AQUATIC CONSERVATION: MARINE AND FRESHWATER ECOSYSTEMS

Aquatic Conserv: Mar. Freshw. Ecosyst. (2009)

Published online in Wiley InterScience
(www.interscience.wiley.com). DOI: 10.1002/aqc.1084

Assessing the effectiveness of conservation management decisions: likely effects of new protection measures for Hector's dolphin (Cephalorhynchus hectori)

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ABSTRACT

1. Fisheries bycatch affects many species of marine mammals, seabirds, turtles and other marine animals.
2. New Zealand's endemic Hector's dolphins overlap with gillnet and trawl fisheries throughout their geographic range. The species is listed as Endangered by the IUCN. In addition, the North Island subspecies has been listed as Critically Endangered.
3. Estimates of catch rates in commercial gillnets from an observer programme (there are no quantitative estimates of bycatch by amateur gillnetters or in trawl fisheries) were used in a simple population viability analysis to predict the impact of this fishery under three scenarios: Option (A) status-quo management, (B) new regulations announced by the Minister of Fisheries in 2008 and (C) total protection.
4. Uncertainty in estimates of population size and growth rate, number of dolphins caught and other model inputs are explicitly included in the analysis. Sensitivity analyses are carried out to examine the effect of variation in catch rate and the extent to which fishing effort is removed from protected areas but displaced to unprotected areas.
5. These methods are applicable to many other situations in which animals are removed from populations, whether deliberately (e.g. fishing) or not (e.g. bycatch).
6. The current Hector's dolphin population is clearly depleted, at an estimated 27% of the 1970 population. Population projections to 2050 under Options A and B predict that the total population is likely to continue declining. In the case of Option B this is driven mainly by continuing bycatch due to the much weaker protection measures on the South Island west coast.
7. Without fishing mortality (Option C) all populations are projected to increase, with the total population approximately doubling by 2050 and reaching half of its 1970 population size in just under 40 years.

Received 20 December 2008; Revised 2 September 2009; Accepted 8 September 2009

KEY WORDS: fisheries; bycatch; protection measures; effectiveness; marine mammal

INTRODUCTION

Fisheries bycatch affects many species of marine mammals, seabirds, turtles and other marine animals (Dayton *et al.*, 1995; Read *et al.*, 2006; Casale *et al.*, 2007). Assessing whether fisheries impacts are sustainable, and whether existing or proposed protection measures are effective, involves estimating population size, the number of animals killed each year and the sustainable level of impact. A Hector's dolphin (*Cephalorhynchus hectori*) case study, described in detail below, highlights many scientific and management issues of relevance to conservation biologists researching not only fisheries impacts but also other human activities that remove individuals from populations (whether deliberately or accidentally). Uncertainties about biological data and human impacts often delay decisions on management of endangered species (Slooten *et al.*, 2000). Some decision-makers think that uncertainty about the risk posed to a species should lead to precautionary decisions while others argue for delaying protective measures until there is stronger evidence that a human activity is having a serious impact. Fully incorporating

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uncertainty into impact assessments should act to minimize such arguments (and the resulting delay) and will make projections more realistic (Lemons, 1995; Martien *et al.*, 1999; Bradshaw and Borchers, 2000).

Uncertainty around each of the inputs is explicitly incorporated into this analysis. Perhaps unexpectedly, this approach is not especially data hungry. A simple assessment can be carried out as long as estimates of population size, number of animals removed each year and population growth rate without human impact are available. If estimates of parameter uncertainty and year to year variability are available, these can be explicitly included in the analysis by sampling from parameter distributions. If a statistical estimate of uncertainty is not available, it is still possible to use a range of plausible values (e.g. uniform distribution spanning the range of likely population growth rates). Sensitivity analyses can be carried out to examine the influence of parameters with very few quantitative data or potentially biased estimates.

Hector's dolphins are endemic to New Zealand waters, with small populations around the South Island and off the North Island west coast. Since at least the early 1970s Hector's dolphins have been caught in commercial gillnet fisheries (Taylor, 1992; Baird and Bradford, 2000). In 2008, the Minister of Fisheries announced a suite of new protection measures for Hector's dolphin. This paper provides an analysis of the likely effectiveness of these measures.

