Biological Conservation 186 (2015) 149–157

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Mitigation of vessel-strike mortality of endangered Bryde's whales in the Hauraki Gulf, New Zealand

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ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form 20 February 2015
Accepted 6 March 2015
Available online 30 March 2015

Keywords:
Vessel collision
Balaenoptera edeni
Bryde's whale
DTAG
Conservation
Mitigation

ABSTRACT

Collisions between traffic and wildlife can have population-level consequences and carry economic costs. Vessel-strike may threaten the viability of whale populations especially where habitat overlaps with frequent vessel traffic; as seen in the Hauraki Gulf, New Zealand, which is the entrance to the busy Ports of Auckland and holds a year-round population of endangered Bryde's whales (*Balaenoptera edeni*). Here, we identify a serious threat: out of 44 Bryde's whale-deaths, 17 of 20 (85%), with known cause of mortality, sustained injuries consistent with vessel-strike; a mortality rate that is likely to be unsustainable. This information started a social forum with stakeholders engaged in science-based discussion of mitigation measures to reduce lethal vessel-strikes in this region. To determine the viability of different mitigation actions we studied Bryde's whale behavior with suction-cup attached tags. Tagged whales ($n = 7$, 62.5 h) spent 91% of their time at depths within the maximum draft of vessels transiting the Gulf, increasing the probability of vessel-strike. Whales are broadly distributed throughout the Gulf so re-routing traffic would not lessen the threat of vessel-strike. Monitoring whales visually is difficult and not applicable at night, when whales rested closer to the surface than during the day. Passive acoustic monitoring is unreliable due to the whales' low vocal activity and because low frequency calls are susceptible to masking from vessel noise. These findings resulted in a Transit Protocol for Shipping including voluntary speed restrictions and a monitoring plan, highlighting the value of scientific and social stakeholders working together for conservation.

1. Introduction

Collisions between animals, vessels and vehicles have been documented on land, in air and at sea (Groot Bruinderink and Hazebroek, 1996; Huijser et al., 2009; Laist et al., 2001; Barrios and Rodríguez, 2004). Collisions with large animals can increase mortality levels contributing to the decline of populations, as well as causing extensive damage to vehicles and, occasionally, the loss of human life (e.g. Huijser et al., 2009).

Vessel strike is a significant cause of death to cetaceans, involving at least 11 species worldwide (Laist et al., 2001; Redfern et al., 2013). While individual threat is well recognized, the population level effects of vessel-strike mortality are often poorly understood for most whale species (Panigada et al., 2006; Berman-Kowalski et al., 2010; van der Hoop et al., 2013). Cetaceans are long-lived and have low rates of reproduction, so increased mortalities can have a large impact on small populations (Laist et al., 2001).

Globally, reported vessel-strikes are likely an underestimation of the actual number, due in part to the challenges in recognizing when it has occurred, an unwillingness to report incidents or uncertainty about where to report incidents (Moore et al., 2004; Campbell-Malone et al., 2008). Nevertheless, the number of recorded collisions has increased markedly since the 1900s and is attributed to the growth in shipping and increased numbers of whales (Laist et al., 2001; Panigada et al., 2006; Douglas et al., 2008). The increase in recorded whale-strikes may also be due to heightened awareness with education of mariners endorsed by the International Maritime Organization (IMO), and other bodies

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http://dx.doi.org/10.1016/j.biocon.2015.03.008
0006-3207/

such as the International Whaling Commission (IWC) (McKenna et al., 2012; Silber et al., 2012). These initiatives are important but the majority of strikes remain unreported as the crew may be unaware that it has occurred (Silber et al., 2010).

As in terrestrial regions where mammals face a high threat of collision (Groot Bruinderink and Hazebroek, 1996; Ramp et al., 2006), reports of vessel collisions with whales are more likely to occur where there is habitat overlap, high levels of traffic and observer coverage (Knowlton and Kraus, 2001; Panigada et al., 2006). The Hauraki Gulf (henceforward the Gulf) in northeastern New Zealand (NZ) is the transit route for ~1400 ships per annum that enter NZs largest port (Ports of Auckland, 2012) and is a busy area for recreational boating. The Gulf is inhabited by several species of cetaceans of which the Bryde's whale (*Balaenoptera edeni*) is the most frequently sighted whale.

Bryde's whales are a baleen whale, 13–15 m in length and distributed throughout the world's oceans between 40°N and 40°S (Kato and Perrin, 2009). They are considered Data Deficient (IUCN, 2012) and remain poorly understood with only a few coastal regions where they are regularly sighted. In NZ, Bryde's whales are listed as a Nationally Critical species due to their small population (<200 adults) (Baker et al., 2010) and the NZ Department of Conservation's (DOC) concern that vessel-strike mortality may be occurring at an unsustainable rate (Behrens, 2009; Baker et al., 2010). The highest reported sighting rates in NZ waters are in the Gulf; the primary habitat for a year-round resident population (Baker and Madon, 2007; Wiseman et al., 2011).

Two main factors influence the collision mortality threat to animals; the likelihood of collision and severity of the trauma (Barrios and Rodríguez, 2004; Jaeger et al., 2005). Reducing the threat to whales typically involves attempting to separate vessels and whales in space and time (e.g., Vanderlaan and Taggart, 2009; Redfern et al., 2013), or reducing vessel speed (e.g., Guzman et al., 2012). Measures aimed at reducing mortality must account for the whales' behavior and the nature of the vessel activities (Gende et al., 2011; Parks et al., 2012; van der Hoop et al., 2012; International Whaling Commission, 2014).

Mitigation measures have economic and possibly social costs. Therefore, biological and socio-economic factors must be considered in the decision making process. Traditional political and judicial approaches when developing conservation law is often slow; heightening the risk that population decline may become irreversible before action is taken. A way to speed up conservation measures is to develop a social process as early as possible, whereby stakeholders are informed about the issues and brought together in a forum to evaluate options (Reed, 2008). This allows different stakeholders, with complex and often conflicting priorities to work together toward efficiently implementing effective measures, thereby reducing the threat to the population. This also enables mitigation measures to be tested before making the decision to adopt them into conservation law.

