate effect from sinking ground line mandated coast-wide in 2009, but further monitoring is needed. Further research is also needed to determine compliance to the rule and other factors that would affect its effectiveness.

Acknowledgements

Thanks to David Mattila, Scott Landry and Jenn Tackaberry for their assistance with this study. Whale watching data were provided by the Dolphin Fleet, Blue Ocean Society, Brier Island Whale and Seabird Cruises, Captain John and Sons/NECWA, and Quoddy Link Marine. 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

Henry AG, Cole TVN, Garron M, Hall L. 2011. Mortality and Serious Injury Determinations for Baleen Whale Stocks along the Gulf of Mexico, United States and Canadian Eastern Seaboards, 2005-2009. US Dept Commer, Northeast Fish Sci Cent Ref Doc. 11-18; 24 p. Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at http://www.nefsc.noaa.gov/nefsc/publications/

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 (2011) Scar-based inference into Gulf of Maine humpback whale entanglement: 2009, 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.

Robbins J, Tackaberry J (2011) Bottom feeding by humpback whales in the Gulf of Maine: prevalence, demography and entanglement risk, Report to the National Marine Fisheries Service, Contract #EA133F09CN0253.

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, 1997-2010. These represent the percentage of individuals confirmed to have acquired new injuries between years. The 95% confidence interval of percentages was calculated based on the standard error. Data from previous sampling periods are reproduced from previous reports (Robbins and Mattila 2004, Robbins 2008; 2009; 2010; 2011).