In summary, the new protection measures are:

1. Amateur gillnetting is banned[1] off most open coasts. Regulations specific to particular areas are:

South Island east and south coasts (Cape Jackson in the Marlborough Sounds to Sandhill Point east of Fiordland)

2. Commercial gillnetting is banned from the coastline to 4 nautical miles (n.mi.) offshore, except at Kaikoura, where it is banned to 1 n.mi. offshore, and in Te Waewae Bay, where it is banned to approximately 9 n.mi. offshore.
3. Amateur gillnetting remains allowed in some harbours, estuaries and inlets. For example, amateur gillnetting for flounder is permitted between 1 April and 30 September in the upper reaches of four harbours on Banks Peninsula, and in a similar area in Queen Charlotte Sound.
4. Trawling within 2 n.mi. of shore is restricted to gear used to target flatfish (as defined by low headline height).

South Island west coast (Cape Farewell to Awarua Point)

5. Commercial gillnetting is banned within 2 n.mi. offshore between 1 December and 28 February.
6. No restrictions on trawling.

North Island west coast (Maunganui Bluff to Pariokariwa Point)

7. Commercial gillnetting is banned off open coasts to 7 n.mi. offshore.
8. Commercial and amateur gillnetting is banned in the entrances of all of the major harbours.
9. Trawling is banned within 2 n.mi. offshore from Maunganui Bluff to Pariokariwa Point, and to 4 n.mi between Manukau Harbour and Port Waikato.

More detailed information and maps showing these areas in detail are available at www.fish.govt.nz/en-nz/Environmental/Hectors+Dolphins/.

In addition, the Minister of Conservation has created four new marine mammal sanctuaries, and extended the area of the Banks Peninsula Marine Mammal Sanctuary. These sanctuaries offer no additional restrictions on fishing. Instead they limit mining and acoustic surveys used in seismic prospecting.

This analysis of the effectiveness of these protection measures uses recent estimates of dolphin abundance (Dawson *et al.*, 2004; Slooten *et al.*, 2004, 2006a), an estimate of catch rate from the commercial gillnet fishery (Baird and Bradford, 2000) and fishing effort data from the Ministry of Fisheries and National Institute of Water and Atmosphere (Davies *et al.*, 2008). Population sizes are estimated for 1970, before commercial gillnetting rapidly expanded in New Zealand waters (Massey and Francis, 1989; Dawson, 1991), for 2009 and for 2050.

Bycatch in trawl fisheries and amateur gillnets is likely to extend several decades further back. Hector's dolphins are known to be caught in inshore trawl fisheries (Baird and Bradford, 2000; Starr and Langley, 2000; DOC and MFish, 2007;). Dolphin bycatch in trawling and recreational gillnets could not be included in these analyses because no quantitative estimates of catch rate are available. These assessments of population status are therefore optimistic.

Three options for future management are compared. The new protection measures implemented in 2008 are compared with total protection throughout the range of the species and with a continuation of management up to 2008 (including two protected areas, created in 1988 and 2001). The new protection measures were based on more than two years of intensive public consultation which resulted in the 'Threat Management Plan' for Hector's dolphin (DOC and MFish, 2007).

METHODS

The areas used in modelling were the 16 fisheries management areas for which fishing effort data were available (Figure 1). These same areas and the same basic modelling approach was used by Martien *et al.* (1999), Burkhart and Slooten (2003) and Slooten (2007).

A surplus production model was used for each of these 16 areas:

$$N_{t+1} = N_t[1 + (\lambda_{\max.} - 1)\ (1 - N_t/K)] - N_t C_t \tag{1}$$

where N_t = population size at time t, $\lambda_{\max.}$ = maximum annual population growth rate, K = population size in 1970 and C_t = the proportion of the population killed by entanglement in gillnets in year t.

The proportion of the dolphin population killed each year (C_t in Equation (1)) was estimated using fishing effort, the entanglement rate and the size of the area:

$$C_t = M\ E_t \tag{2}$$

[1]Depending on the area, amateur gillnetting is banned from the coast to 1, 4 or 7 n.mls offshore. Since almost all amateur setnetting occurs within the first few hundred metres of shore, it is effectively banned under the new restrictions.

