The humpback whale population at risk of ship strikes in the Strait of Magellan, Chile.

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ABSTRACT

A population of humpback whales was discovered in the Strait of Magellan, Fueguian archipelago, Chile in 2003, and has since been monitored using regular photographic mark-resight surveys. The population is centered around the Francisco Coloane Marine and Coastal Protected Area, which is immediately adjacent to, and encompasses part of, the international shipping lanes through the Strait of Magellan, one of the most important shipping lanes in the southern hemisphere. We analyzed the photographic mark-resight data using a robust design in a Bayesian framework to derive estimates of abundance, trend and survival. We then used these estimates to parameterize a simulation model that explored the population consequences of ship strikes. The median abundance estimate of whales in the Strait of Magellan in 2012 was 88 (95% Credible Interval: 81, 95). Using a loglinear model on the derived abundance estimates, the median population growth rate from 2004 to 2012 was positive 0.032 (95%CrI: 0.019, 0.045). However, the median population growth since 2005 was 0.0023 (95%CrI: -0.0095, 0.015) reflecting a stable population. The number of new individuals sighted each year was found to be a function of effort but has also stabilized, supporting the inference that the population is not growing. In the simulation model using an initial population size of 88 whales, the Strait of Magellan population was found to be sensitive to low levels of ship strikes: we found that an additional lethal collision every three years was enough to shift the median population growth rate from stable (0.0023) to decreasing (-0.002). The population would further decline (-0.011) if a collision occurred every other year and involved adult females. Shipping traffic is likely to increase in the Strait of Magellan reflecting the global growth in shipping industry and a local expansion of shipping due to the development of a large scale coal mine. We recommend that a satellite tagging effort be commenced to help identify the vertical (time at surface exposed to ships) and horizontal risk (time spent in shipping lanes) to reduce the uncertainty in our estimates of population risk to ship strikes. Our model can accommodate these additional data and will help clarify the risk and conservation concern.

Keywords: CONSERVATION; ABUNDANCE ESTIMATE; GROWTH; TRENDS; SOUTH AMERICA

INTRODUCTION

The world shipping fleet has changed dramatically in the past several decades with both the volume and average speed of ships increasing substantially (Ross 2005; McDonald *et al.* 2006; Buhaug *et al.* 2009). Coinciding with these changes has been an emerging awareness of the deleterious impacts that shipping may have on individuals and populations of large whales (Tyack 2008). While chronic, low-frequency, underwater noise produced by large ships has been increasing for decades (McDonald *et al.* 2006) and may impact whales via loss of acoustic communication space (Clark *et al.* 2009; Hatch *et al.* 2012) and increased stress (Rolland *et al.* 2012), large ships have also been shown to directly impact the fitness of individuals or populations of whales via collisions (Fujiwara and Caswell 2001; Laist *et al.* 2001). Reducing collisions ('ship strikes') between large ships and large whales has thus become a pressing conservation concern and a priority management issue for a number of agencies within the US and globally (Silber *et al.* 2012). In 2005, the Conservation Committee of the IWC recognized the issue of increasing ship strikes, in part because estimates of anthropogenic mortality are necessary for the Revised Management Procedure, and in part because of the growing understanding that ship strikes may adversely impact local or range-wide populations.

While ship strikes are likely to occur wherever there is spatial and temporal overlap between large ships and whales, the population consequences will be greatest where shipping traffic is high and overlaps with small populations of whales. For example, the important shipping lanes along the US western North Atlantic overlap with important migratory and feeding aggregations of the critically endangered North Atlantic right whale (*Eubalaena glacialis*). Given their small population size, collisions may inhibit population recovery (Fujiwara and Caswell 2001; Kraus *et al.* 2005). In other whale populations, the population dynamics are not as well understood, but due to the high-density shipping traffic overlapping with important feeding, breeding, or migratory areas, such as areas in the Mediterranean, the Gulf of Panama, the Singapore Strait, and Southeast Alaska, the conservation concerns are elevated (Panigada *et al.* 2006; Qu *et al.* 2011; Guzman *et al.* 2012; Hendrix *et al.* 2012).

