SC/67A/HIM/07 Rev1

Bycatch and PBRs for Maui and Hectors dolphin

Elisabeth Slooten, Stephen Dawson

INTERNATIONAL WHALING COMMISSION

Bycatch and PBRs for Maui and Hector's dolphin

Elisabeth Slooten and Stephen Michael Dawson, Departments of Zoology and Marine Science, University of Otago, Dunedin, New Zealand.

SUMMARY

The reported bycatch of NZ dolphin substantially understates the actual level of bycatch, due to very low levels of self reporting by fishermen and low observer coverage. Current total bycatch is estimated at 32 – 40 Hector's dolphins per year off the east coast of the South Island, 42 – 55 Hector's dolphins per year off the west coast of the South Island and 2.4 – 3.8 Maui dolphins per year off the west coast of the North Island. All of these estimates substantially exceed PBR. The CVs on the catch rates and total catch estimates indicate a high level of uncertainty. Observer coverage of 81 – 91% would be required to achieve estimates of dolphin bycatch with a CV of 30% or better, from observer programmes or video monitoring. The New Zealand government is proposing to introduce video camera monitoring for all inshore gillnet and trawling vessels. This would substantially increase the amount of information on dolphin bycatch. Video monitoring would be feasible off the east and west coasts of the South Island where dolphin densities are relatively high. For low density populations, robust estimates of bycatch are unlikely to be obtainable without substantially exceeding PBR. Likewise, determining the effectiveness of current protection measures by monitoring population size is unlikely to be successful due to the low statistical power of being able to detect population trends for Maui dolphins. For small populations such as vaquita, Maui dolphin and the smallest populations of Hector's dolphins, precautionary protection measures are likely to be the only effective way to ensure bycatch is sustainable and avoid further population declines.

INTRODUCTION

During the period 2000-2006 bycatch was estimated at 110 – 150 New Zealand dolphins (Hector's and Maui dolphins) per year (Davies et al. 2008). Current bycatch is expected to be lower, due to substantial improvements in dolphin protection implemented in 2008. On the other hand, new information on dolphin distribution (MacKenzie and Clement 2014, 2016) indicates that the overlap between dolphins and fisheries is much higher than previously thought (Davies et al. 2008).

This paper provides updated estimates of nationwide bycatch under the current level of protection and compares these with Potential Biological Removals (PBR). Issues relating to low observer coverage are identified and explored. We endorse the New Zealand (NZ) government's plans to implement comprehensive video camera monitoring, provided an appropropriate proportion of the footage is reviewed, and provide some advice on sampling design and the need for human observers as well as cameras.

MATERIALS AND METHODS

Data on dolphin deaths observed by government observers on fishing vessels are available on a website created by Dragonfly Consulting for the NZ Ministry for Primary Industries (Abraham et al. 2017). Here we use these official data to estimate the total number of dolphins caught. We estimated the number of gillnet fishing effort in units of days (average length of gillnet used per day = 1195 m) in order to explore sampling issues affecting the accuracy and precision of the bycatch estimates. Unlike metres of net, fishing days can be considered independent sampling units.

Additional data on the catch rate of Hector's dolphins in gillnets come from video monitoring in 2003-2004 (McElderry et al. 2007) and 2012-2013 (MPI 2013). We estimate a dolphin catch rate for trawling based on observer data, using a simple bootstrapping approach. Observer coverage in this fishery has been very low. We also used bootstrapping to estimate dolphin catch rates in the gillnet fishery, taking 1,000 bootstrap samples from years in which data are available from observers or video monitoring, following the approach used by Baird and Bradford (2000).

For Maui dolphins off the North Island west coast we incorporated recent estimates of population trends in our assessment of the likely level of ongoing bycatch, using both frequentist and Bayesian approaches. We followed Wade et al.'s (2012) approach of fitting a linear regression to the natural log of the abundance estimates. To investigate evidence for a difference between the two most recent estimates, we calculated a 95% confidence interval of the difference. We also carried out a Bayesian linear regression of the last three estimates, in OpenBugs (Lunn et al. 2009) using the package R2OpenBugs (Sturtz et al. 2005) in program R (R Core Team 2015). The model was adapted from the simple regression model presented in Kéry (2010) and used the natural log of each abundance estimate. Vague prior distributions were used for all parameters. Four independent Markov chains were initiated at random steps and run for 10,000 iterations each. The first 5,000 iterations of each of these chains were discarded as "burn-in" samples. Convergence of the four chains was assessed with the R-hat statistic (Gelman et al. 2003) and through visual inspection of convergence plots. The posterior distribution of the slope was used to estimate the probability of population increase or decrease.

There are no robust estimates of bycatch in recreational gillnet fisheries, although catches are known to occur (Dawson 1991; DOC 2017). Gillnets can be legally used by amateur fishers for most of the year in South Island harbours and year-round in the harbours in Maui dolphin habitat.

We provide updated PBR estimates for Hector's and Maui dolphins. The PBR method (Wade 1998) aims to ensure that human-caused mortality is below levels that could lead to population depletion. It is based on a logistic model with maximum net productivity level (MNPL) at 0.5K. MNPL is the population size that results in the maximum number of individuals being added to the population per year. At MNPL one would expect the population growth rate to be approximately 0.5 R_{max} (Slooten and Dawson 2008). As the goal is to ensure populations stay at or above MNPL (i.e. above 0.5 K), the population growth rate used in the PBR calculation is 0.5 R_{max}. For marine mammals MNPL is thought to be between 0.5 K and 0.85 K (Taylor and de Master 1993). The method explicitly takes into account uncertainty and potential biases in the available information. PBRs were calculated using using the following equation:

$$PBR = N_{min} \times 0.5\ R_{max} \times F_r$$

Where N_{min} = 20th percentile of the population size estimate, R_{max} = Maximum annual population growth rate and F_r = Recovery factor.

In the design of the PBR method, a range of mortality limits were evaluated based on whether at least 95% of the simulated populations met two criteria: (1) populations starting at MNPL stayed at or above MNPL after 20 years, and (2) populations starting at 0.3 of K recovered to at least MNPL after 100 yr (Wade 1998). Simulations indicated that using the 20th percentile of the population size estimate met those criteria (Wade 1998). N_{min} estimates for Hector's dolphin populations from the most recent population surveys (MacKenzie and Clement 2016, Baker et al. 2016) were used to calculate PBR. When data on productivity are available it is recommended that they be used (Wade 1998). R_{max} has been estimated for NZ dolphin at 0.018 (Slooten and Lad 1991). PBRs based on the default value for cetaceans in general (0.04) are also included for comparison.