DOI: 10.1002/aqc

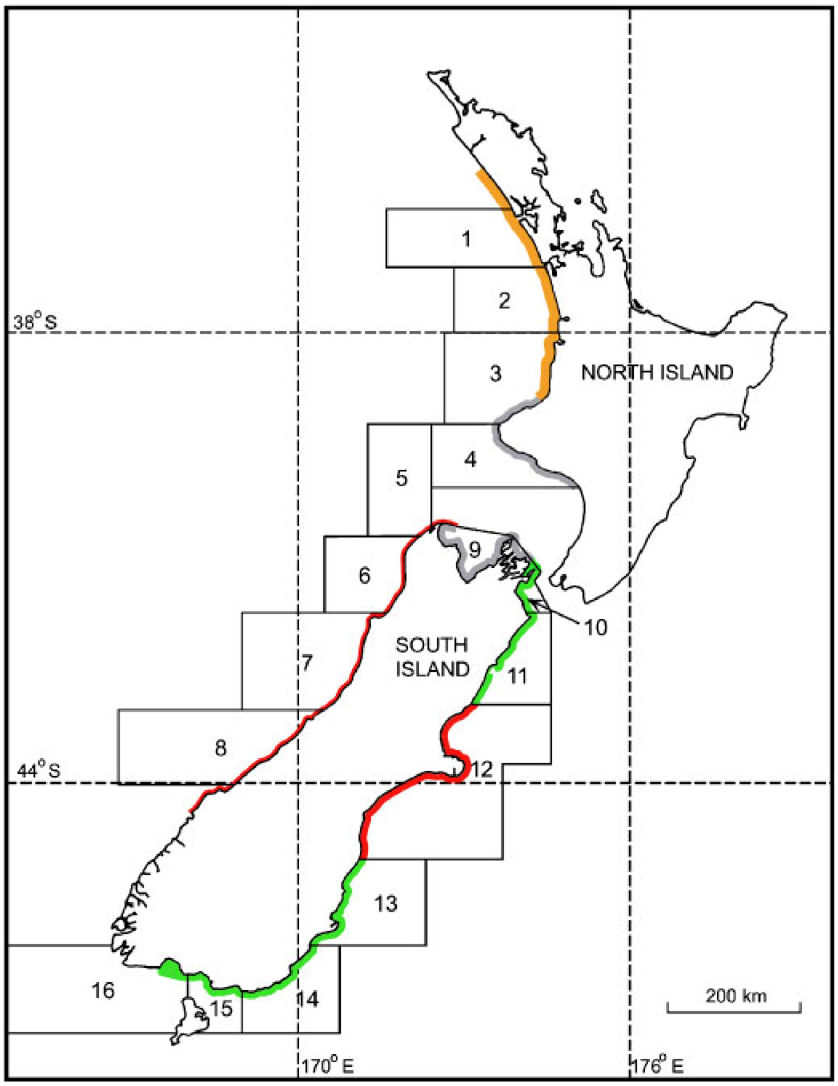

Figure 1. Areas for which data on fishing effort are available (1–16). Coloured areas indicate the new protection measures (to scale). Grey areas: No protection (continued declines expected). Red: Protection for less than a third of the offshore extent of Hector's dolphin distribution (continued declines expected). Orange: No protection inside harbours (populations expected to be held at current, depleted level or very slowly recover). Green: Protection throughout most of dolphin habitat (populations expected to slowly recover). Unshaded areas are outside the normal range of Hector's dolphin.

where E_t = fishing effort at time t (metres of gillnet per km^2) and M = dolphin entanglement rate (proportion of dolphin population caught per unit of fishing effort, E), estimated from an observer programme in area 12 (Baird and Bradford, 2000). This is the only area for which an observer programme has been carried out with sufficiently high observer coverage to estimate catch rate. Baird and Bradford (2000) estimated the catch rate at 0.037 (SE 0.014). A sensitivity analysis was carried out to explore the effect on model predictions of potential over- and under-estimation of the catch rate, by increasing and decreasing the catch rate by 0.25. The New Zealand Ministry of Fisheries provided data on commercial fishing effort (metres of gillnet effort per year in each of the 16 fisheries management areas). For each area, the fishing effort data were divided by the size of the area (km^2) to calculate E for each year. The Sea Food Industry Council assisted in identifying and excluding fishing effort that applied to target species not associated with dolphin bycatch. For example, the majority of gillnetting in area 11 was in deep water, for groper, terakihi, and school sharks (depths >100 m: Colin Sutton, Sea Food Industry Council, pers. commun.), outside the depth range typically used by Hector's dolphins. For this analysis, we therefore included only 10% of the total fishing effort taking place in area 11.