Here we highlight a significant conservation concern from ship strikes in the Strait of Magellan, Fueguian Archipelago, Chile. The Magellan Strait (MS) is one of the most important international shipping lanes in the southern hemisphere used primarily by large container vessels and tankers. While other areas support higher

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absolute volume of ships, the MS is a narrow shipping lane, traversing narrow canals and passes, including several navigationally difficult areas such as Paso Tortuoso where the effective navigational channel is less than 1 nautical mile. While these narrow passages concentrate the shipping volume into small areas, they also result in dynamic oceanographic conditions including localized upwelling (Valle-Levinson *et al.* 2006), resulting in high levels of primary productivity (Saggiomo *et al.* 2011). Not surprisingly, these productive foraging conditions attract aggregations of humpback whales (*Megaptera novaeangliae*), and in 2003 a feeding population of humpback whales was discovered in the Magellan Strait (Gibbons *et al.* 2003). Previously humpback whales seen in the Magellan Strait were thought to be simply migratory individuals moving from their historical feeding grounds near the Antarctic peninsula to unknown breeding areas off the coast of Ecuador or Columbia. However, recent studies have demonstrated that humpback whales aggregate in the MS to feed during the summer months, November-April (Acevedo *et al*. 2006) and show high levels of site fidelity to this area (Acevedo *et al*. 2014).

The Conservation Committee has recognized the need to understand variables that affect the impacts of ship strikes to populations of whales. Here we present results of the first rigorous photographic mark-resight estimates for generating population abundance and growth estimates. We used a robust design (Pollock 1982) model in a Bayesian framework to generate annual abundance estimates, a population growth rate, and an annual survival rate. We subsequently used summaries of the posterior distributions to parameterize a simulation model that explored the consequences of scenarios of ship strikes in the Magellan Strait.

METHODS

The Magellan Strait is located between 52°17´S and 54°15´S in the center of the Fueguian Archipelago in southern Chile. The focus of our study included the approximately 2000 km^2 area encompassing the western portion of Magellan Strait from Mansa Bay to the north of Xaultegua Gulf, including the straits, fjords, and channels between the Magdalena and Cockburn channels in the south to Otway Cove in the north. The area also encompasses the Francisco Coloane Marine and Coastal Protected Area, including the Francisco Coloane Marine Park, the first marine national park in Chile, designated specifically to conserve feeding areas for humpback whales.

Photographic surveys for humpback whales have occurred in this area beginning 2003 with variable effort within and among years (Acevedo *et al.* 2014). While variable, surveys always occurred during the peak feeding period between December and March, with some years extending into April or May. For details on photo re-sight effort and a detailed description of photo catalog, matching, and study area, see methods and Figure 1 in Acevedo *et al*. (2014).

Data Analysis

We used capture-recapture models that utilize the complete data likelihood (CDL) (Royle and Dorazio 2008; Schofield and Barker 2011). Previous approaches to capture-recapture have used the observed data likelihood, which are composed of the individuals that were captured in the study. Yet, in almost all capture-recapture studies there is a portion of the population that was present during the study, but was never captured. The CDL tracks both observed and unobserved trajectories of individuals to incorporate the dynamics of individuals that may have been present but that were not detected.

One important advantage of using the CDL is that the estimate of abundance is incorporated into the model structure explicitly. This approach is in contrast to previous methods for estimating abundances (e.g., Seber 1982) that incorporate estimates of the untagged portion of the population via an expansion using the inverse of the probability of capture. This approach can lead to large annual variability in the abundance estimates due to variability in the probability of recapture; moreover, the magnitude in fluctuation may exceed biologically plausible rates of variability. The CDL approach uses an alternative method of estimating abundance by conditioning upon an unknown total number of individuals in the population (both captured and not captured).