Here we take a multi-disciplinary approach to understanding the threat of mortality to Bryde's whales and to rapidly develop mitigation measures. We initially used stranding data to quantify Bryde's whale mortality threat from vessel-strike in the Gulf. These findings sparked the initiation of a social forum early in the process leading to research targeted at understanding the whales' behavior. Sound and movement recording tags (DTAGs, Johnson and Tyack, 2003) are used to assess the threat of collision for these whales and the potential for passive acoustic detection of individuals. In addition, we analyze vessel movements in the Gulf relative to whale presence to determine whether shipping can be re-routed to an area of lower whale density. During the research phases, the information was combined to assess the options available to reduce the threat of collision to Bryde's whales. Finally, we report on the rapid development of a collision mitigation strategy that has now been adopted by the industry into a Transit Protocol for Commercial Shipping.

2. Methods

2.1. Study site

The Hauraki Gulf, on the northeast coast of New Zealand (36°10′–37°10′S, 174°40′–175°30′E; Fig. 1), is a semi-enclosed embayment covering ~4000 km^2 with water depths of around 50 m. There are three major channels through which large vessels enter or exit the Gulf in transit to the Port (Fig. 1) but there are no designated shipping lanes.

2.2. Records of dead whales

Bryde's whales have been found floating at sea, washed ashore, or wrapped around the bow of a large vessel. Records were retrieved from several stranding databases held in New Zealand; primarily the DOC stranding database (initiated in 1989 and curated at DOC offices throughout NZ) and the National Museum of New Zealand Te Papa Tongarewa. Strandings data were also held by different regional Māori (iwi) and the University of Auckland. A formal process for collecting data from stranded cetaceans has only been in place since the 1990s and there is considerable variation in the quality of data collected. Therefore, the data reported here represent a minimum estimate of the number of whale mortalities. The exact location of the vessel strikes were unknown in all cases and, to date, no strikes have been reported by vessels in the Gulf. Three carcasses have been reported floating at sea but there were no data collected and despite boat-based searches, the carcasses were not recovered. Carcasses were assigned to one of three categories based on diagnostic parameters including evidence of sharp or blunt trauma and whether the whale was alive when struck (Knowlton and Kraus, 2001; Douglas et al., 2008; Campbell-Malone et al., 2008) (Table A1). A photo-identification catalogue of Bryde's whales (curated by R.C.) was also examined for evidence of non-lethal vessel-strike injuries, e.g., zipper-like marks from the propellers of small vessels or large lesions from larger vessels (Campbell-Malone et al., 2008).

2.3. Development of the social forum

Once vessel-strike was identified as an issue of concern, a workshop was convened at the University of Auckland in 2007 to up-skill government agencies and researchers on forensic necropsy protocols in line with international best practice (e.g., Campbell-Malone et al., 2008; Moore et al., 2004). In addition, maritime industry representatives were included to engage them in the evidence-based approach to ascertaining cause of mortality. In 2009, the IWC Chair of the Ship-strike Working Group presented at another workshop outlining the IMO and global shipping industry response to vessel-strike mortality and vessel damage. The focus was on the consideration of best practice guidelines for the maritime industry using the Hauraki Gulf waters due to high levels of Bryde's whale vessel-strike mortality in the Gulf (Behrens, 2009). Research questions were identified after the 2009 workshop and an inclusive process was undertaken to engage stakeholders from industry, local and national government, researchers, non-government organizations and local Māori to form the Bryde's Whale Ship-strike Working Group. The mandate of the forum was to work collaboratively to mitigate vessel-strike mortality to whales.