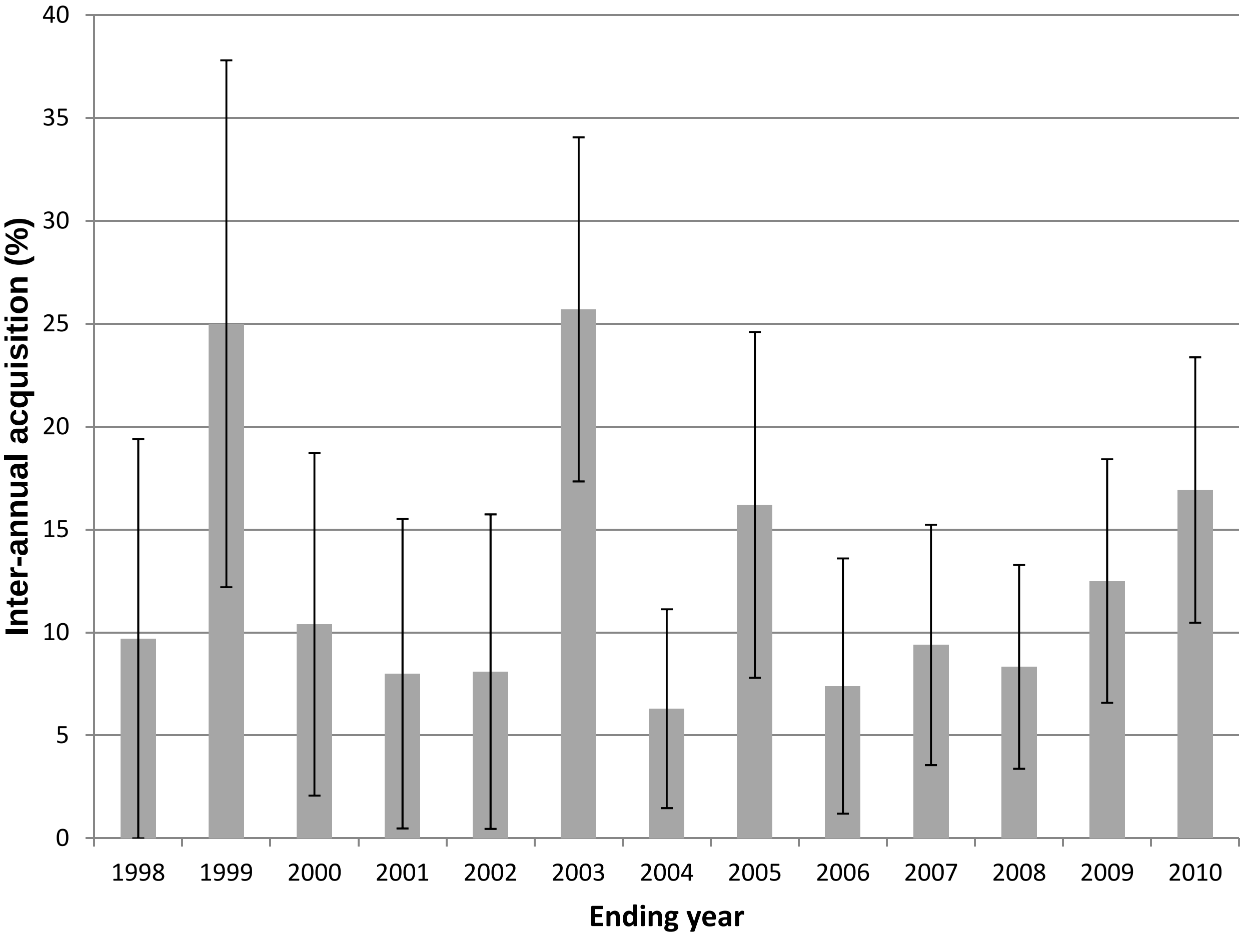

Figure 2: Frequency of unhealed injuries by year and age class, 2003-2009. The 95% confidence interval of percentages was calculated based on the standard error. Data from previous sampling periods are reproduced from Robbins (2011).