The CDL models the annual processes of birth, recruitment into the tagged population, death, and recapture, for each individual as Bernoulli events. The probability of an event can be subsequently modeled as constant over time, varying with time, or as a function of individual level covariates. We provide a brief description of the approach below and more details can be found in Schofield and Barker (2011).

Using the notation of Schofield and Barker (2011), we present some notational details before beginning to define the birth, death, and recapture events. There are $i = 1, \dots N$ individuals in the population during primary periods (years)

$j = 1, \ldots, J$ and secondary periods (months) $t = 1 \ldots T$ The full CDL includes those individuals that have been tagged as well as those that have not (i.e. those with a capture history consisting entirely of 0's), thus individuals that have not been tagged are also included in the population.

The method for incorporating the untagged portion of the population is through data augmentation (Royle and Dorazio 2008). This does not create a problem so long as the index M is large enough to accommodate all tagged and untagged individuals in the population N. There is a latent variable w_i for each individual i that determines which individuals are in the population, such that

$$\sum_{i=1}^{M} w_i = N$$

Note that these are all of the individuals that existed in the population during the period of study including those that may have died during the study.

Recruitment

Individuals have the ability to recruit (or more generally be born) into the population in each year of study. In each year, there is a probability of entering into the population. All individuals present during the study period (i.e., N) are recruited into the population by the last sampling period. The recruitment process for individual i in period j is modeled as a Bernoulli event

$$a^{b}_{i,j} \sim Bern(p^{b}_{i,j}) \qquad (1)$$

The probability of a recruitment event is modeled as a function of additional terms that are included to ensure that a recruitment event only occurs once

$$\begin{aligned} p^{b}_{i,j} &= \psi_{i,j} \bullet z_j + (1 - \psi_{i,j}) \\ \psi_{i,j} &= \psi_{i,j-1} \bullet (1 - a^{b}_{i,j-1}) \end{aligned} \qquad (2)$$

where $\psi_{I,j}$ is a variable that indicates if the individual has been recruited before the current period j ($\psi_{I,j} = 0$ if the individual has not been born before time period j) and z_j is the probability of the individual being recruited during time period j.

Survival

Survival for each individual i in each period j is modeled as the event of remaining alive ($a^{d}_{i,j} = 1$ indicates that individual i is alive in sample period j). $a_{i,j}^{d} \sim Bern(p^{d}_{i,j})$ (3)

The probability of surviving $p^{d}_{i,j}$ in time period j is conditional upon the individual being born prior to the current period j ($a^{b}_{i,m} = 1$, where $m<j$) and the individual has not died previously.

$$p_{i,j}^{d} = a_{i,j-1}^{d}(a_{i,j-1}^{b} \bullet s_{i,j-1} + [1 - a_{i,j-1}^{b}]) \qquad (4)$$

where $s_{i,j}$ is the probability of survival for individual i in time period j. The probability of survival is modeled further as a base survival rate and an annual random effect.

$$\mathrm{logit}(s_{i,j}) = \beta + \eta_j^{1} \qquad (5)$$

where β is the annual survival rate and η^{1}_{j} is an annual random effect. The random effect for survival is modeled as a normal random variable with a mean of 0 and standard deviation sd_1.

$$\eta_j^1 \sim N(0, sd_1^2) \qquad (6)$$

Other metrics of interest arise from variables that indicate whether individual *i* has been born in sample period *j* ($a^b_{i,j}$ = 0 indicates that the individual has yet to be born) or whether individual *i* has yet to die in sample period *j* ($a^d_{i,j}$ = 1 indicates that individual *i* has yet to die in sample period *j*). For example, the annual abundance N_j is computed as

$$N_j = \sum_{i=1}^{N} a^b_{ij} a^d_{ij}.$$

Detection

A detection event for individual *i* in primary period (year) *j* and secondary period (month) *l* is denoted $x_{i,j,l} = 1$. The detection event is modeled as a Bernoulli random variable with probability $p^c_{i,j,l}$.