Simulations that included plausible levels of bias in the available information indicated that F_r needs to be ≤ 0.5 to meet performance criteria (1) and (2) above (Wade 1998). Taylor and Wade (2000) showed that using N (rather than N_{min}) and F_r 1.0 resulted in many of the simulated populations being depleted below 0.5 K. They also carried out robustness trials, exploring plausible flaws in the data or assumptions, including biases in abundance and mortality estimates (Taylor and Wade 2000). For endangered species an F_r of 0.1 is recommended (Wade and Angliss 1996; Wade 1998). For example N_{min} for North Atlantic right whale is 476 individuals, F_r is 0.1 because it is Endangered and the PBR is calculated at 1 individual per year (NMFS 2015). With a PBR this low "any mortality or serious injury for this stock can be considered significant" and the management goal is to reduce fisheries mortality to as close to zero as practicable (Fisheries and Oceans Canada 2014, NMFS 2004, 2015).

RESULTS

NZ dolphins are protected from bycatch in fishing nets in 19% of their habitat. Both gillnets and trawling have been banned in approximately 5% of the habitat of Maui dolphin and 8% of the habitat of Hector's dolphin (Forney et al. 2017). Gillnets are banned in an additional 14% of Maui dolphin habitat and 11% of Hector's dolphin habitat.

A total of 140 NZ dolphin entanglements were reported in New Zealand's progress reports to the IWC for the period 1985-2016 (Table 1). On average, 4.5 NZ dolphin entanglements were reported per year, with higher numbers during periods when interviews with fishers (1985-1988) or observer programmes (e.g. 1998) were conducted. In years when separate statistics were provided, the reported Maui dolphin entanglements were 2, 3, 2 and 1 in 2000, 2001, 2002 and 2012 respectively. Three trawl entanglements of Hector's dolphin were reported in 2006 and one more in 2016. Entanglements reported to the IWC include those reported by government fisheries observers or fishers, and some of the entanglements from video monitoring, the stranding record or caught by recreational fishers. For example, the two dolphins reported for 2015 were both thought to be caught in recreational gillnets. This dataset does not include all known entanglements.

Data on dolphin deaths reported by government observers on gillnetting vessels are available on the website of Dragonfly Consulting (Abraham et al. 2017). We used these official data on fishing effort, observed effort and observed dolphin bycatch (Table 2, Figure 1) to estimate a total number of dolphins caught off the east and west coast of the South Island. The number of fishing days was estimated using the average length of net used per day (1195 m).

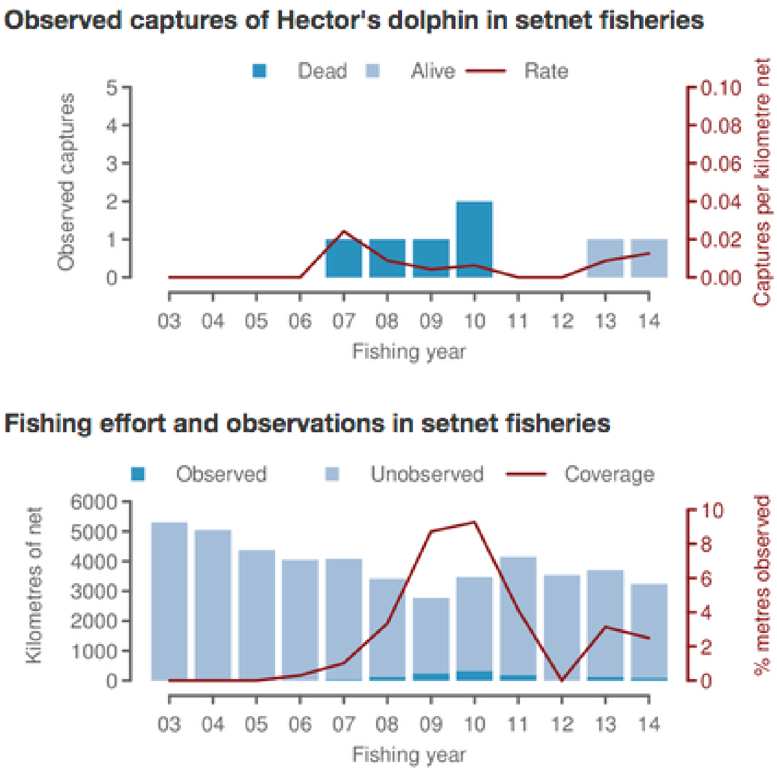


Figure 1. Summary of observer coverage and observed Hector's dolphin bycatch off the east coast of the South Island from 2003-2014 (downloaded from Dragonfly Consulting; Abraham et al. 2017).

Off the east coast of the South Island, the level of observer coverage increased from less than 1% in the 2005-2006 fishing year to 3% in 2007-2008 and to 9% in the first two years after the dolphin protection measures were extended in 2008 (Table 2). Observer coverage then declined to 4, 0, 3 and 2% respectively from 2010 to 2014. The CVs on catch rates and estimated total catch indicate a high level of uncertainty (Table 2). We estimate that observer coverage of 81 – 91% would be required to achieve estimates of dolphin bycatch with a CV of 30% or better.

Observed bycatch off the east coast of the South Island was 0, 1 or 2 dolphins per year (Table 2). Data from the first two years after the current protection measures were introduced, suggested a reduced catch rate (0.005 – 0.007) and reduced number of dolphins caught (11 – 22 individuals per year). However, in the last two years the observer programme reported catch rates (0.010 – 0.015) and estimates of the total number of dolphins caught (32 – 40) were similar to those from the 2007-2008 fishing season, just before the current protection measures were introduced.

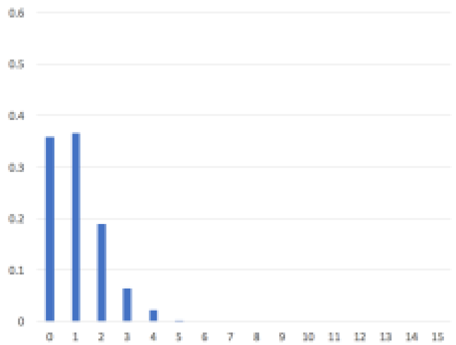
Year	Reported bycatch nationwide	Estimated total bycatch				
		Banks Peninsula	East Coast South Island	West Coast South Island	North Island	Nationwide
1985	3	62[1]				
1986	0	95[1]				
1987	15	44[1]				
1988	22	29[1]				
1989	6					
1990	1					
1991	0					
1992	2					
1993	3					
1994	8					
1995	0					
1996	0					
1997	2					
1998	14	16 (CV 0.39) [2]				
1999	5					
2000	10		35-46[3]	73-96[3]		110-150[3]
2001	13		35-46[3]	73-96[3]		110-150[3]
2002	8		35-46[3]	73-96[3]		110-150[3]
2003	0		35-46[3]	73-96[3]		110-150[3]
2004	2		35-46[3]	73-96[3]		110-150[3]
2005	11		35-46[3]	73-96[3]		110-150[3]
2006	4		35-46[3]	73-96[3]		110-150[3]
2007	1		99 (CV 0.99)	55-73		
2008	0		30 (CV 0.98)	55-73		
2009	2		11 (CV 0.96)	42-55		
2010	1		22 (CV 0.68)	42-55		
2011	0			42-55		
2012	3			42-55	4.97 (0.28-8.04) [5]	
2013	1		32 (CV 0.98)	42-55		
2014	0		40 (CV 0.99)	42-55	3.72 (3.28-4.16) [6]	
2015	2				2.4-3.8	
2016	1				2.4-3.8	
Total	**140**					