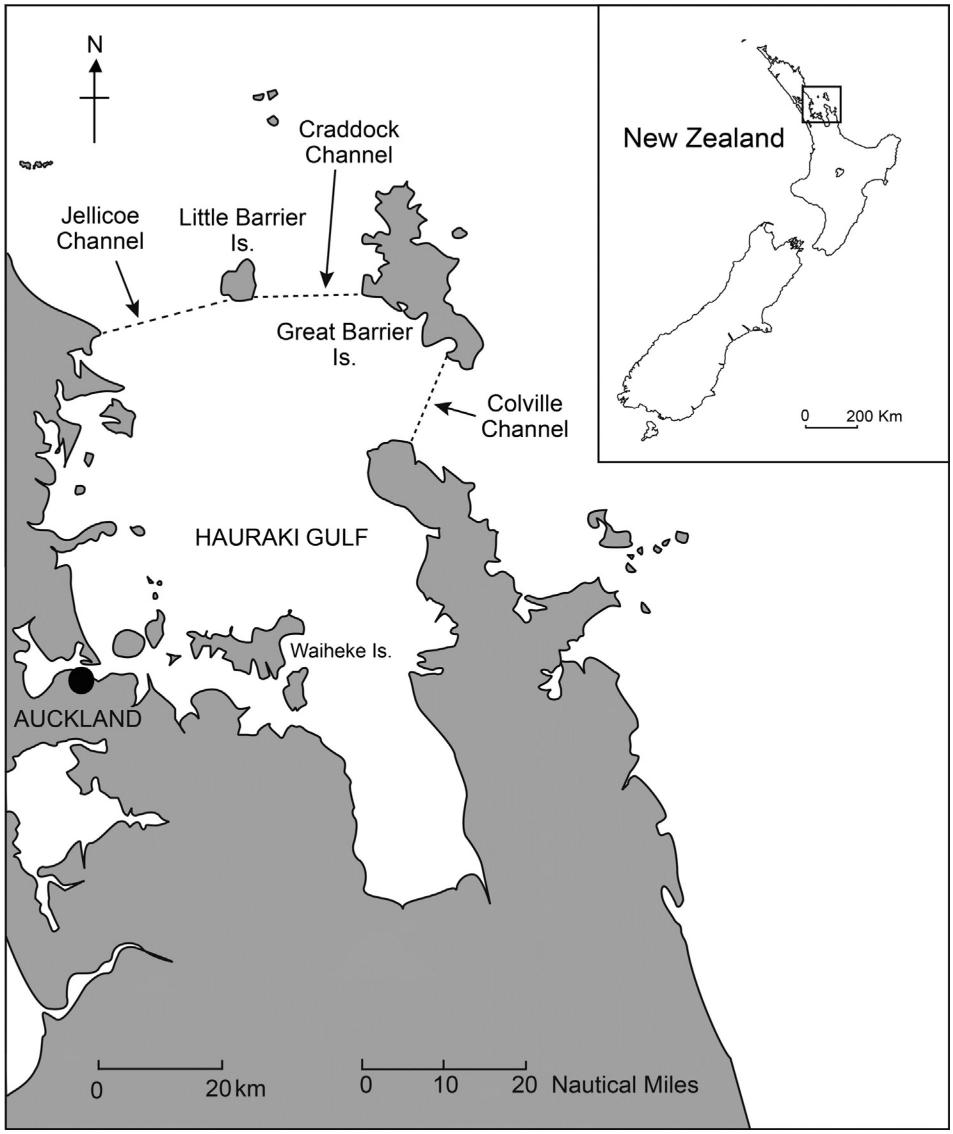

Fig. 1. The Hauraki Gulf showing the three main channels through which large vessels transit to and from the Ports of Auckland (denoted by the black solid circle). The dotted line indicates the area inside which vessels will voluntarily reduce their speed to 10 kts.

2.4. Vessel transits and whale sightings

Automatic Identification System (AIS) data collected between July 2012 and June 2013 were used to analyze vessel traffic patterns for vessels >70 m in length transiting through the Gulf. This length was chosen because larger vessels pose a greater threat to whales (Laist et al., 2001), there are no fast vessels such as high-speed ferries regularly transiting through the Gulf and most AIS-equipped vessels in the Gulf were >70 m (Riekkola, 2013). Vessels transiting through the Gulf during the study period had a maximum draft of 14 m so this value was used to define the threat of vessel-strike to the whales. Position locations every minute were used to map the transit line of each vessel in ArcMap 10.1 (www.esri.com).

Global Positioning System (GPS) locations of whale sightings from 2000 to 2013 ($n = 1647$) were obtained primarily from whale-watch boats (93.7%), research vessels (5.9%) and aerial surveys (0.4%). Annual variation in whale distribution was assessed by comparing whale sightings for 2010–2011, 2011–2012 and 2012–2013. Seasonal plots were not analyzed as there is no seasonal variation in Bryde's whale distribution (O'Callaghan and Baker, 2002; Behrens, 2009).

2.5. Behavioral and acoustic data from DTAGs

To document behavior, a multi-sensor tag (DTAG) was attached with suction-cups to Bryde's whales in 2011 (Johnson and Tyack, 2003). To locate whales for tagging we conducted surveys from a 15 m research vessel, the *RV Hawere*. When a whale was sighted, a 5 m boat with a 60 hp 4-stroke engine was launched, approached the whale and as the whale surfaced the DTAG was deployed from a 6 m carbon-fiber pole. Once the tag was deployed the small boat returned to the *RV Hawere* where surfacing behaviors of the tagged whale were recorded from a distance of at least 300 m. After 2–5 h of observations, the *RV Hawere* returned to shore where the tag was monitored by VHF radio. Once the tag detached and was retrieved, the data were downloaded and the tag was re-charged for another deployment. The same tag was used for all deployments.

DTAGs contain a set of triaxial magnetometers and accelerometers, and depth and temperature sensors sampled at 50 Hz. The activity level of whales during day and night was assessed by calculating the root mean square (RMS) jerk (i.e., acceleration rate; Ydesen et al., 2014) from triaxial accelerometer data decimated to 25 Hz and buffered in 10 s periods to broadly match the whales' fluking rate. This provides an indication of swimming, foraging

(Aguilar Soto et al., 2008; Simon et al., 2012) and surfacing activity. Sensor data were analyzed using *Matlab* 7 (Mathworks).

The tag sampled sound at 96 kHz, with a −3 dB response to 47 kHz. Sensitivity at low frequencies is limited by a single-pole high-pass filter with a −3 dB frequency of 400 Hz although strong sounds can be detected down to ~25 Hz (−25 dB sensitivity compared to the passband). Based on previous studies of Bryde's vocalizations (e.g., Edds et al., 1993; McDonald, 2006; Oleson et al., 2003) audio data were decimated to 2 kHz. Vocalizations were detected by visual inspection of the frequency range 0–125 Hz in scrolling spectrograms (1024 FFT, Hann window, 50% overlap) using *Raven Pro* 1.4 (Cornell Lab of Ornithology). To investigate the possibility that Bryde's also produce medium frequency signals, a subset of the data (all data from two tags covering day and night; T3 and T4, Table 2) was decimated to 8 kHz and scrolling spectrograms (256 FFT Hann window, 50% overlap) were inspected in the band up to 4 kHz. Detected vocalizations were analyzed for RMS level and signal-to-noise ratio (SNR) using *Matlab* 7 to ensure correct interpretation of the acoustic source.