$$x_{i,j,l} \sim Bern(p^c_{i,j,l}) \qquad (7)$$

The probability of detection $p^c_{i,j,t}$ is further modeled as a function of effort in month *t* (in days) using the logit() transformation to keep $p^c_{i,j,t}$ in the interval [0,1], which is appropriate for modeling the probability of detection.

$$\text{logit}(p^c_{i,j,t}) = \gamma_t + \gamma_1 effort_{i,j,t}, \qquad (8)$$

where γ_t is the recapture rate in month *t* (November to June) to reflect different average rates of capture among month and $effort_{i,j,t}$ is a standardized effort variable obtained by subtracting the mean of the raw effort values.

Collision Risk

Using the derived estimates of abundance and trend, we then evaluated the population consequences of collisions using an approach commonly used to understand the population impacts of incidental mortality due to anthropogenic activity, such as by-catch (Williams *et al.* 2009; Worm *et al.* 2013; Gilman *et al.* 2014). The approach includes generating a base model that reflects the current population dynamics, and then imposes different levels of anthropogenic mortality, such as ship strikes, or alternative management actions (Mangel 1993; Underwood *et al.* 2008).

We simulated the dynamics of the population for 30 years assuming a closed population and an initial abundance estimate of 88 unique whales. For our model we assumed no emigration or immigration into the population. While it is likely that humpback whales utilize other areas of the MS or may move to different feeding areas among years, a lack of information about the rates of exchange between this population and others and its geographic isolation reduced our ability to parameterize a movement component of the population model. Nevertheless we felt our assumption of a close population was justified because (1) the number of new individuals identified in the area appears not to be increasing and (2) whales demonstrate a high level of site fidelity to their feeding sites, including within the MS (Acevedo *et al.* 2014).

We constructed the simulation model to include the population processes of birth, maturation, and survival. These processes were modeled in much the same way as the mark-recapture model framework (robust design). Unlike the estimation model, however, we tracked adult female, adult male, and juvenile classes separately in the simulation model. For animals to transition from the juvenile to the adult classes, we defined a maturation function such that all juveniles matured between 6 and 11 years, with an increasing probability of maturing to an adult as age increases beyond 6 years (50% probability of maturity at 8 years and 100% at 11 years).

Probabilities were assigned to the different population processes, and individual life-history events were modeled as Bernoulli random variables with class-specific rates defining the likelihood of events. Mature adult females could produce calves, and we assumed that the reproductive rate was 0.42 for the purposes of this simulation study (Zerbini *et al.* 2010). Survival was class-specific and we assumed annual survival rate was 0.92 for juveniles and 0.95 for adult males and adult females. These survival estimates are lower than some populations in the North

Pacific but commensurate with others in the Pacific and Atlantic (Zerbini et al. 2010). Absent any published information on age structure, we used values of 50% juveniles, 25% male adults, and 25% female adults.

We then used the simulation model to impose an additional mortality component of ship-strikes. The simulation model was constructed to allow for a varying number of whales to be struck and killed (and thus removed from the population) per year, as well as accommodate variation in the class of individuals that were struck. This functionality allowed us to evaluate how different levels of ship strikes, and on different life-history classes, would affect the dynamics of the population. The model was run under 1000 Monte Carlo simulations. The three scenarios considered were:

1. An additional collision every 3 years; collisions occurring randomly on individuals of the 3 classes

2. An additional collision every 3 years; collisions occurring only on adult females

3. An additional collision every 2 years; collisions occurring on females only

We note that the rate of collisions between ships and whales is extraordinarily difficult to estimate. Ships are not required to report collisions and may not detect collisions even if they occur. Thus, in many areas the estimates of mortalities from ship collisions come solely from detection of dead whales at sea or washed ashore. Given the sparse human activities in the MS aside from the commercial shipping traffic, we expect the probability of detection of collisions in the MS to likewise be quite low.

