EFFECTIVENESS OF MITIGATION TO REDUCE ENTANGLEMENT IMPACTS ON HUMPBACK WHALES IN THE GULF OF MAINE

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ABSTRACT

Humpback whales in the Gulf of Maine (GOM) are vulnerable to injury and mortality from human activities, including from entanglement in fishing gear. Over the past decade, two major changes were mandated to commercial fishing practices along the U.S. East Coast to reduce entanglement frequency. Federal rules in 2009 and 2015 reduced the profile of ground line and the number of vertical lines in the water column, respectively. We used data on population abundance and survival from 2000 through 2016 as a basis for evaluating the effectiveness of these initiatives. We focused on a subset of observed entanglement cases that we assessed as having a high probability of involving GOM humpback whales and relevant fisheries. The number of observed events was lowest in 2013 and 2014, but as high in 2016 as in any pre-rule year. There was no correlation between the number of reported events and estimated GOM humpback whale population size, nor between the *per capita* entanglement report frequency and mitigation periods. A Bayesian state-space mark-recapture model did not suggest improvements in population survival rates after the Ground Line Rule. An estimated increase in survival from 2015 to 2016 may have been related to the Vertical Line Rule or other factors. Continued

research will be necessary to evaluate the effectiveness of the Vertical Line Rule for reducing entanglement impacts on Gulf of Maine humpback whales.

Keywords: Bayesian mark recapture, *Megaptera novaeangliae*, by-catch, survival, mitigation

INTRODUCTION

Entanglement in fishing gear is a documented source of injury and mortality to whales, including along the East Coast of the United States. However, event frequency, risk factors and the fate of affected animals can be challenging to assess. Whales often break away from the original site of entanglement carrying some or all of the gear. Most entanglement reports come from opportunistic observers with unknown, likely variable, detection rates. Finally, the exact nature of entanglements and specific causes of negative outcomes can be difficult to assess in a consistent and meaningful way. These data limitations make it difficult to determine the best course of mitigation and the ultimate success of mitigation efforts.

The humpback whale (*Megaptera novaeangliae*) is a migratory species that feeds at mid- to high latitudes and migrates to low latitudes to mate and calve. The primary feeding ground of North Atlantic humpback whales in U.S. waters is in the Gulf of Maine (GOM), which spans the eastern US/Canadian border. This subpopulation is a component of the West Indies Distinct Population Segment and migrates in winter to shared North Atlantic breeding grounds in the Caribbean. Nevertheless, some individuals may remain in U.S. waters year-round, including on a mixed-stock supplemental feeding area along the mid-Atlantic states and Southeast U.S., where only 45.5% of individuals have a GOM sighting history (Barco et al. 2002).

Humpback whales are vulnerable to human sources of injury and mortality in U.S. waters, including fisheries by-catch. Entanglement can reduce the likelihood of survival of both North Atlantic humpback and right whales (Robbins & Landry 2012; Robbins et al. 2015; Pace et al. 2017). Between 1970 and 2009, entanglement was the most common identified cause of humpback whale mortality off the U.S. East Coast, representing at least 25% of all observed deaths (van der Hoop et al. 2013). Between 2011-2015 alone, there were 93 confirmed humpback whale entanglement events witnessed in progress along the east coast of North America, of which 34% (n=32) were assessed as likely to lead to death (Henry et al. 2017). Fewer than 10% of entanglements are thought to be witnessed and reported (Robbins 2012), and so the true number of lethal events is likely higher. Impacts from entanglement and other human sources have consistently exceeded management limits (van der Hoop et al. 2013; Pace et al. 2014).

Several mitigation strategies have been implemented as part of an overarching Atlantic Large Whale Take Reduction Plan to reduce serious injuries and mortality of large whales related to commercial fishing operations. Of particular importance for pot/trap fisheries were two Federal rules put in place in 2009 and 2015, respectively. The first was a broad-based sinking ground line requirement, effective on April 5 2009, that was mandated for all U.S. Atlantic trap/pot fisheries to minimize the amount of excess rope in the water column (NMFS 2008)[1]. A second rule, effective on June 1, 2015, attempted to reduce the amount of vertical lines in the water column by requiring a minimum number of traps per trawl (NMFS 2014)[2]. Coast-wide mitigation measures have logistical and financial implications for the fishing industry and one of the affected whale

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[1] 50 CFR Part 229
https://www.greateratlantic.fisheries.noaa.gov/protected/whaletrp/plan/2008.alwtrp.groundline_final_rule_pub9_02_08.pdf

[2] 79 FR 36586
https://www.greateratlantic.fisheries.noaa.gov/protected/whaletrp/docs/12_12_2014_amendment_final_rule.pdf

populations, the North Atlantic right whale, is believed to be declining despite those efforts (Pace et al. 2017). It is therefore critical to evaluate the effectiveness of current actions for reducing the impacts of commercial fishing operations on large whale populations.