In 1986, the Quota Management System (QMS) was introduced, changing the magnitude and distribution of fishing effort in New Zealand waters (Clark *et al*., 1988, DOC and MFish, 1994). Fishing effort for the years 1970–1982 was chosen from a distribution based on the mean and standard deviation of fishing effort in the same area between 1983 and 1985, before implementation of the QMS. Ministry of Fisheries staff advised that fishing effort data from before 1983 were not sufficiently reliable to be used in these analyses. The data from 1983 onwards include some instances where fishing effort statistics are known to be unreliable. For example, fishermen occasionally report catch without corresponding fishing effort. Obvious mistakes (e.g. typing errors) are carefully checked for by the Ministry of Fisheries.

DOI: 10.1002/aqc

There are no obvious reasons why the data should over-estimate actual fishing effort, but there are some instances where fishing effort is known to be under-estimated. Future fishing effort was based on the level of effort after the introduction of the QMS in 1987. Year-to-year variability in fishing effort was based on the mean and standard deviation (SD) of fishing effort between 1987 and 2008. For each year during each forward projection, a value was randomly selected from a distribution with this mean and SD to represent the level of fishing effort for that year. More detailed information on fishing effort and how it is used in the model was presented in Burkhart and Slooten (2003).

For each run of the model, a maximum population growth rate was selected from a uniform distribution between 1.018 and 1.049 to reflect uncertainty in the estimation of this parameter. The highest and lowest population growth rates span the range estimated by Slooten and Lad (1991) and also those used by Martien *et al.* (1999) and represent a highly optimistic parameterization. The smallest value (1.018) is a 'best' estimate of $\lambda_{max.}$ (Slooten and Lad, 1991). The highest value (1.049) is an estimate of the maximum possible $\lambda_{max.}$ for the species, based on a survival curve for humans and the most optimistic estimate of reproductive rate for Hector's dolphin (Slooten and Lad, 1991). Further, using a uniform distribution between 1.018 and 1.049 means that values at the upper, highly optimistic end are equally likely to be used as values at the lower, more realistic end. Hector's dolphin, like most other small cetaceans, have low potential population growth rates (Perrin and Reilly, 1984; Reilly and Barlow, 1986). It was assumed that the population growth rate is highest in very small populations, with little competition for food, space or other resources. Allee effects (decompensation at very small population sizes, e.g. due to inbreeding, a failure to find mates, reduced effectiveness in feeding or predator defence) were not included.

The rate of movement of individuals between the 16 population units (Figure 1) was estimated at 1% based on movement data from photographically identified individuals (Bräger, 1998; Martien *et al.*, 1999; Bräger *et al.*, 2002; Fletcher *et al.*, 2002; Slooten, 2007). In correspondence with these field data, the movement rate was modelled as 1% of the population moving across any border with another population: i.e. for two adjacent populations, 1% of the individuals in population A will move to population B in any given year, and 1% of the individuals in population B will move to population A. If population A adjoins two populations, B and C, then a further 1% of population A will move to population C (and vice versa).

All calculations were carried out in Microsoft Excel, automated via Visual Basic macros. The goal seek function in Excel was used to estimate population size in 1970 for each area, using distributions for $\lambda_{max.}$ (see above) and current population size (based on recent population surveys: Dawson *et al.*, 2004; Slooten *et al.*, 2004, 2006a). A similar method of back-calculation is described in Smith and Polachek (1979), Barlow and Hanan (1995) and Martien *et al.* (1999). For each of 5000 back calculations, values for N and λ_{max}. were randomly selected from their respective distributions and K was estimated by back calculation. The forward projections used these 5000 consistent sets of values, maintaining the relationship between K, N and $\lambda_{max.}$ for each forward projection of the model.

The year 2050 was chosen as a reasonable timeframe for assessing the outcome of management decisions taken now. This is just over three Hector's dolphin generations, allowing sufficient time to show the effect of different levels of protection. Population size in 2050 was also compared with original population size in 1970 and with half of the 1970 level. This latter level was chosen because marine mammal legislation in some countries requires that populations are kept at or above half of the original, unexploited population size (Wade, 1998; Taylor *et al.*, 2000).