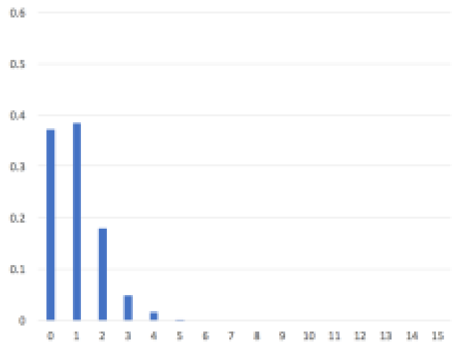
Table 1: Number of reported Hector's and Maui dolphin entanglements in fishing gear in New Zealand's national progress reports to the IWC Scientific Committee. In most cases, the year in column one is the calendar year. Data sources for estimates not calculated in this paper: [1]Dawson (1991); [2]Baird and Bradford (2000); [3]Davies et al. (2008); [4]Slooten and Davies (2011); [5]Currey et al. (2012); [6]Slooten (2014).

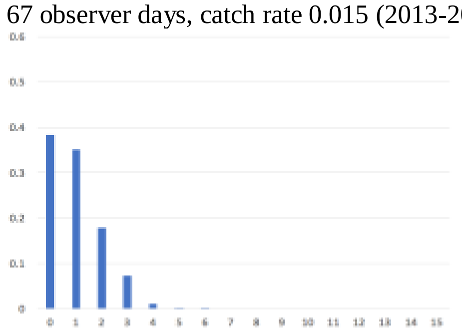
A serious problem is that low levels of observer coverage do not simply increase uncertainty in catch rate, but can also cause a negative bias in the catch rate estimate. Two dolphins were observed caught in 2009-2010, the year with the highest observer coverage (269 days). In years with observer coverage of 200 or fewer days, 0 or 1 dolphin captures were observed. As expected, for very low levels of observer coverage the most likely outcome was failing to observe dolphin bycatch. For example in the 10 observer days during the 2005-2006 fishing season, the probability of observing zero bycatch was 0.75 for a catch rate of 0.029 (the 2006-2007 catch rate) and 0.92 with a catch rate of 0.011 (the 2007-2008 catch rate). Bootstrap sampling indicates that observer coverage < 200 days results in a high probability of failing to observe bycatch (Figure 2).

Fishing year	Gillnet effort (m)	Observed (m)	Gillnet days	Observed days	Observer coverage	Observed catch	Catch rate (CV)	Total Catch (CV)
2002-2003	5,313,000	-	4,446	0	0			
2003-2004	5,042,635	-	4,220	0	0			
2004-2005	4,376,412	-	3,662	0	0			
2005-2006	4,040,566	11,950	3,381	10	<0.01	0	-	-
2006-2007	4,078,945	41,340	3,413	35	0.01	1	0.029 (1.00)	99 (0.99)
2007-2008	3,409,007	113,930	2,853	95	0.03	1	0.011 (1.00)	30 (0.98)
2008-2009	2,776,151	241,965	2,323	202	0.09	1	0.005 (1.00)	11 (0.96)
2009-2010	3,471,280	321,680	2,905	269	0.09	2	0.007 (0.71)	22 (0.68)
2010-2011	4,147,910	171,300	3,471	143	0.04	0	0	-
2011-2012	3,541,465	0	2,964	0	0	-	-	-
2012-2013	3,696,465	115,800	3,093	97	0.03	1	0.010 (1.00)	32 (0.98)
2013-2014	3,231,531	79,910	2,704	67	0.02	1	0.015 (1.00)	40 (0.99)

Table 2. Summary of gillnet fishing effort, observer coverage and observed NZ dolphin bycatch off the east coast of the South Island from 2003-2014.


67 observer days, catch rate 0.015 (2013-2014)


97 observer days, catch rate 0.010 (2012-2013)


202 observer days, catch rate 0.005 (2008-2009 fishing year)

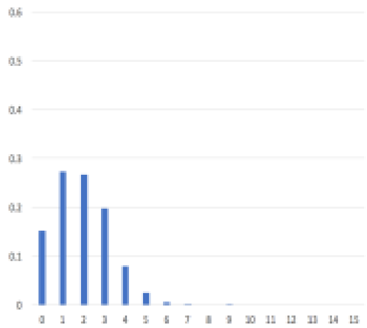

269 observer days, catch rate 0.007 (2009-2010)

Figure 2. Estimates of observed bycatch off the east coast of the South Island since 2008, with associated observer coverage and catch rate.

To explore the effect of the number of observer days in more detail, we used the average observed catch rate of 0.008 (8 dolphins per 1000 days fishing) during the period 2009-2014 (Table 2) and tested different levels of observer coverage. The catch rate was kept constant at 0.008 and we took 1,000 bootstrap samples for observer coverage levels expected to result in 1, 2, 4 and 8 observed dolphin captures respectively.

At relatively high levels of observer coverage, the results form an approximately normal distribution, centred on the expected value (e.g. 8 dolphins observed caught for 1000 days fishing observed; Figure 3). Because the results are bounded at 0 (it is not possible to observe fewer than 0 dolphin deaths) the distribution becomes progressively more skewed at low levels of observer coverage, with zero dolphins observed becoming an increasingly likely outcome for low levels of observer coverage. When the expected number of catches observed is close to one, the probability of detecting one dolphin catch and failing to detect bycatch are roughly equal (graph for 125 observer days in Figure 3).