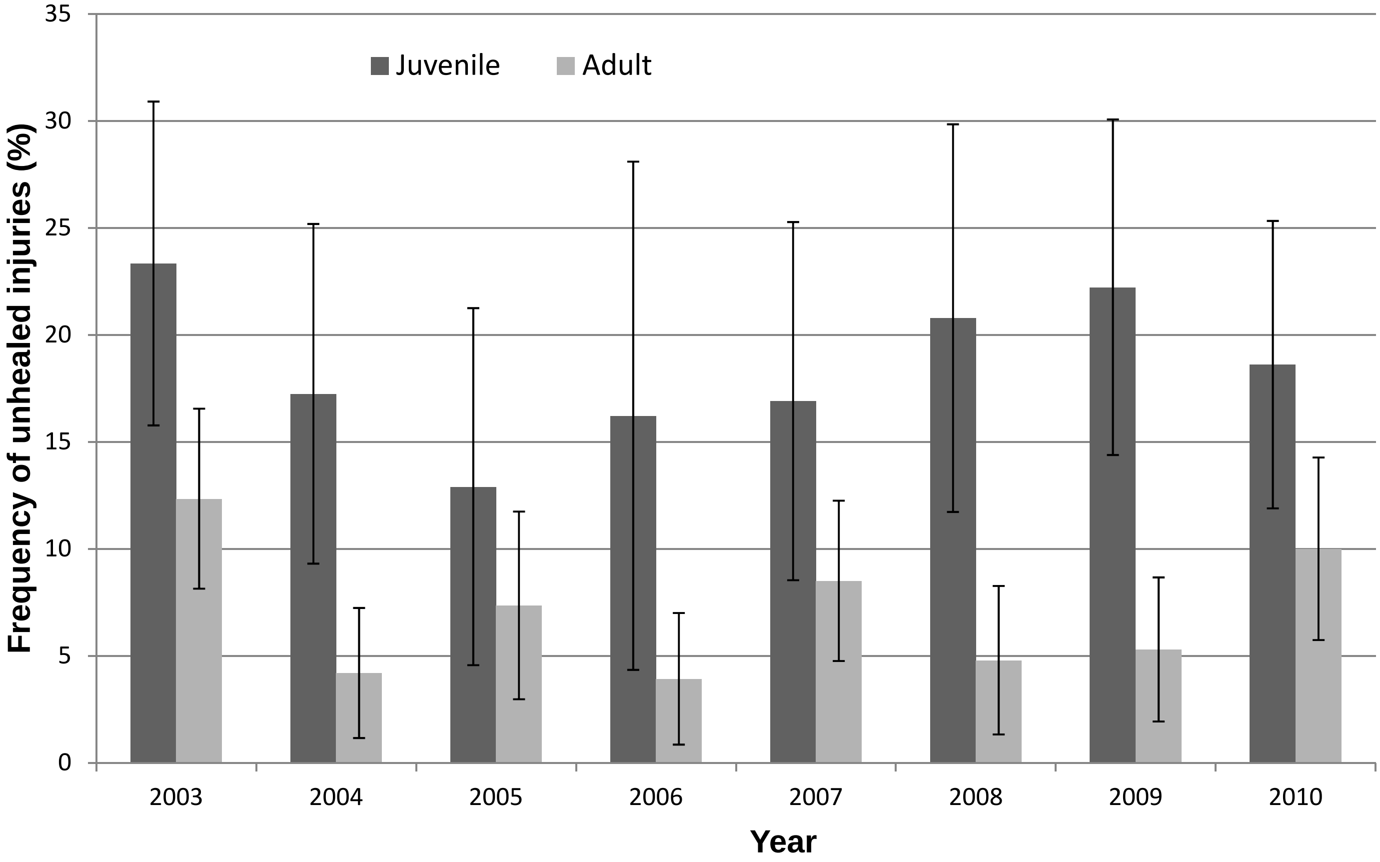

Figure 3: Examples of unhealed injuries interpreted as entanglement-related in 2010. None were observed while carrying gear. Note that there are wrapping scars, notches and other injuries in at least two areas in all inferred entanglement cases. Most were limited to skin lacerations and abrasions. Unless otherwise noted, images were taken by PCCS under permit 633-1778.

Minor injuries on a yearling on August 11, 2010. The event that produced these injuries occurred after April 2, 2010.

Injuries observed on a juvenile on July 27, 2010. They were acquired after August 6, 2009.

Partially healed injuries observed on a mature female on May 24, 2010. The event that caused these injuries occurred sometime after July 15, 2008.

Injuries on a yearling on September 9, 2010. These injuries were acquired after October 21, 2009. Dolphin Fleet image.

Figure 4: Examples of injuries produced by documented 2010 entanglements reencountered in this study after the gear was shed. Note that there are wrapping scars, notches and other injuries in at least two areas of the posterior peduncle/flukes. Images were taken by PCCS under NOAA permit 633-1778.

Bearclaw, September 23, 2010. This whale was disentangled on August 31, 2010.

Vault, October 19, 2010. The gear was shed without successful intervention sometime after August 7, 2010.

Figure 5: Model averaged estimates of Gulf of Maine humpback whale entanglement scar acquisition, 1997-2010. 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).