Evaluating the effectiveness of mitigation depends on accurate data on affected populations as well as entanglement events. In addition to well-established entanglement and stranding response networks, there has been annual photo-identification research on the free-ranging GOM humpback whale population since the 1970s. A recent study yielded data on annual abundance and trend of GOM humpback whales from 2000 through 2016 (Robbins and Pace, 2018). Here, we used those and other data from the GOM humpback whale population to investigate evidence for reduced entanglement impacts following the Ground Line Rule (GLR) and Vertical Line Rule (VLR).

METHODS

Data

We used data from GOM humpback whale population studies as the foundation for evaluating entanglement impacts. 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). CCS has conducted photo-identification research on the free-ranging population since the 1970s, but we focused on data from directed surveys of humpback whale aggregation sites from 2000-2016 and opportunistic photo-identification data shared with CCS by regional collaborators operating off New England and in the Bay of Fundy, Canada. Analyses were informed by the results of a Jolly-Seber Bayesian state-space abundance model implemented to assess population trends in the GOM from 2000-2016 (Robbins and Pace 2018).

Demographic characteristics of identified GOM whales were known from the CCS Gulf of Maine Humpback Whale Catalog. Sexes were known from 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, a documented calf. Age was known for individuals that were dependent calves at first encounter. 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, but it could have been older. Female humpback whales in the GOM can produce a calf as early as age five, although the average age at first reproduction is closer to nine years (Clapham 1992; Robbins 2007). Individuals first cataloged as calves and less than five years old were categorized as juveniles. Those without a known year of birth and first cataloged less than four years prior to sampling were of unknown age class, but thought to be predominantly juveniles (Robbins 2007).

Entanglement data were collected by the Atlantic Large Whale Disentanglement Network (ALWDN), which provides formal reporting, disentanglement response and awareness training along the eastern seaboard of the United States. Photographs of identifying features were obtained whenever possible so that the individual could potentially be re-identified with or without entangling gear. We also included entanglements that were documented after death by the Northeast and Southeast Marine Mammal Stranding Networks. We excluded those cases assessed by NMFS as having involved recreational gear (e.g., hook/mono), entrapments (e.g., weirs), anchor lines or other materials inconsistent with commercial fishing gear (NOAA unpublished data, Cole & Henry 2013; Henry et al. 2014, 2015, 2016; Henry et al. 2017) [3]. Cases that were Federally determined to involve gear originally set in Canada (NOAA unpublished

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[3] https://www.greateratlantic.fisheries.noaa.gov/protected/whaletrp/reports/index.html

data, Cole & Henry 2013; Henry et al. 2014, 2015, 2016; Henry et al. 2017) were excluded from analysis regardless of original report location.

Analyses

Both the GLR and the VLR were designed to reduce the likelihood of interactions with commercial fishing gear and thereby the incidence of life-threatening events. As neither specifically targeted aspects of fishing gear entanglements that cause negative outcomes, we hypothesized that success should result in a significant reduction in event frequency. However, we recognized that reported entanglements are only a subset of the events that occur. Thus, we also hypothesized that improvements in latent mortality might be detected in population survival rates.

1. Frequency of observed entanglement reports

Changes in the number of entanglement reports over time were informed by the results of a Jolly-Seber Bayesian state-space abundance model (Robbins and Pace 2018). For each year, we calculated a *per capita* entanglement report rate as the number of observed entanglement events divided by the annual point estimate of abundance. Population abundance estimates were less reliable prior to 2003, and so we excluded those earlier years.

Whales found south of the GOM along the U.S. East Coast are not necessarily from the GOM population (Barco et al. 2002). We therefore first attempted to identify the subset of reported entanglement events that were most likely to involve GOM humpback whales. When available, we matched identifying shots of entangled whales to the CCS Gulf of Maine Humpback Whale Catalog. In some cases, a skin sample obtained by disentanglement teams was used to genetically match individuals to the catalogued population using techniques described by Palsbøll et al. (1997). However, many entanglements were not adequately documented to allow a determination of whether a specific catalogued GOM individual was involved. We then focused on the location of the first report. We assumed that an entanglement likely involved the GOM population if first reported between Massachusetts and western Nova Scotia, including the offshore waters of the GOM. By comparison, only 45.5% of cases first detected south of the GOM were likely to be members of this population (Barco et al. 2002), and so we applied this percentage to more southerly events. Finally, for reports detected within the GOM, there was also a potential for seasonal transients from other North Atlantic feeding populations, particularly outside of the peak season for which GOM abundance estimates had been calculated (June 22-October 7). We used a G-test (Sokal & Rohlf 1981) to compare the prior sighting histories of identified individuals reported entangled during peak versus shoulder seasons to provide insight into population identity.

The *per capita* report rate attempted to place observed events into context relative to the number of individuals in the population. However, it did not reflect the number of whales actually observed in a given year and changes in effort or detection among mitigation periods. We therefore also developed a *per observed individual* metric based only on platforms collecting photo-identification data in the GOM, including population researchers and the whale watching vessels that collect and share photo-identification data with CCS. The *per observed individual* index was then calculated annually as the number of entanglement events first detected by these platforms divided by the total number of individuals that they identified at least once.