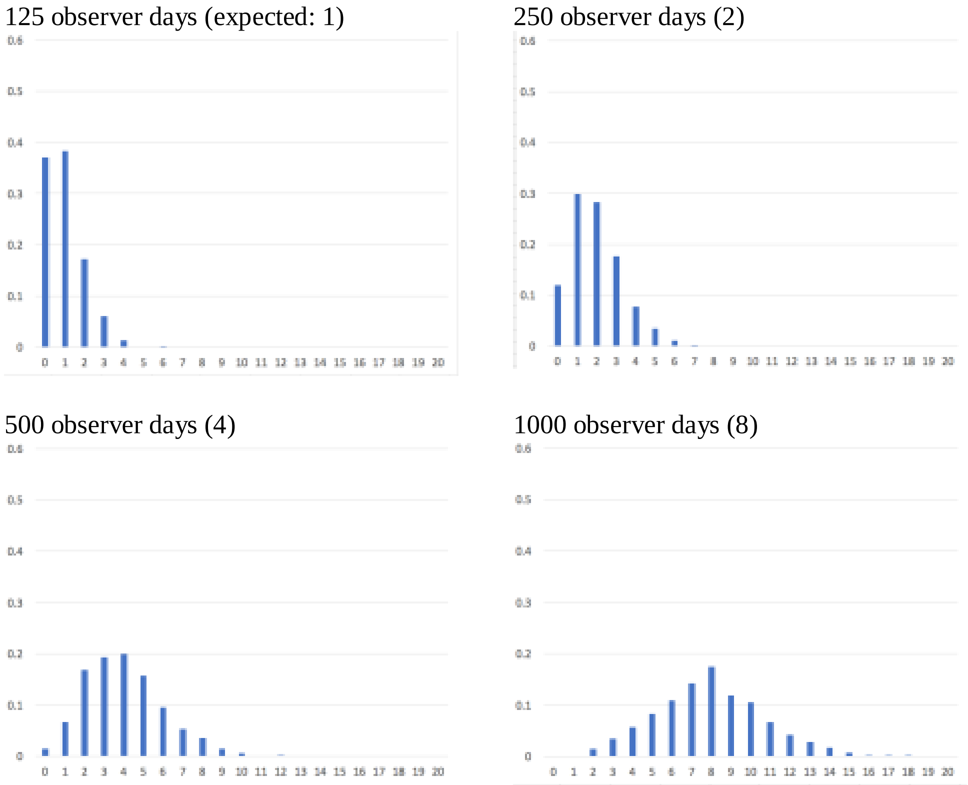


Figure 3. Bootstrap results (n=1000) for a catch rate of 0.008 and observer coverage expected to result in 1, 2, 4 and 8 observed dolphin captures, respectively.

Catch rate estimates are also available from video monitoring off the South Island's east coast (McElderry et al. 2007; MPI 2013), the same area as the observer data in Table 2. Two Hector's dolphin captures were observed in video footage from 89 gillnet hauls in the 2003-2004 fishing season, a catch rate of 0.02 per haul (McElderry et al. 2007). There was no observer programme during 2002-2003, however observer programmes in the 2006-2007 and 2007-2008 fishing seasons resulted in similar catch rates of 0.01–0.03 dolphins per day of observer coverage. Estimated total bycatch from video monitoring in 2002-2003 (93, CV 0.69) was very similar to the observer estimate from 2006-2007 (99, CV 0.99).

Two Hector's dolphin captures were observed in video footage from 39 gillnet hauls in 2012-2013 (MPI 2013). This catch rate of 0.05 (CV 0.71) was much higher than the catch rates of 0.010 and 0.015 from the observer programme in 2012-2013 and 2013-2014 (Table 2). If the sample of viewed video footage was representative, an estimated 159 (CV 0.70) Hector's dolphins were caught during the 2012-2013 fishing year off the east coast of the South Island. All of the video footage from one fishing vessel, which reported a dolphin capture, was viewed. For the remaining 5 fishing vessels participating in the video monitoring programme, 3 hauls were viewed (on average 7% of the hauls). Viewing all of the video footage would provide a robust catch rate from video monitoring during 2012-2013. At least 81% of the video footage would need to be viewed to achieve a CV of 0.30 or better. This would also help ensure that the video sample viewed was representative of the fishery as a whole.

Off the west coast of the South Island, estimated bycatch was 73 – 96 Hector's dolphins per year during 2000-2006 (Davies et al. 2008). Since 2008, reported gillnet fishing effort in this area has reduced from 1.5 – 2 million metres of gillnet per year to around 1 million (Abraham et al. 2017). This is likely to be partly due to the extension to the protection measures in 2008. However, new reporting criteria may have contributed. In recent years fishing effort is only reported if there were three or more vessels and three or more companies or persons fishing within an area (Abraham et al. 2017). Figure 4 gives an indication of the level of under-reporting of fishing effort off the west coast of the South Island. If we take the apparent reduction in fishing effort at face value, the estimated number of Hector's dolphins caught per year off the west coast of the South Island is estimated to have dropped from 73 – 96 individuals per year to 42 – 55 individuals per year since 2008 (Table 1).

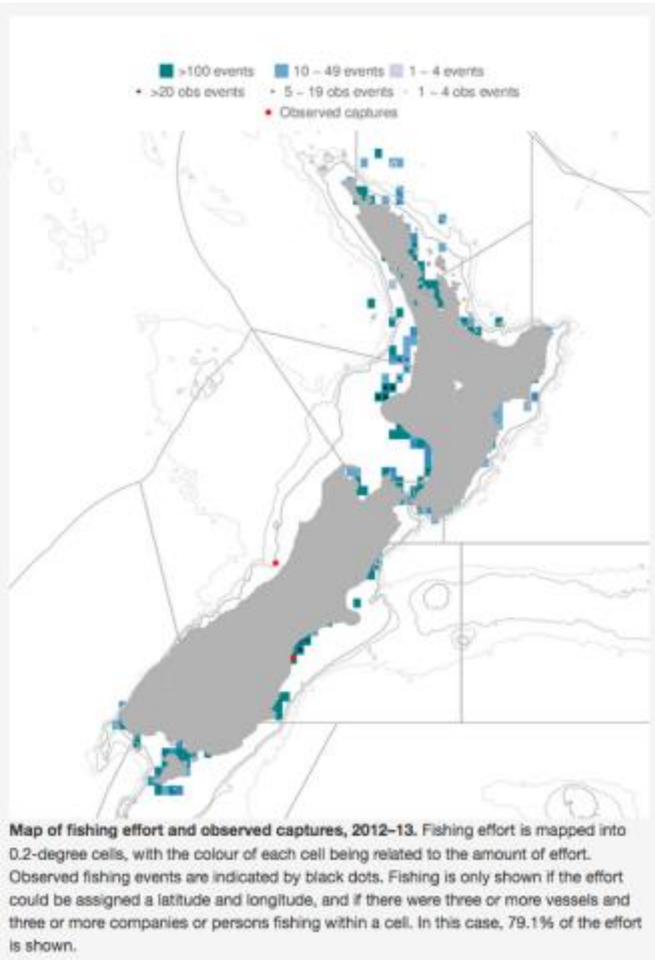


Figure 4. Map of fishing effort and observed captures in 2012 – 2013, demonstrating the problem with fishing effort reporting. Fishing effort is only shown if the effort could be assigned a latitude and longitude, and if there were three or more vessels and three or more companies or persons fishing within a cell. In this case, 79.1% of the effort is shown (downloaded from Dragonfly Consulting; Abraham et al. 2017). The Hector's dolphin capture on the east coast was in an area where fishing effort was reported, however the dusky dolphin caught on the west coast appears in an area where no fishing effort was reported.

Davies et al. (2008) estimated bycatch off the south coast of the South Island at 1.5 – 1.9 Hector's dolphins per year. Insufficient information is available from observer programmes to allow estimation of the current level of bycatch in this area. There are no estimates of bycatch for the north coast of the South Island. As for the south coast of the South Island, this is an area where low observer coverage and/or very low population density make it difficult to estimate the level of bycatch. For example, sighting rates on aerial surveys off the east coast of the South Island range from 0.01 sighting per km of transect line in low density areas to 0.31 in high density areas. By comparison, sighting rates off the North Island and the north and south coasts of the South Island range from 0 to 0.004 per km of transect line (MacKenzie and Clement 2014, 2016; Slooten et al. 2006).