Nevertheless, we have been working on a similar effort to understand the population consequences and shipping risk to whales in Glacier Bay National Park, Alaska. Conditions in the MS are perhaps most reflective of conditions in the archipelago of southeastern Alaska, including Glacier Bay, where humpback whales accrue to feed during the summer months in the narrow canals and straits, and are exposed to large cruise ship traffic (Chenoweth *et al*. 2011; Gende et al. 2011). The spatial and temporal overlap of whales and large cruise ships have resulted in several lethal collisions since 2001 (Neilson *et al*. 2012). While the true number of whales struck and killed in Glacier Bay is unknown, there were 2 dead whales detected in Glacier Bay since 2001with injuries consistent with death due to ship strike (Gende and Hendrix 2009). Thus, in 13 years, there have been 2 whale deaths attributed to an exposure level of 450 ship transits per year. From 1995-2010, the average number of ship using the MS during the summer has been 860 (data courtesy the Gobernado Maritimo det Punta Arenas). It thus a single collision every three years seems plausible given the level of shipping traffic through the MS.

RESULTS AND DISCUSSION

The robust design model was fitted in a Bayesian framework, therefore the results are presented as the median estimate along with the symmetric 95% probability interval, also called the 95% credible interval (95%CrI). The robust design model estimated that the annual survival rate was 0.89 (95% CrI: 0.89 (0.86, 0.92) for the combined juveniles and adults. The abundance estimate in 2003, which was the first year of the study, was 17 (95%CrI: 12, 25) (Figure 1).

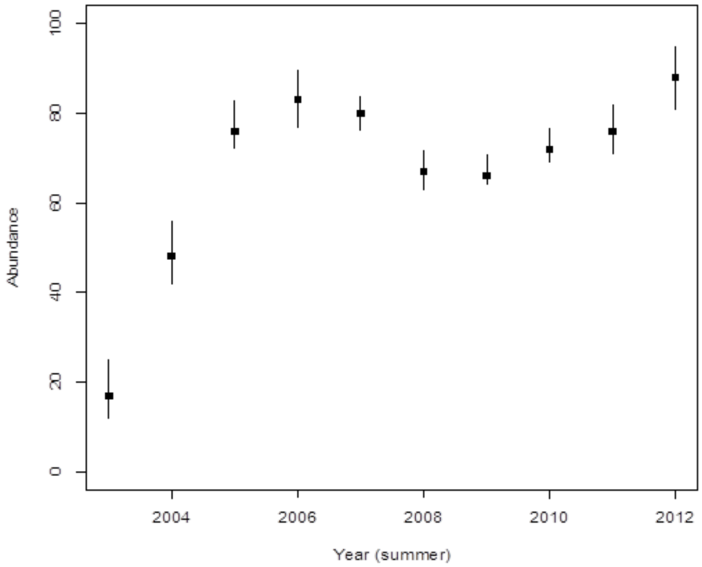


Figure 1. Annual estimates of abundance for humpback whales observed in AMCP from 2002/2003 to 2011/2012. Boxes represent median and lines indicate 95% credible intervals of the annual estimate.

Subsequent estimates of abundance were higher: in 2004 the median estimate was 48 whales (95%CrI: 42,56) and in 2005 the median estimate was 76 whales (95%CrI: 72,83). The annual abundance of whales was stable for the remainder of the study, and in 2012 the median estimate of abundance was 88 (95%CrI: 81, 95). The median estimate of population growth rate from 2004 to 2012 was 0.032 (95%CrI: 0.019, 0.045), whereas the median estimate from 2005 to 2012 was 0.0022 (95%CrI: -0.0095, 0.015).

The model estimated that there were 153 (95%CrI: 147, 160) unique whales identified in the study, whereas 144 individual whales were captured (i.e., had non-zero capture histories). This result indicated that there were between 3 and 16 whales that were available for capture, but were not detected in the study (i.e., had all zero capture histories). The probability of capture varied among secondary sampling periods as a function of effort and the month in which the effort was spent. Effort varied among secondary sampling periods from 0 to 13 days per month. The probability of capture varied as a function of effort with an increasing probability of capture as effort increased (Figure 2). Moreover, the probability of capture also varied among months, with the highest probability of capture occurring January – March, intermediate probability of capture in months December and April and lowest probability of capture in November and June (Figure 2).