For each of these measures of report per unit animal, differences among mitigation periods were based on ANOVA (Sokal & Rohlf 1981), considering the GLR and VLR both separately and combined into a single post-mitigation period.

2. Population survival rates

Not all entanglement events are witnessed and/or reported, despite the existence of well-established research programs and trained networks for both entanglement and stranding response. However, population survival rates include the latent effects of entanglement, along with other insults, and so have the potential to inform mitigation efforts. We evaluated annual population survival rates in relation to mitigation periods, assuming status quo through 2008, a GLR effect after 2008 and an additional VLR effect from 2015 onward. Survival was estimated through mark-recapture statistical modeling as extended Cormack-Jolly-Seber models (CJS, Cormack 1964; Jolly 1965; Seber 1965) similar to those described in Lebreton et al. (1999) but relying upon a Bayesian, state-space formulation to perform the estimation process using Markov Chain Monte Carlo (MCMC) simulation. Specifically, we modified the approaches of Kéry and Schaub (Kéry & Schaub 2011) and Royle and Dorazio (Royle & Dorazio 2012) to accommodate known sources of survival and recapture heterogeneity described by Robbins (Robbins 2007). Conditioning on first captures within the study period, we built a known state matrix in which each cataloged animal observed from 2000-2016 was represented by a row and each year was represented by a column. Between the first and last observations of each whale, an annual value was entered indicating whether the whale was seen alive or dead. After the last sighting, the state value was unknown and estimated by the model.

We used logistic relationships with linear combinations of predictors (Lebreton et al. 1992) to estimate survival and capture probabilities while accounting for sources of heterogeneity. In the main model, survival probability was modeled in relation to mitigation actions and other effects as follows:

$$\text{Logit}(\phi i,t) = \beta 1 + \beta 2 * (1\text{-sex}i) * \text{Adult}i,t + \beta 3[\text{Age}i,t] + \beta 4[\text{Rule1}t] + \beta 5[\text{Rule2}t] + \varepsilon t$$

Where: ϕi,t was the survival probability of the ith individual for the tth interval, $\beta 1$ was the intercept whose value in the logit was the mean of calf survival, $\beta 2$ was the added effect on survival of being a female > 4 years old, sexi was a data value of 0 for female, 1 for male and NA for unknown, Adulti,t was a data value of 1 if the ith animal was classed as age > 4 in the tth interval, $\beta 3$[Agei,t] was a set of factors for each age group 1,2,3, 4 and 5, Agei,t was an index representing an age value ranging from 1 – 5 for the ith individual at time interval t. Rule1t and Rule2t were indicator variables for the timed establishment of the GLR and VLR, respectively. Finally, εt was the random effect of year on survival.

Similarly, we modeled capture probability as:

$$\text{Logit}(\text{P}i,t) = \alpha 1 + \alpha 2 * (\text{sex}i) + \alpha 3 * (1\text{-Adult}i,t) + \text{Time}t + \zeta i$$

Where: $\alpha 1$ was the intercept and hence the effect on capture probability due to being female, $\alpha 2$ was the added effect from being male, and $\alpha 3$ was the added effect from being juvenile. Timet was the linear effect of the year t on average capture probability with Timet=2000 as 0. ζi was the random effect of the ith individual on capture probability.

For estimation, we assigned vague priors on all linear logistic terms except the random coefficients εt and ζt, as uniform(-10,10). Random coefficients ε_t and ζ_i were given normal (0, δ) and normal (0, σ) priors, respectively. Standard deviation terms δ and σ were given vague priors of uniform (0.001,10). The observed data (seen or not seen) were considered dependent on the animal being alive was modeled as Bernoulli(P[s]).

Finally, missing data on the sex of individual whales was modeled as Bernoulli(ρ), where

ρ was given a somewhat informative beta(5,5). Using the above structure, data were modeled using program JAGS (Version 4.0.0) MCMC simulator (Plummer 2003) accessed via Program R (R Core Team 2012) and package "run.jags" (Version 2.0.2-8, Denwood 2016). When dealing with model parameters in all simulation exercises, we provided random starting values from within the range of the prior for that parameter. Covariates concomitant with capture histories in the data augmentation set were unknown for sex and age=5 and adult=1 adult for age class. We provided initial values for unknown states ($state.init_{ij}$) which were $state.init_{ij}=1$ prior to the first year seen and $state.init_{ij}=3$ after the last year seen, and a value of 1 for all animals in the augmentation set of capture histories. Unknown sexes were assigned a Bernoulli(0.5) random initial value. We used an adaptation + burn in phase of 5,000 iterations and sample size of 20,000 iterations for estimation. JAGS code for the primary model is provided in Appendix I. In all cases, to determine when the algorithms had converged, we used three chains and computed the Gelman-Rubin convergence statistic, which we required to be <1.1 for all model parameters (Gelman & Rubin 1992). The hypothesis of a change in total population survival corresponding to mitigation efforts, either from the GLR alone or after the VLR, was evaluated based on the median of the posterior probability distribution.