To evaluate whether low frequency noise, e.g., due to water flow over the tags, impeded the detection of down-sweeps, we estimated the proportion of time that the noise floor was low enough to permit visual detection of these calls in the spectrograms. We estimated the minimum SNR at which detection is possible by adding white noise to the Tag 6 down-sweeps until they were no longer visible. The calls were detectable at SNRs over a 20–60 Hz band of 2 dB. Allowing a conservative SNR of 6 dB we computed an RMS noise threshold for detectability. Taking the five long tag deployments in which the tag was placed in a similar location on the whale to Tag 6, the RMS level in the 20–60 Hz band was computed in consecutive 2 s intervals (with 50% overlap) to match the duration of calls (Fig. A1). The noise floor in these deployments would have allowed detection of down-sweeps at the RL of those in Tag 6 during 99% of the time for all tags, and would have allowed

Table 1
Records of the 17 whales categorized as: (1) confirmed and (2) probable/possible vessel strike mortalities (see Table A1) in the Hauraki Gulf, 1996–2014. The total overall length (from tip of rostrum to tail fluke notch) is reported where known. The whales' sex was determined either by direct observation (noted by N in the DNA column) or using molecular markers (noted by a Y in the DNA column and a 'Bed' (for *Balaenoptera edeni*) reference code). Note that some whales were given a name by local Māori and this is used for reference purposes. Samples are archived in the New Zealand Cetacean Tissue Archive (curated by R.C; Thompson et al. (2013)). The category for determining mortality follows Table A1 and brief details of the injuries are outlined. The source of information was from Ngatiwai (NW), Department of Conservation (DOC), University of Auckland (UA) and Massey University Veterinary Pathology Lab (MU). Data were checked by M. Moore (Woods Hole Oceanographic Institute) or S. Hunter (Massey University Veterinary Pathology Lab) for expert validation of category assignment for the mortality event.

	Date	Length (m)	Sex	DNA	Category	Details	Code (name)	Source
1	5 Nov 1996	15.4	F	Y	2	Whale flensed and injuries, factures and hematoma, consistent with blunt force trauma	Bed05 Kaurinui	NW
2	26 Jul 1997	–	–	N	2	Indications of broken jaw prior to landing, but unable to confirm	–	DOC
3	9 Sept 1997	14.6	F	Y	2	No external injuries. Whale flensed and injuries to back of skull consistent with blunt force trauma	Bed07	DOC
4	20 Apr 1998	–	–	N	2	Arrived on bow of large vessel	–	DOC
5	13 Aug 1999	13.3	F	Y	1	Bruising and vertebrae fractures top of spine and right hand side consistent with ante-mortem blunt force trauma	Bed11 Pukenihinihi	DOC
6	27 Oct 2000	13.8	M	N	1	Vertebrae behind the skull broken, for several meters, plus many of the ribs were crushed. Extensive bruising indicative of ante-mortem blunt force trauma. Spinal process on most of the vertebrae fractured close to the main vertebral bone	– Te Riri	DOC
7	7 Jan 2003	11.4	M	Y	2	Damage to base of skull and pectoral fins. Necrotized tissue around neck region consistent with bruising	Bed18	DOC
8	1 Jul 2003	11.8	M	Y	1	Animal found on the bow of a container vessel in port, massive cranial injuries posterior to blowhole	Bed19	DOC
9	6 Nov 2003	8.6	F	Y	2	Evidence of bruising to flesh around scapula region	Bed22	DOC
10	20 Jun 2005	7.0 (no fluke)	F	N	1	Tail fluke detached, large gash on one side consistent with sharp trauma of unknown origin	–	DOC
11	31 Dec 2006	10.4	F	Y	1	Surface examination and incisions in the region of hematoma defined the extent of bruising indicative of ante-mortem blunt trauma. Broken pectoral fin, large hematoma on ventral surface, clean lateral cut near caudal attachment point of the right fluke	Bed30	DOC/UA/MU
12	4 Feb 2007	11.5	M	Y	2	Both pectoral fins broken, some ventral surface damage. Large area of tissue damage in mid-right lateral region. Genital region damaged and partly scavenged	Bed28	DOC/UA
13	1 Oct 2007	11.3	M	N	2	Large, dorso-transverse sharp trauma injury approximately 90 cm posterior of dorsal fin. Three dislocated lumbar vertebrae, blubber red in color	–	NW/DOC
14	9 Sept 2011	12.1	M	Y	1	Severe blunt force trauma injuries. Fractures to 15 vertebrae and extensive disruption of the vertebral ligaments and tendons. Two left ribs fractured near origin of the costo-vertebral joint. Mid-region tear allowed evisceration of intestines. Extensive hemorrhage to the soft tissues and vertebral musculature indicating ante-mortem injury	Bed33	DOC/MU/UA
15	31 Jan 2012	15.0	F	Y	1	Extensive, recent muscular trauma and hemorrhage indicating ante-mortem blunt force trauma to the right lateral head and right body wall	Bed36 Mokai	DOC/MU/UA
16	11 Nov 2012	14.55	F	Y	1	Severe trauma to left thoracic region; bruising of musculature over rib-cage; hemorrhage and tearing of intercostal muscles as well as broken ribs. Indicative of blunt trauma while whale alive	Bed37	DOC/MU/UA
17	12 Sept 2014	15.3	M	Y	1	Extensive fractures to thoracic vertebrae and ribs particularly on the left side; hemorrhage in the left thoracic musculature extending along the left side of the body. Bruising and fractures consistent with blunt force trauma when the whale was alive	Bed38 Taranga	DOC/MU/UA

Table 2
Summary of Bryde's whale DTAG deployments. Whale ID is coded by the tagging order, plus the code of the Bryde's whale photo-identification catalogue for the Hauraki Gulf. A dive was defined as an immersion deeper than 2 m, with no threshold in duration. Dive data are provided as the mean (5–95 percentiles). All whales spent more than half of the time shallower than 14 m.

Date	Tag start	Tag end	Tag duration (hh:mm)	Whale ID	1st sighted	# dives	Dive duration (min.)	Depth dives (m)	% time 2–14 m
1 Aug	12:57	13:20	0:23	T1_No photo	–	28	0.8 (0.3–2.0)	7.8 (2.5–15.0)	99
9 Aug	14:22	14:34	0:12	T2_HG023	May 2003	6	1.6 (0.4–2.8)	11.4 (2.0–19.7)	82
9 Aug	14:51	11:05	20:14	T3_HG023	May 2003	336	2.5 (0.3–5.7)	7.6 (2.1–20.6)	96
22 Aug	11:18	23:58	12:40	T4_No nicks	–	454	1.1 (3.1–3.0)	7.1 (2.2–16.0)	98
26 Aug	10:54	6:13	19:19	T5_No nicks	–	1037	0.9 (0.2–3.6)	5.7 (2.1–15.0)	92
27 Sep	11:07	14:23	3:16	T6_HG045	Aug 2004	114	1.7 (3.1–6.5)	8.8 (2.3–20.4)	67
28 Sep	15:25	21:58	6:33	T7_HG087	Sep 2011	428	0.6 (0.3–1.1)	6.7 (2.2–11.7)	99

detection of down-sweeps at the RL of the down-sweep recorded in Tag 4 in 91–96% of the time for the five whales.