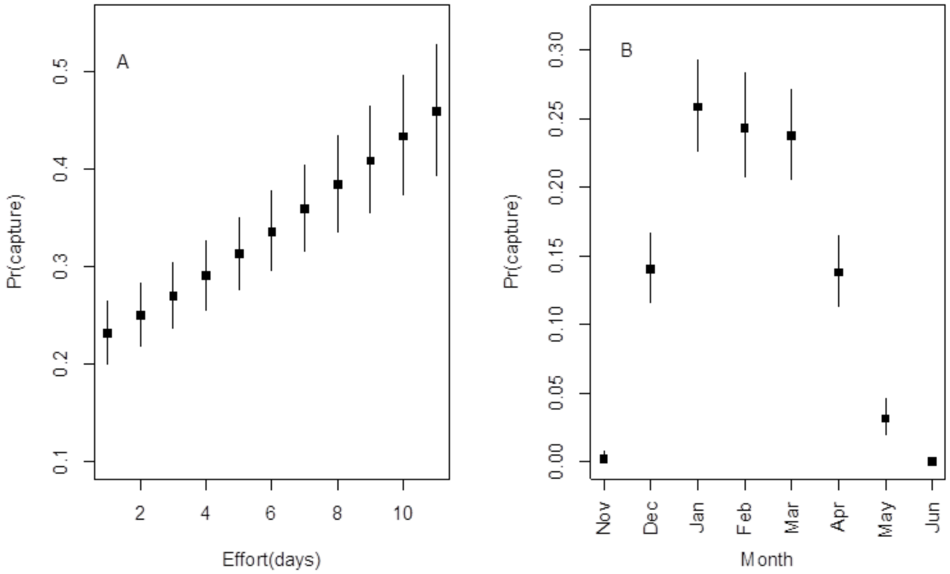
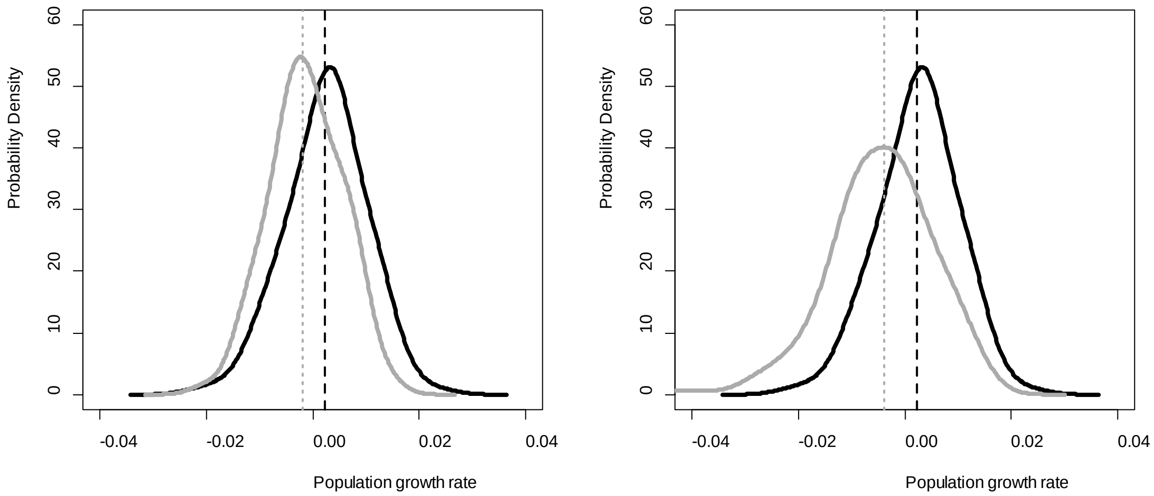


Figure 2. Probability of capture as a function of effort in January (A) and probability of capture among sampling months (B) at average effort of 2.45 days per month. Boxes represent median and lines indicate 95% credible intervals.