GOM population survival rates vary with age and sex, and so changes in the demography of entangled individuals could potentially obscure latent entanglement impacts. We used a G-test (Sokal & Rohlf 1981) to determine whether there were significant differences in the demography of individuals involved in observed entanglements before and after the rules were implemented.

RESULTS

Reported entanglement rate

After excluding cases known to involve non-commercial and non-U.S. origin gear (n=67), the majority (70.4%, n=176) of humpback whale entanglement cases between 2000 and 2016 was first detected within the Gulf of Maine/Bay of Fundy. South of the Gulf of Maine, only three cases, including one mortality, definitively involved an individual with a prior GOM history. However, many cases were not individually identifiable and so we applied a 45.5% photo-identification based match rate from Barco et al. (2002) to all southern cases to arrive at an approximate number of GOM humpback whales potentially involved in those waters each year.

Within the Gulf of Maine, 72.6% (n=85) of adequately marked entangled individuals had a prior sighting history. These individuals were first reported entangled in all seasons, but were most common in summer (July-Sept, n=16) or spring (n=11). By contrast, individuals that were not previously catalogued were first reported primarily in fall (Oct-Dec, n=5) or spring (April-June, n=4), with only two seen entangled in summer. Consequently, nearly half (47.8%, n=22) of individuals seen entangled in shoulder seasons had no prior GOM sighting, versus only 14.1% (n=10) in the peak season (G=15.60, df=1, p<0.001). Given this significant difference, we considered it possible that approximately one-third of all entangled whales first seen in the GOM in shoulder seasons might not be represented in our peak season GOM population survival and abundance estimates. We therefore applied a 33% proration to shoulder season events when examining trends over time in relation to population estimates.

After applying the spatial and seasonal proration to observed entanglement cases, we focused temporal analyses on 166 reported events between 2000 and 2016. Whereas GOM population estimates increased across the study period, entanglement reports varied annually from as few as four cases in 2013 to 15 cases in 2003 and 2016. There was little to no evidence that entanglement reports had increased as a linear function of population abundance (Figure 1).

Entanglement reports followed similar trends whether calculated *per capita* or *per observed individual*, with the lowest entanglement report frequency per unit animal occurring during 2013-2014 and returning to peak values by the end of the study when the VLR was in effect (2016, Figure 2). Prior to mitigation actions (2003-2008), the mean *per capita* rate of reported entanglements was 0.014 per year (SD=0.0050) versus 0.009 (SD=0.0038) after the implementation of the GLR (2009-2014) and 0.011 (SD=0.0049) after the addition of the VLR (2015-2016). Taking both mitigation periods together yielded a *per capita* rate of 0.009 (SD=0.0039) from 2009 through 2016. The results were not significantly different whether the mitigation periods were combined (F=3.39, p=0.091, df=13) or compared individually (F=1.81, p=0.209, df=13).

When focusing on the subset of entanglement cases reported by GOM groups that observe and identify individual humpback whales (60.8%, n=76), a similar pattern was observed (Figure 2). The frequency of detected events per unit animal ranged from 0.007 (SD=0.0041) from 2000 through 2008 versus 0.004 (SD=0.0025) after the GLR (2009-2014) and 0.005 (SD=0.0043) after the VLR (2015-2016). As in the case of the *per capita* rate, these outcomes were not statistically different whether the mitigation periods were combined (F=1.19, p=0.292, df=16) or treated individually (F=1.27, p=0.309, df=16).

Prior to the rules, reported entanglements of identified GOM individuals primarily involved presumed juveniles (32.7%, n=18) and mature females (25.5%, n=14), with fewer events involving mature males (16.3%, n=9), confirmed juveniles (14.5%, n=8), and calves (10.9%, n=6). After the implementation of the GLR and the VLR, there was a significant change in the demographic composition (G=11.88, df=4, p=0.018). Reports less frequently involved calves (1.6%, n=1) and mature males (3.2%, n=2), while mature females (30.6%, n=19) and both presumed (48.4%, n=30) and confirmed juveniles (16.1%, n=10) remained preferentially affected.

Population survival

The results of the Bayesian state-space model suggested no change in population survival rates in relation to the GLR alone as compared to prior years (Figure 3). However, it did suggest an increase in apparent survival from 2015 to 2016, coinciding with the initiation of the VLR (Figure 3). It has yet to be determined whether this increase in survival was specifically entanglement-related. The model estimated improvements in survival across all age and sex classes.

DISCUSSION

Entanglement is a source of injury and mortality to humpback whales and other whale species in U.S. waters. Coast-wide Federal rules were enacted in 2009 and 2015 to reduce the likelihood of entanglement and thereby the probability of entanglement-related mortalities. Robbins and Pace (2018) developed a series of estimates of population abundance and annual estimates of apparent survival for Gulf of Maine humpback whales prior to and after these mitigation efforts were put in place. Here, we used these newly available data as a basis for evaluating the success of mitigation in relation to observed events and latent mortality. Our results suggest no reduction in the frequency of observed entanglements in relation to the GLR or the VLR. There was also no evidence for a change in population survival after the GLR. However, there was evidence of an increase in population survival rates after the implementation of the VLR. While reduction in latent mortality from entanglement is one possible explanation for this finding, this requires further study.