Results are reported for the four regions for which management solutions are being discussed as part of the development of a Threat Reduction Plan for Hector's dolphin (DOC and Mfish, 2007): North Island west coast (areas 1–4) and the South Island west (5–8), east (9–13) and south coasts (14–16). These four management areas are broadly based on regions with genetically distinct populations (Pichler *et al.*, 1998). The alternative management options explored here are past management, total protection and the new protection measures implemented in 2008.

Past management (Option A)

Management up to 2008 included two protected areas. The Banks Peninsula Marine Mammal Sanctuary was created in 1988 and covers the central part of area 12 (Dawson and Slooten, 1993). A protected area on the North Island west coast, created in 2001, includes areas 1, 2 and about three-quarters of area 3 (Figure 1). Some fisheries mortality continues inside and immediately outside both of these protected areas (Dawson and Slooten, 2005; DOC and Mfish, 2007). The proportion of the population found inside and outside the Banks Peninsula Marine Mammal Sanctuary has been estimated using a series of line-transect surveys (Dawson *et al.*, 2004; Slooten *et al.*, 2006b; Rayment *et al.*, 2009). The average proportion of Hector's dolphin groups sighted outside the 4 n.mi. sanctuary boundary was 37.5% (Rayment *et al.*, 2009). Adding Hector's dolphins found inside area 12 but north and south of the sanctuary boundaries, results in an estimated 61% of the population being outside the sanctuary and exposed to gillnet fisheries. This may under-estimate the level of exposure, as there have been continued dolphin catches inside the sanctuary (DOC and MFish, 2007) partly because trawling and recreational gillnetting are still allowed inside the sanctuary and partly due to illegal gillnetting within the sanctuary. The estimate above assumes that all fishing effort was outside the sanctuary boundaries and all individuals within the sanctuary were fully protected.

It is more difficult to estimate the proportion of the North Island Hector's dolphin population still exposed to gillnets. Dolphin sightings have been made in the harbours and to the south of the protected area. In addition, trawling continues inside the protected area and gillnetting continues inside the harbours. Gillnet effort inside the harbours is higher than the level for the open coast before the protected area was created. Taking all of these factors into account, we used 25% as a conservative estimate of the proportion of the population that was not protected (from 2001 onwards).

New protection measures (Option B)

In order to quantify the effect of the new protection measures, the different levels of protection in different areas need to be taken into account as well as the fact that in several places the

DOI: 10.1002/aqc

protected areas are smaller than fisheries statistics areas (areas 1–16 in Figure 1).

New protection measures:

Areas 1, 2 and part of area 3: Gillnets banned from 0–7 n.mi. from shore

Areas 4, 9 and about 25% of areas 3 and 10: No gillnetting restrictions

Areas 5–8: Gillnets banned from 0–2 n.mi. from shore for three months in summer

Areas 11–16 and part of area 10: Gillnets banned from 0–4 n.mi. from shore

Data on the distribution of dolphins (Dawson *et al.*, 2004; Slooten *et al.*, 2004, 2006a; Rayment *et al.*, 2009) and fishing effort (Davies *et al.*, 2008) were used to estimate the corresponding reduction in dolphin exposure to gillnets for each area (Table 1). Uncertainties as to whether fishing effort from newly protected areas will be removed from the fishery or displaced to other, non-protected areas were also taken into account. For example, after the Banks Peninsula Marine Mammal Sanctuary was created in 1988, a very high proportion of the fishing effort (on the order of 80–90%) was displaced offshore and alongshore to areas left unprotected. The protection measures announced in 2008 involve areas much larger than the Banks Peninsula Sanctuary and there is very little potential for alongshore displacement of effort. However, offshore displacement of fishing effort is likely to occur in most areas.

Three scenarios were modelled to represent uncertainty about the extent to which the new protection measures will result in removal or displacement of fishing effort (Table 1). Scenario B1: All fishing effort is removed from protected areas. Any past fishing effort in an area that is now protected is simply removed from the fishery. Scenario B2: Half of the current fishing effort is displaced. Half of the fishing effort in newly protected areas is removed, the other 50% is displaced offshore. Scenario B3: All fishing effort is displaced. In addition, in Scenario B3 the exposure level is increased to take into account potential non-compliance with the new regulations as well as dolphin catches in continued commercial and recreational gillnet and trawl fisheries (see below). The resulting exposure level in each area depends on the proportion of the dolphin population and the proportion of fishing effort inshore (0–4 n.mi.) and offshore (4–15 n.mi. from shore). Table 1 shows the resulting exposure levels for the three scenarios.