The results of the simulation model demonstrated that a single collision every three years, randomly distributed among the sex/age classes, results in the median population growth rate shifting from stable (0.0023) to decreasing (-0.002; Figure 3). The impacts to the population would be greater if the collisions occurred with adult females (Figure 3). In fact, if an additional adult female is involved in a collision every 2 years, the population would decline at a rate of about 1.1% per year.



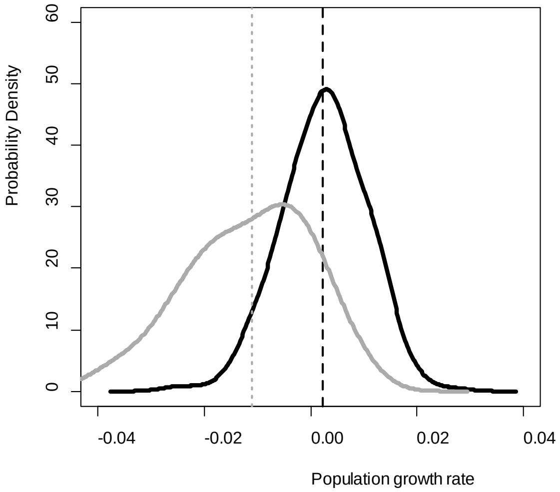


Figure 3. Probability density functions of the population growth rate parameter of humpback whales in the Strait of Magellan, southern Chile. The distribution around the dotted lines (medians) represents the parameter uncertainty. Black line demonstrates the existing conditions based on parameters derived from the mark-recapture model conducted using a Robust Design. Blue lines represent the implications should the population sustain (a) an additional collision every 3 years where the collision was randomly selected from different age (adult vs. juvenile) and sex classes; (b) an additional collision every 3 years if the collision was an adult female, and (c) an additional collision every 2 years with adult females representing all collisions.

The robust design, mark-recapture model and the simulation model thus demonstrates two key findings. First, the population of whales using the MS is relatively small, and appears to be stable or only slightly increasing, unlike many other populations of humpback whales in the south and north Pacific which are increasing (Zerbini *et al*. 2010; Hendrix *et al*. 2012). This may be due to the population reaching carrying capacity for the area or because collision rates area sufficiently high such that they limit population growth.

Second, owing to the high level of shipping traffic through the area, the population dynamics of whales in the Strait of Magellan is extremely sensitive to the risk of collisions. We recognize that population models are sensitive to their assumptions and we attempted to parameterize our models with the most accurate estimates available. While some of these parameters will undoubtedly changes as more information is collected on the attributes of the whales in and near the MS, our simulation model achieved a stable abundance and age structure when simulations were run to 100 years or longer. We thus feel that the overall simulation model captured the dynamics of the population in the MS even if a given parameter may change slightly.

Perhaps more importantly is that we assumed that the whales in the MS are all equally susceptible to ship strikes. While the rate of ship strikes in the MS will never be known, the uncertainty in risk can be significantly reduced by a directed effort to understand the level of spatial and temporal overlap between the whales and ships. Whales utilize hot spots within the MS, reflected by high concentrations which often coincide with areas of upwelling and aggregations of sardines and lobster krill (J. Acevedo, unpublished data). Yet it is unknown the temporal persistence of these hotspots, and the how many of these hotspots occur within the shipping lanes through the MS. Whales are also known to feed subsurface and thus another important parameter would be to examine the ‘vertical risk’, i.e., how much time is spent in the upper levels of the water column and thus exposed to shipping traffic.

Thus an obvious next step is to initiate a satellite tagging effort to quantify these important movement parameters. Our model has been constructed to account for this information which will more accurately reflect the risk to the population of humpback whales in the MS and perhaps clarify whether mitigation measures, such as speed regulations, should be pursued.

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