A complicating factor for assessing entanglement impacts on humpback whales on the U.S. East Coast is accounting for the stock identity of affected individuals. The Gulf of Maine is one of the primary feeding grounds in the North Atlantic and the main aggregation site for humpback whales in U.S. North Atlantic waters. However, this species also occurs in coastal waters south of the Gulf of Maine, from Rhode Island to Florida, and some individuals come from other North Atlantic feeding grounds (Barco et al. 2002). We attempted to focus on events with the highest likelihood of involving GOM whales because entanglement frequency and impacts were being evaluated in the context of population-specific abundance and survival models. We took a proportional approach to population assignment in some cases because the available data were not always adequate to assign on a case-by-case basis. However, the actual proportions of GOM whales off the mid-Atlantic states and southeast U.S. may be annually variable and the published inter-area match rate from an earlier period (1990-2000, Barco et al. 2002) may no longer apply. A proportional approach also complicates other methods of assessing changes in entanglement rates over time, such as the time elapsed time between events (Pace et al. 2014). Work is currently on-going to re-evaluate the frequency of exchange with southern waters, including a wider portion of the coastline (Brown et al. 2017; Mallette et al. 2017). That research may warrant a revision to the estimated proportions employed or the proportional approach taken here. Similarly, we prorated the entanglements observed in the Gulf of Maine during shoulder seasons to clarify trends over time in relation to peak-season abundance estimates. However, further research is needed to more fully evaluate the appropriateness and implications of a constant proportional reduction for shoulder season events.

Entanglement reports are opportunistic and their annual frequency likely depends on variety of factors in addition to true incidence, such as observer coverage and awareness. One method of evaluating change over time is by standardizing counts by a known unit, such as a *per capita* estimate based on population abundance. One advantage of a *per capita* approach is that it provides information on entanglement report frequency in relation to population trends. For example, as whale populations recover, it is conceivable that the likelihood of interacting with gear could increase even with gear reductions, with a concomitant increase in negative outcomes. This is the first study to estimate GOM humpback whale entanglement report frequency relative to a series of statistical population estimates, and the results confirm that reported entanglements have not changed in a linear fashion with population size.

The new availability of annual estimates of GOM population abundance also aided in evaluating changes in entanglement frequency over time in relation to management efforts. Our analysis suggests no significant change in the entanglement rate per unit individual from the GLR or VLR. However, both metrics exhibit temporal similarities that may be worth further exploration for insight into entanglement and/or detection rates. For example, both suggested that not only were entanglement report counts as high in 2016 as they had been prior to mitigation actions, they were also high *per capita* and *per observed individual*. Similarly, the years with the lowest observed entanglement report counts (2013-2014) were also the two-year period with the lowest entanglement reporting rates per unit animal. Humpback whale oriented platforms in the Gulf of Maine are an important source of entanglement reports and many collect systematic sighting and effort data. Here, we used sightings data from those platforms to create a simple, alternative metric. However, a more detailed analysis of effort and sighting data in the future could help to further evaluate entanglement rate and potentially quantify detection rates in specific, primarily coastal, areas.

Entanglement reports are the observed events, which are a subset of the total number of entanglements that occur. Population survival rates have the potential to identify latent mortality, but include all sources of mortality, including entanglement but also other human impacts and natural causes. Our results do not indicate an improvement in population survival rates after the GLR, but there was evidence of a potential increase in survival from 2015 to 2016, the last year of our study. This effect appears to extend all demographic classes, including mature females, which made up a large percentage of entanglement events across mitigation periods, along with presumed juveniles. The latter is notable in light of their relatively low percentage in the GOM population (Robbins and Pace 2018, Figure 2). Survival impacts for presumed juveniles may have been obscured in our analysis because confirmed and suspected juveniles were treated as one class for survival, whereas suspected juveniles were more frequently involved in observed entanglement events. Further work is necessary to determine whether the estimated increase is a positive effect of the VLR or other factors. It is also important to note that an Unusual Mortality Event (UME) began in 2016 and is still underway. The population level impacts of the UME, and the degree to which entanglement has been a causative factor, remains to be determined. As a more general issue, there are no proportional or cause-specific rates of mortality for GOM humpback whales and this makes it difficult to monitor entanglement-related impacts from population data. The most direct approach would be based on the percentage of entanglement mortalities out of all observed deaths. However, between 2011 and 2015, there were 69 confirmed humpback whale mortalities, of which only 27% (n=19) could be assessed as either entanglement related or excluded from an entanglement cause (Henry et al. 2017). Entanglement mortality can potentially be estimated by other means, such as based on the frequency of entanglement events, the entanglement survival rate and population abundance (Robbins et al. 2009). Scar-based entanglement rates are one potential source of entanglement frequency, but estimates were not available for the entire period of study here. Overall, current results suggest a potential survival benefit from the VLR, but this should be considered preliminary given that it is based on a single VLR survival estimate, may reflect changes in other sources of mortality and immediately precedes an Unusual Mortality Event.