3. Results

3.1. Whale mortalities

Although DOC initiated a protocol to report cetacean mortalities in 1989, the first confirmed record of a dead Bryde's whale in the Gulf was in 1996. The reason for this is unknown but may be due to the lack of records kept in the early years after the protocol was established, as we know there were whales and large vessels in the Gulf prior to this time. From 1996 to 2014, 44 Bryde's whale carcasses have either stranded onshore or been recovered at sea (average = 2.3 whales/annum; range = 1–4; Table 1). The cause of mortality was examined for 20 carcasses. Vessel strike was the confirmed or probable cause of death for 17 (85%) whales and three died due to entanglement in mussel aquaculture spat line ($n = 2$) and unidentified fishing gear ($n = 1$). The whales' injuries were consistent with blunt force trauma, including broken and dislocated bones and hematoma in whales with no external injuries (Table 1). Only three of the 17 dead whales had evidence of sharp trauma, with external cuts caused by propellers.

There was no sex-bias among the 17 probable vessel strike whales (Table 1). Vessel-strike mortality was recorded for juvenile and adult whales but not for calves, even though calves are observed in the region year-round. It cannot be ruled out that the two unmeasured whales may have been calves (whales 2 and 4 in Table 1). The average length (tip of the rostrum to the fluke notch) was 12.8 m ($n = 14$, range = 8.6–15.4 m).

3.2. Stakeholder working group actions

The 2007 workshop resulted in DOC (agency responsible for marine mammals) and local Māori supporting the formation of a forensic necropsy team led by veterinary pathologists (Table 1, events 14–17). The 2009 workshop stimulated the research-led investigation of why Bryde's whales were vulnerable to vessel-strike (see Sections 3.3 and 3.4 below). The scientist's recommendation to the working group that vessels slow to 10 kts prompted an industry investigation into the economic cost of slowing down. The total cost, primarily through increased fuel consumption earlier in the voyage allowing time to transit the Gulf at 10 kts, was estimated at US$3.7 million–$5.9 million per annum; noting that this did not include any consequential losses such as omitting calls to the Ports of Auckland or itinerary changes for cruise lines (Denne and Hoskins, 2013).

To minimize potential economic ramifications of a slowdown, in collaboration with the working group, industry led the development of a series of options to mitigate the threat of whale and vessel collision resulting in the September 2013 voluntary Transit Protocol for Shipping (http://www.poal.co.nz/news_media/publications/POAL_HG_Protocol.pdf). We analyzed the feasibility of re-routing shipping in this study (see Section 3.3 below) and a preliminary study found infrequent reporting of sightings with few responses by vessels to reported sightings (Riekkola and Constantine, 2014). Interviews with bridge-crew were not conducted for this study but would be useful to ascertain how they were interpreting the voluntary transit protocol measures and whether uncertainty over requirements resulted in low response levels.

3.3. AIS equipped vessel tracks and whale distribution

A total of 767 unique vessels >70 m in length transited the Gulf one or more times between July 2012 and June 2013. Over 2.4 million AIS data points generated a line density grid illustrating common paths (Fig. 2A). Cargo ships formed the majority of vessels (75%); passenger ships (5%) had the largest average length (234.4 m) and tankers (17%) had the largest average draft (9.1 m). The average draft of all vessels >70 m was 8.5 m (range = 3.3–14 m, $n = 767$).

The distribution of whales between July 2000 and June 2013 ($n = 1647$ sightings) was broad, with some yearly variation (Fig. 2B–D), but centered near the middle of the Gulf, probably a result of the majority (93.7%) of the data coming from a whale-watch vessel with a limited distribution (Fig. 2B). Including those conducted in this study, wider surveys have found whales throughout the Gulf not covered by the whale-watch vessel (Baker and Madon, 2007; Behrens, 2009).

3.4. Behavioral data from DTAGs

Between 1 August and 28 September 2011, seven DTAGs were deployed on six individual whales (total recording time = 62.5 h; range = 0.2–20.3 h per deployment; Table 2). Three of the tagged whales had distinctive marks and two of these had been seen prior to this study (in 2003 and 2004), and are considered part of the resident population. Given the relatively short deployments, most whales remained within a few kilometers of where they were tagged with 30 km (23 h time-lag) being the maximum distance. The five whales tagged for more than one hour spent most of their time at shallow depths. Defining the collision threat depth layer as either 8.5 m or 14 m (respectively, the mean and maximum draft of large vessels in the Gulf), whales spent an average of 73% and 91% of their time shallower than these depths (Fig. 3 and Table 2). Tag data confirmed that Bryde's whales do not log at the surface but rather perform continuous short, shallow dives both day and night (Fig. 4). To minimize the inclusion of respiration events in the analysis we defined a dive as deeper than 2 m. Dives were on average 1 min long (5–95% range = 0.2–4.5 min) and 7 m deep (5–95% range = 2–16 m) (Table 2).