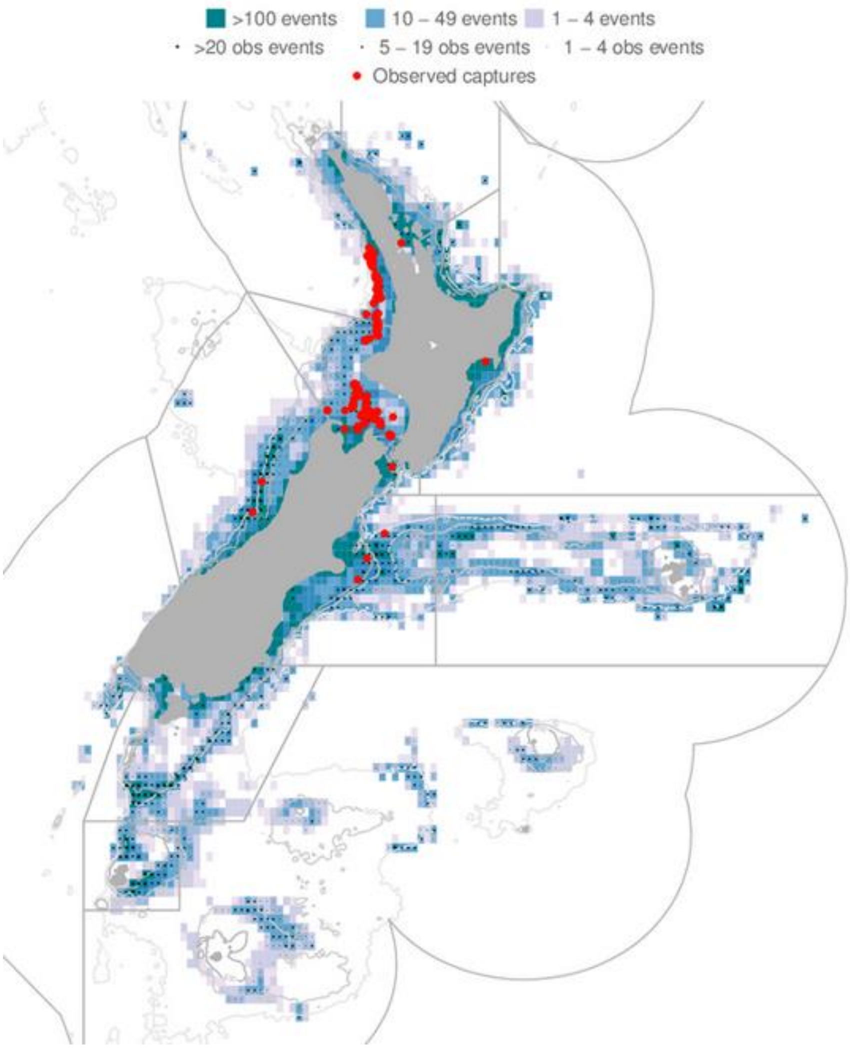


Figure 5. Fishing effort and observed captures of whales and dolphins in trawl fisheries from 2000-2014 (downloaded from Dragonfly Consulting; Abraham et al. 2017).

Observer coverage in Maui dolphin habitat off the west coast of the North Island is 14.6% for trawling vessels (IWC 2016). Observer coverage for gillnetting vessels in Maui dolphin habitat is estimated at 12.7 % for vessels > 6 m (IWC 2016). Small vessels (<6m) commonly used by commercial gillnetters in the large harbours on the North Island west coast have no observer coverage. Observer coverage drops to 2% when all gillnet vessels are included (MPI 2016). An expert panel estimated fisheries mortality of 4.97 Maui dolphins per year (Currey et al. 2012). After two small extensions of the protected area for Maui dolphins this was estimated to have dropped to 3.25 – 4.16 per year (Slooten 2014). The most recent estimate of population decline for Maui dolphin is 2% per year (Baker et al. 2016; Slooten and

Dawson 2016). This rate of decline combined with a maximum rate of increase of 1.8% (Slooten and Lad 1991) would be consistent with a human-caused mortality of about 2.4 dolphins per year.

Estimating the number of NZ dolphins caught in trawling is challenging. The catch rate in trawling has been estimated at 0.002 NZ dolphins per tow (Baird and Bradford 2000). Trawling is legal in >90% of the habitat of NZ dolphins. A simple bootstrapping exercise resulted in an estimate of 46 (CV 1.0) trawl catches per year for the South Island east coast. The North Island west coast and South Island north coast are hotspots for cetacean bycatch in trawling (Figure 5). NZ dolphin numbers are relatively low in these areas, possibly as a result of intensive inshore trawling and gillnetting activity in this area. The low densities of NZ dolphins make bycatch in the trawl fishery very difficult to detect.

PBR estimates

Updated estimates of PBR for regional populations of NZ dolphins are shown in Table 3. We applied the standard approach of using N_{min} estimates over areas small enough to ensure that there is only one population and one fishery in each region (Taylor 2005). Given that Hector's dolphin is listed as Endangered and Maui dolphin as Critically Endangered by both national (Department of Conservation) and international agencies (IUCN), we used a recovery factor of 0.1.

	0-20 nautical miles		**4-20 nautical miles**	
	PBR 4%	**PBR 1.8%**	**PBR 4%**	**PBR 1.8%**
West Coast North Island	0.12	0.05		
North Coast South Island	0.18	0.08	0.18	0.08
West Coast South Island:				
Hector	2.84	1.28		
Greymouth	2.04	0.92	0.07	0.03
Okarito Lagoon	3.24	1.46	0.75	0.34
Jackson Bay	0.19	0.09		
Milford Sound	0.05	0.02		
East Coast South Island:				
Cloudy-Clifford	1.60	0.72	0.77	0.35
Kaikoura	0.51	0.23		
Clarence	0.19	0.09		
Pegasus	1.65	0.74	0.81	0.37
Bank Peninsula north	4.14	1.86	2.34	1.05
Bank Peninsula south	4.47	2.01	1.40	0.63
Timaru	2.50	1.13	1.34	0.60
South Coast South Island	0.35	0.16		

Table 3. Potential Biological Removal (PBR) for regional populations of Maui (west coast North Island) and Hector's dolphins (all other populations), estimated following the methods of Wade (1998). We used two offshore ranges: Shoreline to 20 nautical miles offshore (full offshore range for which population estimates are available) and 4-20 nautical miles (proportion of the population outside protected areas) and two levels of Rmax, the default value of 4% for cetaceans and the 1.8% Rmax estimate for Hector's and Maui dolphins.

Table 3 provides PBR estimates for the default Rmax of 4% for cetaceans as well as the Rmax of 1.8% estimated for NZ dolphins. We have provided estimates for the total population in regional areas as well as the population outside protected areas, though this clearly undermines the intent of the protected areas.