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Figure 1: Counts of reported entanglements likely involving GOM humpback whales versus annual estimates of population abundance from Robbins and Pace (2018). The results provide little evidence of a direct correlation between entanglement reports and population size.

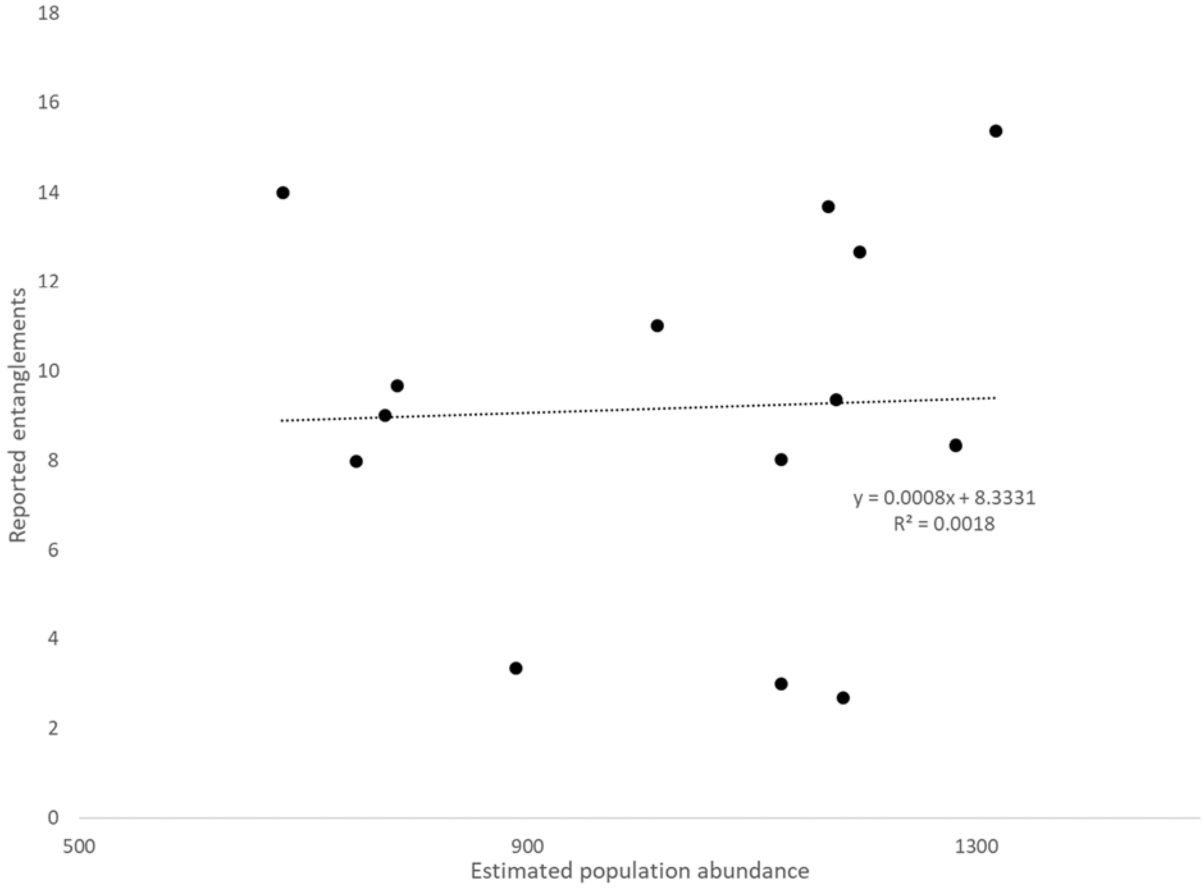


Figure 2: Reported entanglements per unit individual. Circles represent the *per capita* rate, or entanglements likely to have involved Gulf of Maine humpback whales divided by the estimated population abundance (2003-2016). Solid squares represent reports *per observed individual*, as derived from GOM observers reporting individual humpback whales with or without entangling gear, 2000-2016. Both metrics suggested similar trends, including a period of low entanglement reports per unit individual in 2013-2014 and a relatively high rate in the last year of the study. However, there was no statistical difference among mitigation periods.