Four tag deployments covered day ($n = 22$ h of recordings) and night ($n = 35$ h of recordings) showing circadian differences in activity patterns, with deeper diving during the day. Dives were

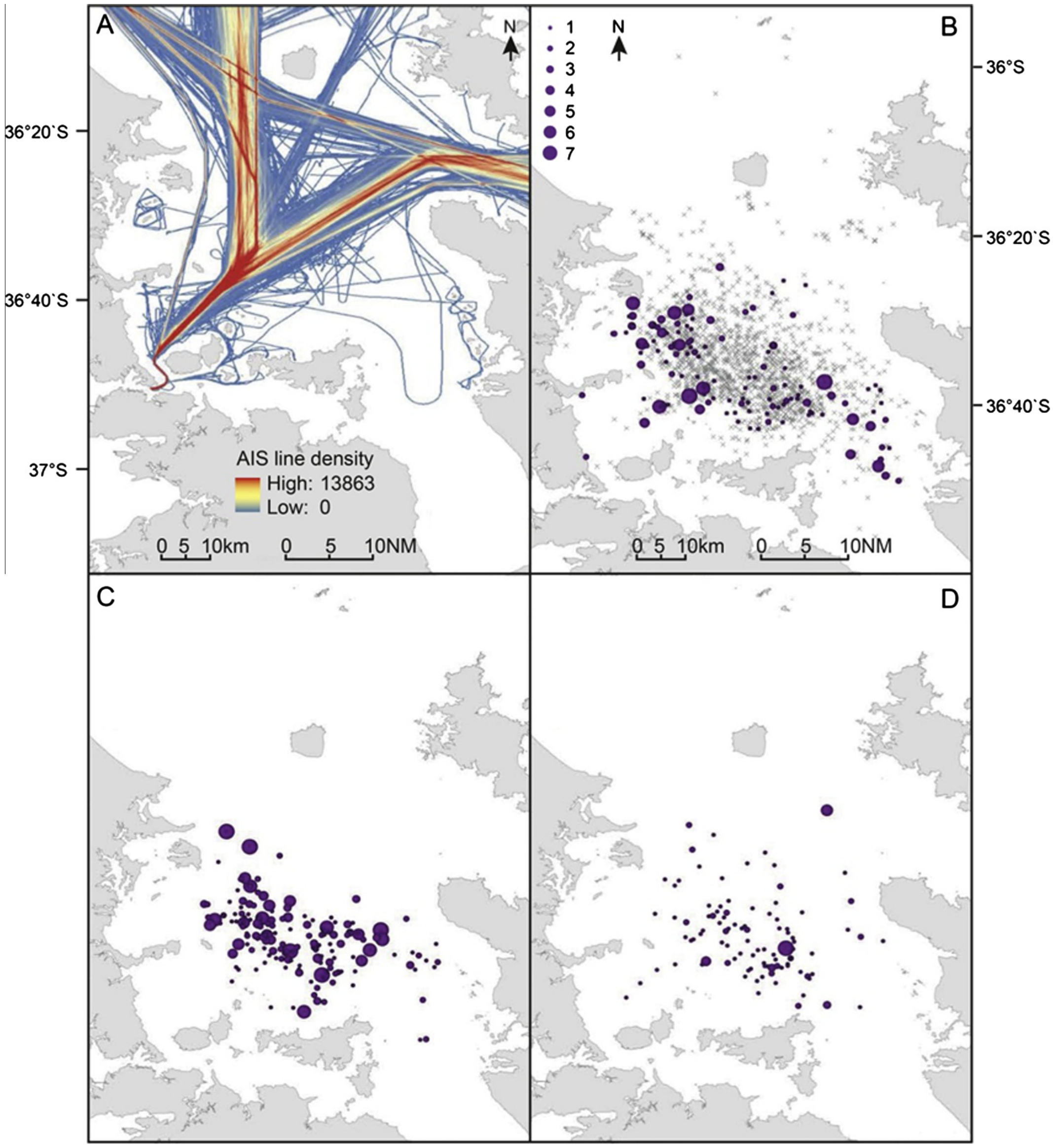

Fig. 2. (A) Line density of vessel transits (>70 m in length) throughout the Hauraki Gulf from July 2012–June 2013. The distribution of all Bryde's whale group sightings from 2000 to 2013 ($n = 1647$ groups) are shown in light gray (B) with yearly sightings shown for comparison over the years (B) July 2012–June 2013 ($n = 123$ groups); (C) July 2011–June 2012 ($n = 156$ groups) and (D) July 2010–June 2011 ($n = 96$ groups). Note that the circle sizes reflect overlapping locations of independent whale sightings.

shorter in duration during the day than at night (average = 0.9 min and 1.4 min respectively; *t*-test, $p < 0.05$). Pooling all data, the mean dive depth was 7.3 m (SD = 5.5 m) during the day and 5.5 m (SD = 6.4 m) at night ($t = 6.85$, $p = <0.0001$). Surface foraging events were frequently observed and the tag data showed depth transitions and jerk peaks consistent with lunges both at the surface and at depth (Simon et al., 2012). There were significant circadian differences overall activity levels for all whales as measured by the RMS jerk (*t*-test, $p < 0.00$ all tags) with more activity during the day.

3.5. Vocalization rates

Two vocalization types were recognizable in the DTAG recordings. These comprised a brief tone ($n = 1$) at ~50 Hz, similar to Heimlich et al. (2005), and down-sweep calls ($n = 7$) similar to previous Bryde's recordings in NZ (McDonald, 2006), and elsewhere (Oleson et al., 2003; Heimlich et al., 2005) (Fig. A1). Two tag recordings had down-sweep calls with six calls occurring in the same tag deployment (Tag 6) and one in Tag 4. The RMS received levels (RLs) of the Tag 6 down-sweeps were within 1 dB of each other indicating that they were most likely produced by the tagged whale. The Tag 4 down-sweep had a received level 10 dB lower, possibly due to the different location of the tag on the whale or an indication of the call being produced by another whale.