Because dolphins inside protected areas cannot be caught, including them in PBR calculations results in unsustainable catch rates for dolphins outside protected areas.

Most PBRs are less than one individual per year, with a minimum of 0.03 – 0.07 for the offshore Greymouth region on the South Island west coast and a maximum of 2.01 – 4.47 dolphins per year for the full distribution off southern Banks Peninsula on the South Island east coast. The estimated 32 – 40 NZ dolphins caught per year in gillnet fisheries off the east coast of the South Island (Table 2) compares with a PBR of 3 – 15 individuals for that area. PBRs for the whole South Island range from 4 to 24, depending on the value used for R_{max}, and which offshore range is used. Current estimates of Hector's and Maui dolphin bycatch far exceed PBRs. No bycatch estimates are available for the north and south coasts of the South Island. The PBRs for these two areas are well below one individual per year. For these areas monitoring bycatch in real time, in order to ensure bycatch does not exceed PBR, is not practicable using observer programmes and/or video monitoring.

DISCUSSION

Estimates of current gillnet bycatch off the east coast of the South Island are on the order of 30 – 40 Hector's dolphins per year, based on observer data. Data from video camera monitoring could improve this estimate if made available for analysis. Off the west coast of the South Island an estimated 42 – 55 Hector's dolphins are caught each year in gillnets. We estimate current bycatch of Maui dolphins at 2.4 – 3.8 individuals per year. All of these estimates exceed PBR.

The relatively high level of continuing bycatch off South Island east coast is consistent with independent data on Hector's dolphin survival rates from Banks Peninsula (Gormley et al. 2012). Research using photographic capture-recapture analysis shows a 5.4% improvement in survival rates in this area – one of the South Island east coast hotspots for Hector's dolphins. Partial protection of this population has reduced a 6% per year population decline to a decline of around 1% (Gormley et al. 2012). The probability of population recovery was recently estimated at 41%, compared to 7% previously (Gormley et al. 2012). For the remaining populations, the most recent population estimates (MacKenzie and Clement 2016) are lower than estimates from before 2004 (Slooten et al. 2004; Dawson et al. 2004; Slooten and Dawson 2016) and the rate of decline is consistent with the continued level of bycatch.

We estimated trawl bycatch at 46 (CV 0.99) Hector's dolphins per year off the east coast of the South Island. Other areas with high levels of inshore trawling effort have relatively low dolphin densities and no estimates are available for these areas. Likewise, no estimates are available for the number of Hector's or Maui dolphins caught in recreational gillnet fisheries.

Low and sporadic observer coverage in New Zealand's inshore fisheries results in a high level of uncertainty of the level of fisheries mortality in gillnet and in particular trawl fisheries (Baird and Bradford 2000; Dawson and Slooten 2005; Rowe 2009; Abraham et al. 2010; Thompson et al. 2013). The first observer programme (Baird and Bradford 2000) achieved the highest level of observer coverage (22.6%). Baird and Bradford (2000) recommended increasing observer coverage to 56 – 83% in order to obtain robust estimates of bycatch (CV of 30% or better) for the Banks Peninsula. We estimate that observer coverage of 81 – 91% would be required to achieve a CV of 30% for observer programmes or video monitoring off the east coast of the South Island.

Dolphin densities are relatively high off the east (and west) coast of the South Island. Given the high level of observer coverage required in these high density areas, it may not be possible to obtain statistically robust bycatch estimates for areas with much lower dolphin densities. The east coast of the South Island has 3000 or so gillnet fishing days per year. An observer coverage of 81 – 91% would result in a bycatch estimate with a CV of 30% or better. Off the North Island, and north and south coasts of the South Island, Hector's and Maui dolphin population density is an order of magnitude lower.

Accurate real-time monitoring of bycatch is unlikely to be feasible for areas with low dolphin density. However, the risk of gillnet and trawl fisheries to these small populations is high. In areas with very low dolphin density, managing bycatch may be the only way to ensure these populations are not extirpated (e.g. transition away from fishing methods known to cause dolphin mortality). For example, the PBR for Maui dolphins is 0.05 – 0.12 per year. It would be extremely difficult to determine, using observer programmes or video monitoring, whether this level of bycatch is exceeded. In very small populations (such as Maui dolphin and vaquita) it becomes very difficult to accurately estimate bycatch and population size (Slooten and Dawson 2016), let alone establish a causal link between protection measures and either increasing population size or decreasing bycatch.

The current level of observer coverage means that even in areas with relatively high dolphin density observers are most likely to detect 1 dolphin capture per year or fail to detect any captures. This is a major challenge for obtaining robust estimates of either the catch rate or the total bycatch. Other problems associated with low observer coverage include the potential for bias (e.g. fishermen avoiding area with high dolphin densities on days they carry an observer) and increased pressure on observers and fishers to fail to report catches.

An obvious solution to the challenges of designing observer programmes or video monitoring is to set quantitative targets, based on estimates of precision and bias. The New Zealand government is proposing to introduce video camera monitoring for all inshore gillnet and trawling vessels. If the footage is viewed, this would substantially increase the amount of information on dolphin bycatch. Video monitoring would be feasible off the east and west coast of the South Island where viewing 81 – 91% of the footage would provide robust estimates of bycatch. The effectiveness of video monitoring also depends on the "view" and image quality of the system, the system's reliability, the skill and diligence of the people employed to view the resulting video records. Appropriate follow-through by the authorities is also required, and has so far been lacking (e.g. MPI 2013).

Even if on-board video systems meet all expectations and are employed on all fishing vessels, there will be a need for on board observers to estimate drop-out (e.g. Tregenza et al. 1997; Hamer et al. 2011; Uhlmann and Broadhurst 2015). In the 2012-2013 video camera monitoring, one fisherman let out his gillnet as soon as he saw a dead dolphin in the net. On one occasion the dolphin was retained in the net, and reported. Another dolphin caught in the same net dropped out after the net was let out and left static for almost an hour. This capture was not reported.

Other problems identified in recent video camera trials in New Zealand include camera failure and fishermen turning the cameras off or failing to turn them on (McElderry 2007; MPI 2013). In a current trial of video observation in New Zealand's snapper fishery, 80% of the cameras failed. Most of these problems can be solved. Camera systems can be set up to activate automatically when the net is hauled and designed so they cannot be manually switched off. Cameras with a wide field of view may help ensure drop-out can be documented but will offer less detail in any one part of the image, which may compromise species identification or condition assessment. By far the largest problem is the time taken to review footage, and the question of who carries out that task. Viewing only a small fraction of the footage increases the risk that the catch rates are not representative of the full monitoring programme.

Even with 100% video or observer coverage, bycatch estimation will remain problematic for very small populations (e.g. North Island, north and south coasts of the South Island). Dolphin densities are very low in these areas and there is a very high risk of exceeding the PBR without being able to obtain a robust estimate of bycatch.