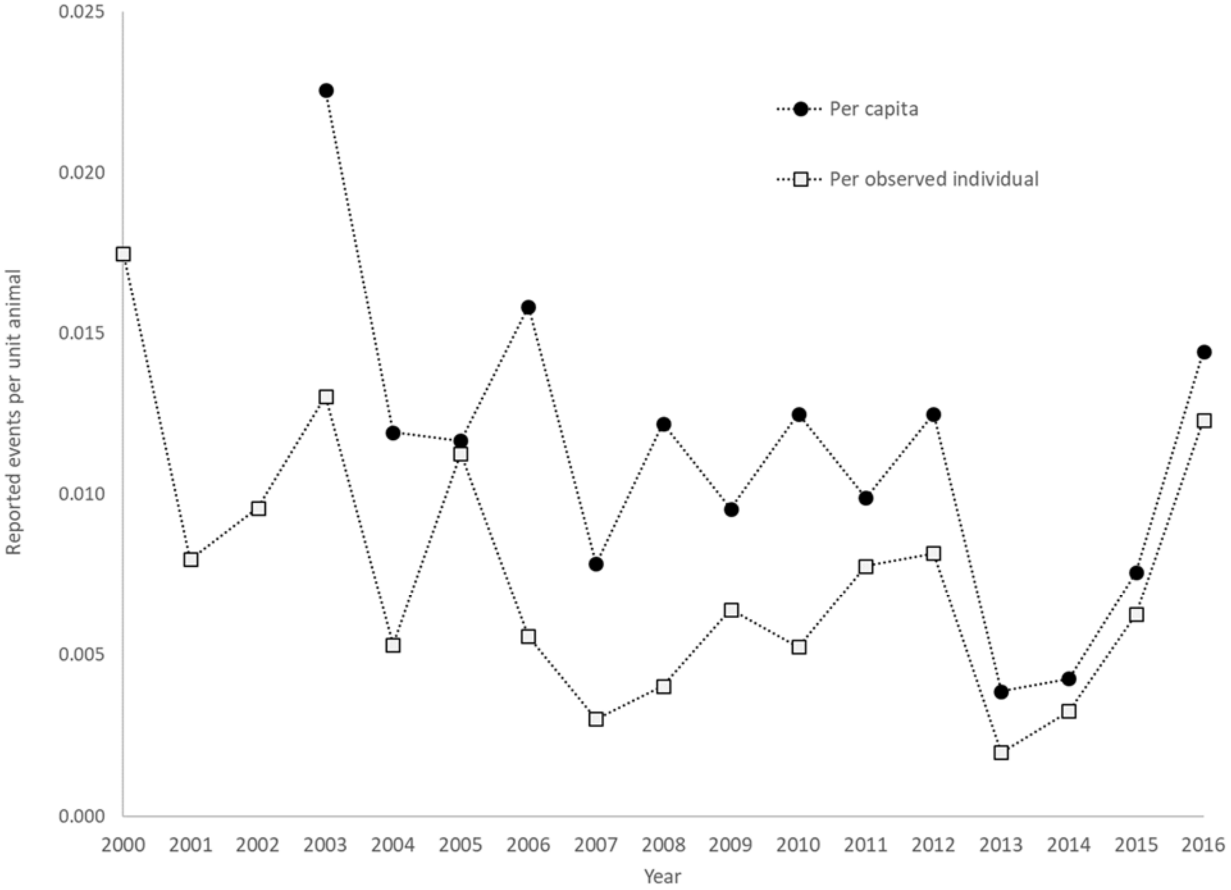
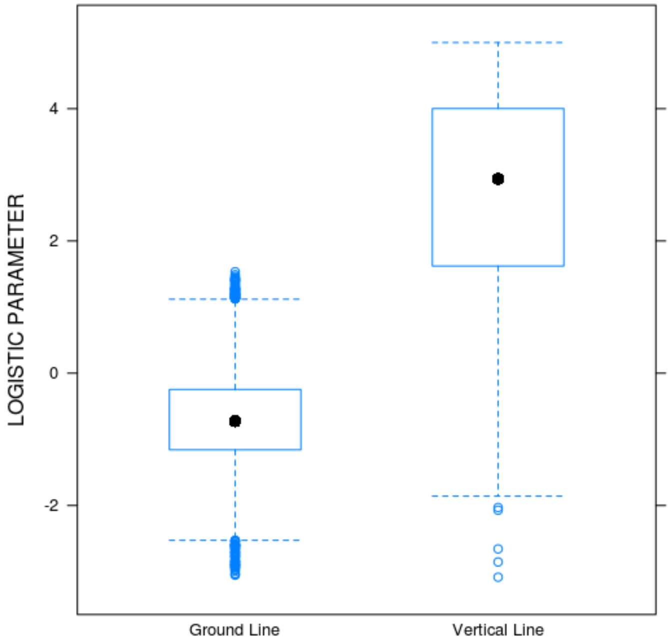


Figure 3. Evidence for a change in Gulf of Maine humpback whale survival rates in relation to mitigation periods based on a Cormack-Jolly-Seber Bayesian state-space model. The results suggest no increase in survival from the Ground Line Rule alone (2009-2014) relative to status quo (2000-2008). However, there was modest evidence of an increase in survival after the Vertical Line Rule was implemented (2015-2016). Further work is necessary to determine whether this effect was directly related to vertical line reduction and whether it continued in subsequent years.