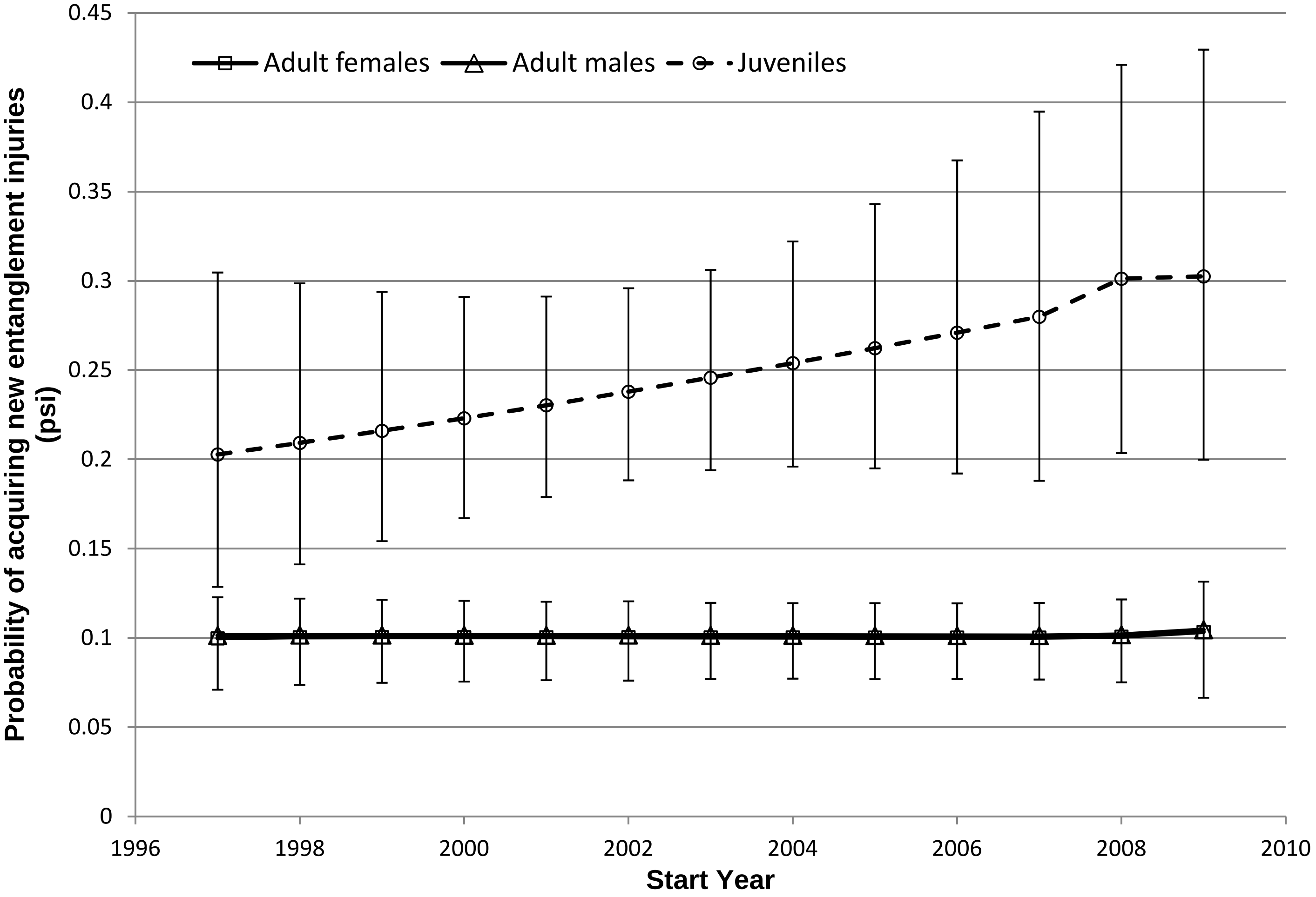

Table 1: Notations used to describe multi-state models of entanglement scar acquisition in Gulf of Maine humpback whales.

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 apparent survival to address heterogeneity (transience) identified during goodness of fit testing.
	.	Parameter held constant
	a	Differences between juveniles and adults (only in juvenile model)
	g	Differences between adult males and adult females (only in adult model)
	e	Differences between individuals with and without new entanglement injuries
	t	Variability across years
	T	Linear trend in the annual probability of acquiring new injuries.
	/GL09	Sinking ground line effect starting in 2009. Prior hypothesized trend is noted before the /
	/GL10	Sinking ground line effect starting in 2010. Prior hypothesized trend is noted before the /
	*	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 (highlighted row). 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)	0.992 (3.949, 13)	0.892 (7.186, 13)	0.809 (6.872, 11)
3G.sr p-value (X^2, df)	<0.001 (57.751, 25)	0.040 (33.562, 21)	0.005 (37.156, 18)
3G.sm p-value (X^2, df)	0.951 (74.318, 96)	0.951 (45.646, 63)	0.546 (51.163, 53)
M.ITEC p-value (X^2, df)	0.038* (24.652, 14)	0.002* (28.775, 11)	0.586 (8.297, 11)
M.LTEC p-value (X^2, df)	0.077* (19.520,12)	0.025* (19.071, 9)	0.166 (12.922, 9)
C-hat ($\Sigma X^2/\Sigma df$)	0.907	1.049	0.944
Median c-hat	1.065	1.078	

*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, 1997-2010. 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. Models with a Delta QAICc <2 are considered equally plausible and those greater than 10 have no support from the data.