The advantages of video monitoring include the ability to monitor for long periods, day and night. Installing and running the video equipment on board vessels is much cheaper than placing human observers on board. Challenges for video monitoring include drop out of marine mammals outside the view of the camera(s), technical problems and cameras being turned off or not turned on. The cost of viewing video footage is considerable and this can lead to only a small proportion of the footage being viewed.

The solutions are relatively simple. If cameras are placed on sufficient numbers of vessels and a sufficient proportion of the video footage is reviewed to ensure monitoring coverage of 81 – 91% robust estimation of bycatch should be possible. Human observers would be needed to estimate drop out and ground truth the information in the video footage. If insufficient funding is available to do this throughout the range of Hector's and Maui dolphins then the best strategy would be to implement high observer and camera coverage in some areas, until robust estimates of bycatch have been obtained, and then sample another area.

A 68% probability of continued population decline for Maui dolphins is not encouraging and continued population monitoring has very low statistical power to detect population recovery or continued declines (Slooten and Dawson 2016). In addition, the population is unlikely to follow a steady rate of increase or decline. Populations that experience changes in survival and reproductive rates tend to follow non-linear patterns of growth or decline (Slooten and Lad 1991). In other words, a short-term population increase may in fact be part of a long term population decline, and vice versa.

Acknowledgements
We would like to thank Lindsay Wickman for help with the Bayesian linear regression.

REFERENCES

Abraham ER, Thompson FN, Berkenbusch K, Knox C, Mansfield R, Neubauer P, Richard Y. 2017. Protected species bycatch in New Zealand fisheries. Data on fishing effort, observed bycatch and for fisheries with sufficient observer coverage also estimates of total bycatch: www.dragonfly.co.nz

Abraham ER, Thompson FN, Oliver MD. 2010. Summary of the capture of seabirds, marine mammals and turtles in New Zealand commercial fisheries, 1998-99 to 2007-08. Aquatic Environment and Biodiversity Report 45.

Baird S, Bradford E 2000. Estimation of Hector's dolphin bycatch from inshore fisheries, 1997-98 fishing year. Report for Department of Conservation, Wellington, New Zealand.

Baker CS, Steel D, Hamner RM, Hickman G, Boren L, Arlidge W, Constantine R. 2016. Estimating the abundance and effective population size of Maui dolphins using microsatellite genotypes from 2015-2016, with retrospective matching from 2001 to 2016. Report to Department of Conservation, Wellington, New Zealand www.doc.govt.nz/pagefiles/49075/maui-dolphin-abundance-2016.pdf

Currey RJC, Boren LJ, Sharp BR, Peterson D 2012. A risk assessment of threats to Maui's dolphins. Ministry for Primary Industries and Department of Conservation, www.doc.govt.nz-getting-involved-consultations-current-threat-management-plan-review-for-mauis-dolphin-

Davies NM, Bian R, Starr P, Lallemand P, Gilbert D, McKenzie J 2008. Risk analysis for Hector's dolphin and Maui's dolphin subpopulations to commercial set net fishing using a temporal-spatial age-structured model. Wellington, Ministry of Fisheries. www.fish.govt.nz-NR -rdonlyres-B034115D-247A-42E5-B08FF5D267046C59-0- HectorNIWA-riskanalysis.pdf

Dawson SM 1991. Incidental catch of Hector's dolphin in inshore gillnets. Mar Mamm Sci 7(3): 283-295.

Dawson S, Pichler F, Slooten E, Russell K, Baker CS. 2001. The North Island Hector's dolphin is vulnerable to extinction. Marine Mammal Science 17 (2): 366-371.

Dawson, S.M. and Slooten, E. 1988. Hector's Dolphin *Cephalorhynchus hectori* : Distribution and abundance. Reports of the International Whaling Commission, Special Issue 9: 315-324.

Dawson SM, Slooten E. 2005. Management of gillnet bycatch of cetaceans in New Zealand. Journal of Cetacean Research and Management 7: 59-64.

Dawson SM, Slooten E, DuFresne S, Wade P, Clement D 2004. Small-boat surveys for coastal dolphins: Line-transect surveys for Hector's dolphins *(Cephalorhynchus hectori)*. Fish Bull 201: 441-451

DOC 2017. Department of Conservation Hector's and Maui dolphin incident database. www.doc.govt.nz-our-work-hectors-and-maui-dolphin-incident-database-

DOC and MFish. 2007. Department of Conservation and Ministry of Fisheries. Hector's and Maui's dolphin Threat Management Plan. Available at www.fish.govt.nz -NR-rdonlyres-088EFD8C-E207-4798-9315-COAF2FC6FFB2-0-DRAFTTMP FINAL.pdf

Dragonfly Consulting 2016. Capture of Hector's dolphin in setnet fisheries, in the East Coast South Island area. Downloaded on 30 September 2016 from https:--data.dragonfly.co.nz-psc-v20150002-hectors-dolphin-setnet-all-vessels-east-coast-south-island-all-

Ferreira, S.M.; Roberts, C.C. 2003. Distribution and abundance of Maui's dolphins *(Cephalorhynchus hectori maui)* along the North Island West Coast, New Zealand. DOC Internal Series 93, Department of Conservation, Wellington.

Fisheries and Oceans Canada. 2014. Recovery Strategy for the North Atlantic Right Whale (*Eubalaena glacialis*) in Atlantic Canadian Waters. *Species at Risk Act* Recovery Strategy Series. Fisheries and Oceans Canada, Ottawa. vii + 68 pp. https:--www.registrelep-sararegistry.gc.ca-default.asp?lang=En&n=717856D0-1

Forney, K.A., Southall, B.L., Slooten, E., Dawson, S., Read, A.J., Baird R.W. and Brownell, R.L. 2017. Nowhere to go: Noise impact assessments for marine mammal populations with high site fidelity. Endangered Species Research, DOI: 10.3354/esr00820

Gelman, A., J. B. Carlin, H. S. Stern and D. B. Rubin. 2003. Bayesian data analysis. 2nd edition. Chapman &Hall-CRC, Boca Raton, FL.

Gormley, A.M., Slooten, E., Dawson, S.M., Barker, R.J., Rayment, W., du Fresne, S. and Bräger, S. 2012. First evidence that marine protected areas can work for marine mammals. J. Appl. Ecol. 49:474-480.

Hamer DJ, Ward TM, Shaughnessy PD, Clark SR. 2011. Assessing the effectiveness of the Great Australian Bight Marine Park in protecting the endangered Australian sea lion Neophoca cinerea from bycatch mortality in shark gillnets. Endangered Species Research 14: 203-216.

Heron, M. 2016. Independent review of MPI/Mfish prosecution decisions: Operations Achilles, Hippocamp and Overdue. https://mpi.govt.nz/protection-and-response/environment-and-natural-resources/sustainable-fisheries/independent-review-of-prosecution-decisions/

IWC 2016. Report of the Scientific Committee of the International Whaling Commission. IWC-66-Rep01, reporting on the meeting of the Scientific Committee in Bled, Slovenia 7-19 June 2016.