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Appendix I

```
###### Made to run in r package runjags  #####
#-------------------------------------
# Parameters:
# phi: survival probability
# pcap: capture probability
#-------------------------------------
# States (S):
# 0 dead
# 1 alive

# Observations (O):
# 1 seen
# 0 not seen
#-------------------------------------

   model {

   epsilon ~ dunif(0.0001,4)       ###  prior on standard deviation of catchability
   omega<- 1/(epsilon*epsilon)     ###  precision for use in jags/bugs

   for (i in 1:(M))
    {
      Gotcha[i]~dnorm(0,omega)     ###  prior on random catchability of individuals
    }

    # Priors and constraints
   sigma~dunif(0.001,10)              #######   prior for sd of random year effect on phi
   tau<-1/(sigma*sigma)

   #### for pcap, The intercept is mean for Adult Males at t=1

   pie~dbeta(5,5)                        # prior for sex
   Alpha0 ~ dunif(-5,5)        # Adult Males at t=1
   AlphaSex ~ dunif(-5,5)      # Prior for female on capture rate
   AlphaAge ~ dunif(-5,5)      # Prior for Juvenile on capture rate
   AlphaTime[1]<-0            #  Mean includes effect of Time 1
   for (t in 2:(n.occasions-1)) {
     AlphaTime[t]~dnorm(0, 0.01)I(-10, 10)
   }

   # for survival parameters

   eta[1]<-0
   for (t in 2:(n.occasions-1)){
     eta[t]~dnorm(0,tau)}

   b0 ~ dunif(-5,5)
   BetaSex ~ dunif(-5, 5)
```

```
# Priors for male sex effects on survival
   BetaAge[1] <- 0
#  reference category is calves (Age=1 in input)
   for (i in 2:6) {
     BetaAge[i] ~ dunif(-6, 6)
#   Categorical effect of each age(1,...,5+) but (Age=2,...,6 in input)
   }  # i

   GndLine ~ dunif(-5, 5)
   VertLine ~ dunif(-5, 5)

#########  Probability models

   for (i in 1:M){
    sex[i]~dbern(pie)
    for (t in f[i]:(n.occasions-1)){
      logit(pcap[i,t]) <- Alpha0 + AlphaSex*(1-sex[i]) + AlphaTime[t] + AlphaAge*(1-Adult[i,t]) +
Gotcha[i]
      logit(phi[i,t]) <- b0 + BetaAge[Age[i,t]] + BetaSex*(1-sex[i])*Adult[i,t] + GndLine*Rules[t,1] +
VertLine*Rules[t,2]  + eta[t]
   } #t  for time
   } #i  for individual

    # for logistic parameters
   for (t in 2:(n.occasions-1)){
   pcap1[t-1] <- 1 / (1+exp(-Alpha0 - AlphaTime[t]))
# Back-transformed recapture of females
   pcap2[t-1] <- 1 / (1+exp(-Alpha0 - AlphaSex- AlphaTime[t]))
# Back-transformed recapture of males
   pcapj1[t-1] <- 1 / (1+exp(-Alpha0 - AlphaAge- AlphaTime[t]))
# Back-transformed recapture of juv females
   pcapj2[t-1] <- 1 / (1+exp(-Alpha0 - AlphaAge- AlphaSex- AlphaTime[t]))
# Back-transformed recapture of juv males
   phi01[t-1] <- 1 / (1+exp(-b0-GndLine*Rules[t,1]-VertLine*Rules[t,2]-eta[t]))
# Back-transformed survival of calves
   phi11[t-1] <- 1 / (1+exp(-b0-BetaAge[2]-GndLine*Rules[t,1]-VertLine*Rules[t,2]-eta[t]))
# Back-transformed survival of yearlings
   phi21[t-1] <- 1 / (1+exp(-b0-BetaAge[3]-GndLine*Rules[t,1]-VertLine*Rules[t,2]-eta[t]))
# Back-transformed survival of 2-year-olds
   phi31[t-1] <- 1 / (1+exp(-b0-BetaAge[4]-GndLine*Rules[t,1]-VertLine*Rules[t,2]-eta[t]))
# Back-transformed survival of 3-year-olds
   phi41[t-1] <- 1 / (1+exp(-b0-BetaAge[5]-GndLine*Rules[t,1]-VertLine*Rules[t,2]-eta[t]))
# Back-transformed survival of 4-year-olds
   phiaf[t-1] <- 1 / (1+exp(-b0-BetaSex-BetaAge[6]-GndLine*Rules[t,1]-VertLine*Rules[t,2]-
eta[t]))     # Back-transformed survival of adult females  (coded 1-sex in logit)
   phiam[t-1] <- 1 / (1+exp(-b0-BetaAge[6]-GndLine*Rules[t,1]-VertLine*Rules[t,2]-eta[t]))
# Back-transformed survival of adult males
    }
```

```
# Likelihood
for (i in 1:M){
  # Define latent state at first capture
  z[i,f[i]] <- 1
  for (t in (f[i]+1):n.occasions){
    # State process
    z[i,t] ~ dbern(mu1[i,t])
    mu1[i,t] <- phi[i,t-1] * z[i,t-1]
    # Observation process
    y[i,t] ~ dbern(mu2[i,t])
    mu2[i,t] <- pcap[i,t-1] * z[i,t]
    } #t
  } #i

}
```