Model	**Delta QAICc**	**AICc Weight**	**QAICc**	**Parameter count**
phi(m/a)p(a*t)psi(T)	0.00	0.1891	4263.85	34
phi(m/a*e)p(a*t)psi(T)	0.57	0.1425	4264.41	36
phi(m/a)p(a*t)psi(./GL09)	1.22	0.1027	4265.07	34
phi(m/a)p(a*t)psi(.)	1.25	0.1012	4265.10	33
phi(m/a)p(a*t)psi(T/GL10)	1.95	0.0714	4265.80	35
phi(m/a)p(a*t)psi(T/GL09)	1.99	0.0699	4265.84	35
phi(m/a*e)p(a*t)psi(T/GL10)	2.21	0.0628	4266.05	37
phi(m/a*e)p(a*t)psi(T/GL09)	2.40	0.0571	4266.24	37
phi(m/a*e)p(a*t)psi(.)	2.83	0.0459	4266.68	35
phi(m/a)p(a*t)psi(./GL10)	2.84	0.0458	4266.68	34
phi(m/a*e)p(a*t)psi(./GL09)	2.93	0.0436	4266.78	36
phi(m/a)p(a*t)psi(T/GL09T)	3.96	0.0261	4267.81	36
phi(m/a*e)p(a*t)psi(T/GL09T)	4.32	0.0219	4268.16	38
phi(m/a*e)p(a*t)psi(./GL10)	4.50	0.0200	4268.34	36
phi(m/a)p(a*t)psi(t)	18.56	0.0000	4282.41	45
Other reduced forms of the global model with less support from the data are not shown.				
Global: phi(m/a*e)p(a*e*t)psi(t)	23.76	0.0000	4287.60	60

Table 4: Top model selection results for adult humpback whale entanglement scar acquisition, 1997-2010. 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. Models with a Delta QAICc <2 are considered equally plausible and those greater than 10 have no support from the data.

Model	**Delta QAICc**	**AICc Weight**	**QAICc**	**Parameter count**
phi(m/.) p(g+t) psi(.)	0.00	0.2821	5893.01	18
phi(m/g) p(g+t) psi(.)	0.42	0.2289	5893.43	20
phi(m/g) p(g+t) psi(g)	2.38	0.0860	5895.39	21
phi(m/.) p(g+t) psi(GL10)	2.54	0.0791	5895.56	20
phi(m/e) p(g+t) psi(.)	2.77	0.0705	5895.79	20
phi(m/.) p(g+t) psi(GL09)	3.72	0.0440	5896.73	20
phi(m/.) p(g+t) psi(g)	3.98	0.0386	5896.99	20
phi(m/.) p(g+t) psi(T)	4.06	0.0371	5897.07	20
phi(m/g) p(g+t) psi(g)	4.41	0.0312	5897.42	22
phi(m/g) p(g+t) psi(T)	4.48	0.0300	5897.50	22
phi(m/.) p(g+t) psi(g+T)	6.01	0.0140	5899.02	21
phi(m/g) p(g+t) psi(g+T)	6.44	0.0113	5899.45	23
phi(m/e*g) p(g+t) psi(.)	6.67	0.0100	5899.69	24
phi(m/e) p(g+t) psi(g)	6.76	0.0096	5899.77	22
phi(m/e) p(g+t) psi(g)	6.76	0.0096	5899.77	22
phi(m/e) p(g+t) psi(T)	6.84	0.0092	5899.85	22
phi(m/e) p(g+t) psi(g+T)	8.79	0.0035	5901.81	23
phi(m/e*g) p(g+t) psi(g)	10.68	0.0014	5903.69	26
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)	45.99	0.0000	5939.00	62

Table 5: Model averaged estimates of apparent survival of Gulf of Maine humpback whales, by age class, sex and scar-based entanglement status, 1997-2010. Model selection supported a survival effect for juveniles after new injuries (see Table 3).

Class	**New entanglement injuries**	**Apparent survival***	**SE**	**95% Confidence interval**	
				Lower	**Upper**
Juveniles	No	0.842	0.0345	0.7623	0.8987
	Yes	0.781	0.0702	0.6151	0.8889
Adult females	No	0.970	0.0056	0.9571	0.9795
	Yes	0.970	0.0123	0.9335	0.9866
Adult males	No	0.971	0.0068	0.9542	0.9820
	Yes	0.971	0.0143	0.9253	0.9893

*The estimates shown exclude the first interval after entry.