4. Discussion

This study has compiled evidence of serious threat to Bryde's whales from vessel strike in the Gulf. A high rate of mortality attributed to collisions combined with a small population size, and a strong overlap in distribution of whales and vessels in three-dimensions make this an urgent problem (see Laist et al., 2001; Panigada et al., 2006; Douglas et al., 2008 for mortality rates in other areas). A significant part of the NZ Bryde's whale population shows long-term fidelity to the Gulf (O'Callaghan and Baker, 2002; Behrens, 2009) and this is reinforced by our study: two of the three individually identifiable tagged whales were first observed here over seven years prior to our research. Since 1996, a

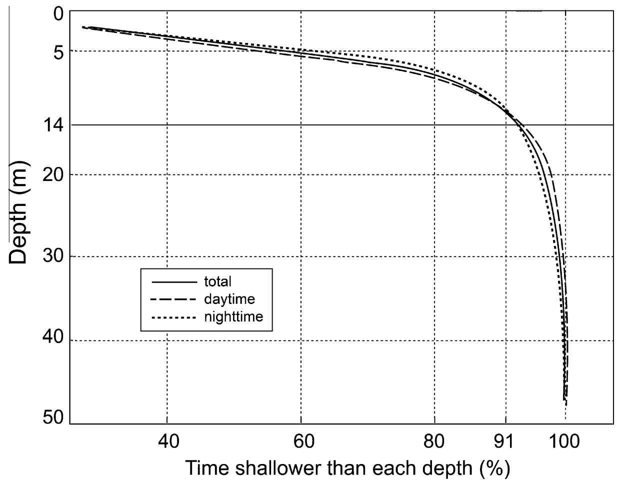

Fig. 3. Proportion of time spent by all whales shallower than the depth on the *y*-axis during day (dashed line), night (dotted line) and in total (solid line). Whales spent > 90% of their time in the potential collision zone (shallower than 14 m) indicated by the solid horizontal line.

minimum average estimate of 2.3 whales per year have been killed by vessel-strikes in the Gulf. The population level effects of this mortality are currently unknown due to a lack of population trend data (Baker et al., 2010), but in the face of uncertainty about the local population and individual threat profiles, we may not be able to detect these effects before it is too late for the population to recover.

The objective of the current study was to gather information about whale distribution and behavior to inform a conservation management process as early as possible. After an initial investigation into the cause of mortalities (Behrens, 2009), a forum was initiated in 2012 to search for rapid, but economically acceptable solutions to this problem. The forum involves government, scientists, international and domestic shipping companies, NGOs and local Māori. The data presented here have enabled the forum to assess mitigation options that resulted in a voluntary protocol being adopted and endorsed by the shipping industry within two years of deliberations. Such a relatively fast response is critical to minimize further loss of whales while more comprehensive measures are being developed. In the following, we demonstrate how the integrated set of whale sightings, behavioral data and vessel tracks gathered in this study help evaluate the efficacy of different measures to reduce vessel-strike mortality of Bryde's whales in the Gulf.

4.1. Shipping exclusion areas

Spatial mitigation, i.e., directing shipping away from areas of high whale density, has been effective in some local areas especially if adopted or endorsed by the IMO (Silber et al., 2012; Vanderlaan and Taggart, 2009; Wiley et al., 2013) but overall it has not translated into a significant population level change in vessel-strike mortalities despite considerable mitigation effort in the intensely studied east coast regions of USA and Canada (van der Hoop et al., 2013). Compliance is generally high when the economic implications of rerouting are negligible, there is a dedicated outreach program and enforcement (e.g., Silber and Bettridge, 2012; Wiley et al., 2013).

Our results indicate that re-routing traffic to avoid Bryde's whale aggregations whilst maintaining safe navigation is unlikely to be effective in the Gulf. Tagged whales remained in the Gulf but ranged widely, in some cases over a few hours. Bryde's whales have a broad diet of zooplankton aggregations dispersed by winds and currents, and schooling fishes (Jarman et al., 2006; Carroll et al., submitted for publication). The ephemeral nature of their prey, shifts in prey choice and the relatively uniform environment mean that the majority of the Gulf holds potential prey. The broad, unpredictable distribution of whales throughout the Gulf means there are no navigable pathways for vessels that do not overlap with areas used by whales (Fig. 2). Thus neither static spatial separation nor dynamic management of shipping lanes currently appears to be effective for protecting these whales.

4.2. Acoustic methods to locate or exclude whales

Passive acoustic monitoring (PAM) devices have been used to detect whale calls and alert vessels (Van Parijs et al., 2009). Down-sweeps are the most characteristic Bryde's call, are the only

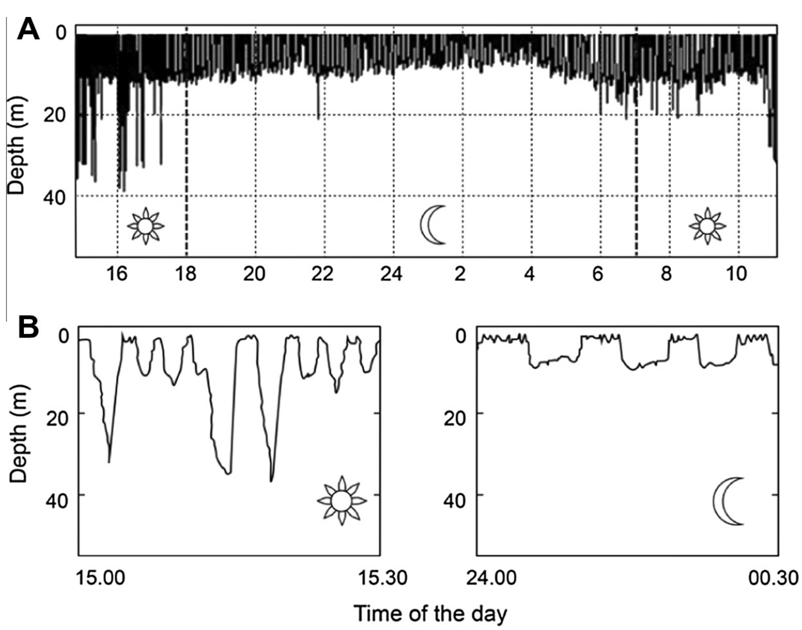

Fig. 4. (A) Example dive profile of a Bryde's whale in the Hauraki Gulf (Table 2: T3_HG023) with sunset and sunrise times indicated by vertical dashed lines. (B) Enlarged sections during two time periods (15:00–15:30 and midnight 24:00–00:30) are representative of the variation in dive patterns during day and night.

call-type identified in NZ to date (McDonald, 2006) and therefore the only one suited for monitoring the whales' in the Gulf. But these signals were scarce with only seven down-sweeps identifiable in 58 h of recordings with sufficiently low noise level; a finding consistent with previous research in the Gulf region (McDonald, 2006). Given the scarcity of vocalizations in the Gulf and the potential for masking of these low frequency signals by shipping noise, PAM is unlikely to be effective as a real-time detection method to alert vessels. Moreover, given the large distances that can potentially be covered by whales between vocalizations, the alert radius would likely be too large to be useful.