IWC 2017. Information downloaded from International Whaling Commission webpage during May 2016: https:--iwc.int-home Scientific Committee Progress Reports from 2002 onwards: https:--iwc.int-scprogress Older reports available from: https:--archive.iwc.int-pages-search.php?search=!collection73&k=

Kéry, Marc. 2010. Chapter 8 - Normal Linear Regression. In *Introduction to WinBUGS for Ecologists* (pp 103-113). Academic Press, Boston.

Lunn D, Spiegelhalter D, Thomas A, Best N. 2009. The BUGS project: Evolution, critique and future directions (with discussion). Statistics in Medicine 28: 3049-3082.

MacKenzie DL, Clement DM 2014. Abundance and distribution of South Island east coast Hector's dophin. New Zealand Aquatic Environment and Biodiversity Report 123, Report to Ministry for Primary Industries, Wellington, New Zealand. March 2014. www.mpi.govt.nz-document-vault-4350

MacKenzie DL, Clement DM 2016. Abundance and distribution of South Island west coast Hector's dophin. New Zealand Aquatic Environment and Biodiversity Report 168, Report to Ministry for Primary Industries, Wellington, New Zealand. March 2014. www.mpi.govt.nz-document-vault-12129

McElderry H, McCullough D, Schrader, J, Illingworth J. 2007. Pilot study to test the effectiveness of electronic monitoring in Canterbury fisheries. Department of Conservation Research and Development Series No. 264, ISBN 0-478-14150-5, www.doc.govt.nz-upload-documents-science-and-technical-drds264.pdf

MPI 2013. Operation Achilles Preliminary Investigation Report. Ministry for Primary Industries Report by Fisheries Compliance Investigator DCM Sanders, 26 July 2013. Available from Ministry for Primary Industries, Wellington, New Zealand. https://mpi.govt.nz/document-vault/14032 https://www.youtube.com/channel/UCV2HIKfznb1DcxUYaDysXNw

MPI 2016b. Information provided by the Ministry for Primary Industries, Wellington, New Zealand in response to an Official Information request.

NMFS 2004. Recovery plan for the North Atlantic right whale. Prepared by the Office of Protected Resources, National Marine Fisheries Service (NMFS). http:--www.nmfs.noaa.gov-pr-pdfs-recovery-whale_right_northatlantic.pdf

NMFS 2015. Stock Assessment for North Atlantic right whale. Prepared by National Marine Fisheries Service (NMFS). www.nmfs.noaa.gov-pr-sars-pdf-stocks-atlantic-2015-f2015_rightwhale.pdf

Perrin WF, Reilly SB. 1984. Reproductive parameters of dolphins and small whales of the family Delphinidae. Reports of the Scientific Committee of the International Whaling Commission, Special Issue 6: 97-133

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http:--www.R-project.org-.

Reilly SB, Barlow J. 1986. Rates of increase in dolphin population size. Fishery Bulletin 84: 527-533.

Rowe SJ. 2009. Conservation Services Programme observer report, 1 July 2004 to 30 June 2007. Department of Conservation, Marine Conservation Services Series 1.

Slooten E 2014. Effectiveness of extensions to protected area for Maui's dolphin in 2012 and 2013. Paper SC-65b-SM08 presented at the 2014 Scientific Committee meeting in Bled, Slovenia.

Slooten E, Dawson SM. 2008. Sustainable levels of human impact for Hector's dolphin. The Open Conservation Biology Journal 2: 37-43.

Slooten E, Dawson SM. 2010. Assessing the effectiveness of conservation management decisions: Likely effects of new protection measures for Hector's dolphin. Aquatic Conservation: Marine and Freshwater Ecosystems 20: 334–347.

Slooten E, Dawson SM. 2016. Updated population viability analysis, population trends and PBRs for Hector's and Maui dolphin. Report to NOAA, USA https://www.regulations.gov/document?D=NOAA-NMFS-2016-0118-0076

Slooten E, Dawson SM, Rayment WJ 2004. Aerial surveys for coastal dolphins: Abundance of Hector's dolphins off the west coast, South Island of New Zealand. Mar Mamm Sci 20: 117-130

Slooten E, Davies N 2011. Hector's dolphin risk assessments: Old and new analyses show consistent results. Journal of the Royal Society of New Zealand 42: 49-60.

Slooten E, Lad F 1991. Population biology and conservation of Hector's dolphin. Can J Zool 69: 1701-1707.

Slooten E, Dawson SM, Rayment WJ, Childerhouse SJ 2006. A new abundance estimate for Maui's dolphin: What does it mean for managing this critically endangered species? Biol Conserv 128: 576-581

Sturtz, S., Ligges, U., and Gelman, A. 2005. R2WinBUGS: A Package for Running WinBUGS from R. Journal of Statistical Software, 12(3), 1-16.

Taylor BL, DeMaster DP. 1993. Implications of non-linear density dependence. Mar Mamm Sci 9: 360-371.

Taylor BL. 2005. Identifying units to conserve. In: Reynolds JE III, Perrin WF, Reeves RR, Montgomery S, Ragen, TJ, Eds. Marine mammal research: Conservation beyond crisis. Baltimore MD, John Hopkins Univ Press, 2005; 149–164.

Taylor, BL, Wade, PR. 2000. "Best" abundance estimates and best management: Why they are not the same. In: Ferson S, Burgman M, Eds. Quantitative Methods for Conservation Biology. NY, Springer. 2000; 96-108.

Thompson FN, Berkenbush K and Abraham ER 2013. Marine mammal bycatch in New Zealand trawl fisheries 1995-96 to 2010-11. New Zealand Aquatic Environment and Biodiversity Report No. 105, Available from Ministry for Primary Industries.

Tregenza NJC, Berrow SD, Hammond PS, Leaper R. 1997. Harbour porpoise *(Phocoena phocoena* L.) by-catch in set gillnets in the Celtic Sea. ICES Journal of Marine Science 54: 896-904.

Uhlmann SS, Broadhurst MK. 2015. Mitigating unaccounted fishing mortality from gillnets and traps. Fish and Fisheries 16: 183-229.

Wade PR. Calculating thresholds to the human-caused mortality of cetaceans and pinnipeds. Mar Mamm Sci 1998; 14: 1-37

Wade PR, Angliss RP. Guidelines for assessing marine mammal stocks: Report of GAMMS Workshop, 1996, Seattle, Washington. NOAA Technical Memorandum 1997; NMFS-OPR-12.

Wade PR, Hamner RM, Constantine R, Baker CS. 2012. The Potential Biological Removal (PBR) and probability of decline for Maui's dolphin. Appendix 1 of Currey RJC, Boren LJ, Sharp BR, Peterson D 2012. A risk assessment of threats to Maui's dolphins. Ministry for Primary Industries and Department of Conservation, www.doc.govt.nz-getting-involved-consultations-current-threat-management-plan-review-for-mauis-dolphin-