Acoustic alarms have been proposed to move whales from the path of vessels. The efficacy of these has not been tested with Bryde's whales, but research on right whales showed that alarms may increase the potential for collision (Nowacek et al., 2004). In the longer term, whales may habituate to alarm sounds if they are exposed often as may happen in the Gulf, given the small area and the high rate of vessel traffic. Bow-mounted active sonars have been proposed as a mitigation measure however the detection distance of these sonars is relatively small and the number of false alarms increases rapidly with speed. All ships entering the port would need to install the sonar and have trained crew which may be appropriate for vessels such as ferries regularly transiting the Gulf but is unlikely to be economical for vessels visiting less frequently. An alternative approach would be to install a network of whale detection sonars on the sea-floor. However, several hundred devices would be required to cover shipping lanes making this an expensive option.

4.3. Real-time visual detection of whales

Bryde's whales are challenging to detect visually due to their brief surfacings and solitary habits. Moreover, the large container ships forming the majority of traffic in the Gulf typically have a blind area in front of the vessel and limited ability to respond rapidly. Nonetheless, as a result of the forum the shipping industry agreed to post a dedicated watch onboard and report whale sightings that allowed other vessels to avoid the area. This may be effective during daylight for the brief periods at the surface. However, our research shows at night the whales come closer to the surface and become less active making them most vulnerable to collision with a vessel precisely when visual detection is least likely.

4.4. Speed regulations in the Gulf

Vessel speed increases the probability of strikes and of their lethality, particularly above 10 kts (Vanderlaan and Taggart, 2007; Silber et al., 2010; Wiley et al., 2011). At lower speeds, the risk of death via direct strike or hydrodynamic forces that pull the whale toward the ship are considerably reduced (Silber et al., 2010). Given that our data provides robust reasons for eliminating other mitigation options, we suggest that the most effective immediate measure is to slow vessel traffic. The economic consequences of this are increased passage time and a possible change in fuel consumption by travelling at a sub-optimal speed (Silber and Bettridge, 2012). In the Gulf, slowing from the average current speed of 13.2–10 kts would add an average of 40 min to a vessel transit of about 190 min.

Since the initiation of the forum in 2012, all potential mitigation measures have been discussed. The shipping industry surveyed their members about what mitigation options would be acceptable and conducted an assessment of the cost of implementation. They have adopted a voluntary protocol that includes voyage planning to slow vessels to 10 kts despite concerns about potential economic impacts. However, these costs should be revisited now the AIS data are available. Similar economic concerns related to a reduction in speed in other regions have proven unfounded (Silber and Bettridge, 2012); slowing to 10 kts may cost less than initially predicted. As the desired whale conservation resulting from the voluntary measures is predicated on their success, it is important that there is ongoing evaluation of the uptake of, and adherence to the voluntary measures currently in place. Other studies have found voluntary measures were not effective in sufficiently reducing the speed of vessels around whales (Wiley et al., 2008; Lagueux et al., 2011; Silber et al., 2012). Outreach initiatives such as the report cards (Wiley et al., 2013) and research directed at measuring the success of mitigation measures are important to ensure conservation success.

The industry is currently investigating narrowing the shipping routes to the port. As we have shown, this may not afford the whales' greater protection as they are not aggregated in a predictable area. A year-round mandatory speed restriction has never been adopted at the IMO; therefore the proposed optimal mitigation method to reduce the threat to Bryde's whales is currently untested and may take several years to implement. A seasonal slow-down in the Panama Canal provides a test-case for the Gulf (Guzman et al., 2012). Any solution adopted requires follow-up to test its efficacy (van der Hoop et al., 2013) and members of the forum have agreed this is crucial.

The behavior and ecology of Bryde's whale makes this species a tough target for mitigation: it is challenging for visual or acoustic detection and ranges widely throughout the Gulf to exploit a variety of ephemeral prey. Here we have shown that early coordination of science with a social forum representing all stakeholders can spark rapid engagement when a conservation issue has high priority. This engagement has already resulted in early, albeit voluntary mitigation measures that despite the high-level international concern by the IMO and IWC, is not typical in the field of shipping and whale strike. Ongoing discussion and evaluation is critical to continue to develop effective measures to protect the Bryde's whales.

Acknowledgements

This research was funded by the Auckland Council, University of Auckland, DOC, Marie Curie Post-Doctoral Fellowship (N.A.S.), Fulbright (R.C.) and support from the Marine Alliance for Science and Technology Scotland (M.J.). Many thanks to Brady Doak, Peter Browne, Arthur Cozens, Angela Little, Peter Crabb, Emily Douglas, Tim Higham, Phil Brown, Karl McLeod, Thelma Wilson, Rob Chappell, William Goodfellow, Andy Light, Jo Logan, Celia Witehera, Te Tui Shortland, Anton van Helden, Van Veñegas, Yvette Wharton, John Atkins and Vivian Ward. Thanks to the tāngata whenua of the Gulf and Kordia Ltd for their support; to Michael Moore, Stuart Hunter and Craig Pritchard for valuable necropsy work; David Wiley, Brad Cabe and Mike Thompson for vessel-strike discussions; and to all members of the working group who continue to work hard to find solutions; it is truly a team effort. Finally, thanks to three reviewers who made helpful comments on this manuscript. This research was conducted under a DOC permit PER/02/2009/01 and University of Auckland Animal Ethics permits AEC 03/2008/R636 and 910 (R.C.).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2015.03.008.

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