The new protection measures are simplest in areas 10–16, where gillnetting is banned inshore from 0–4 n.mi. Total protection is assumed inshore in scenarios B1 and B2, i.e. 100% compliance with the new regulations, effective policing and no illegal fishing. In the B1 scenario all of the inshore fishing effort is removed from the fishery, and offshore fishing effort is left at its previous level. Estimating the exposure level for each scenario involves multiplying the proportion of the dolphin population inshore and offshore with the new level of fishing effort, doing the same for past fishing effort and then dividing the former into the latter. For example, in area 10 the exposure level for Scenario B1 is $((0.77 \times 0)+(0.23 \times 0.35))/((0.77 \times 0.65)+(0.23 \times 0.35)) = 0.14$. In the past, 0.77 of the dolphin population (inshore) was exposed to 0.65 of the fishing effort. In Scenario B1, 0.77 of the population is fully protected but the remaining 0.23 (offshore) is still exposed to 0.35 of the fishing effort. In Scenario B2 half of the past inshore fishing effort is displaced and offshore effort becomes $0.35+(0.65/2) = 0.68$. The regulations in areas 10 and 11 include exemptions to allow continued gillnetting in the Marlborough Sounds (northern part of area 10) and to 1 n.mi. offshore around Kaikoura Peninsula (in middle of area 11). For the B1 and B2 scenarios the optimistic assumption has been made that this does not reduce the level of protection. Calculations are slightly more complex for areas 5–8 on the west coast of the South Island. Here gillnetting is banned out to 2 n.mi. offshore, instead of 4 n.mi. in other areas, and for three months of the year instead of year-round. Therefore, inshore fishing effort was reduced to 0.5 for three months of the year (past fishing effort $\times ((0.5 \times 3/12)+(9/12))$). For Scenario B2, half of the removed fishing effort was displaced offshore, as above.

In the B3 scenario all of the inshore fishing effort is shifted offshore for areas 10–16. For areas 5–8 gillnets are banned out to 2 n.mi. (a third of the offshore distribution of the dolphins) for only three months of the year. In this worst case scenario, we assume that this is not sufficient to reduce the dolphins'

Table 1. The proportion of the dolphin population and the distribution of past fishing effort within 0–4 n.mi. and 4–15 n.mi. from shore (first five columns below, see Figure 1 for location of the areas). Three potential scenarios of future fishing effort are included. B1: All fishing effort is removed from protected areas. B2: Half of the current fishing effort is displaced. B3: All fishing effort displaced. Exposure levels (last three columns) take into account the offshore distribution of fishing and dolphins, and for Scenario B3 continued exposure to gillnetting and trawling (calculations are explained in Methods section)

Area					Future								
	Dolphins		Past fishing		B1		B2		B3		Exposure		
	0–4	4–15	0–4	4–15	0–4	4–15	0–4	4–15	0–4	4–15	B1	B2	B3
5	1.00	0.00	0.77	0.23	0.67	0.23	0.67	0.28	0.77	0.23	0.88	0.88	1.35
6	0.93	0.07	0.51	0.49	0.41	0.49	0.41	0.54	0.51	0.49	0.81	0.82	1.25
7	0.93	0.07	0.68	0.32	0.56	0.32	0.56	0.38	0.68	0.32	0.83	0.83	1.25
8	0.99	0.01	0.83	0.17	0.64	0.17	0.64	0.26	0.83	0.17	0.78	0.78	1.25
10	0.77	0.23	0.65	0.35	0.00	0.35	0.00	0.68	0.00	1.00	0.14	0.27	0.80
11	0.96	0.04	0.88	0.12	0.00	0.12	0.00	0.56	0.00	1.00	0.01	0.03	0.35
12	0.62	0.38	0.28	0.72	0.00	0.72	0.00	0.86	0.00	1.00	0.61	0.73	1.15
13	0.81	0.19	0.31	0.69	0.00	0.69	0.00	0.85	0.00	1.00	0.34	0.42	0.70
14	0.92	0.08	0.31	0.69	0.00	0.69	0.00	0.85	0.00	1.00	0.16	0.20	0.44
15	0.65	0.35	0.43	0.57	0.00	0.57	0.00	0.79	0.00	1.00	0.42	0.57	0.93
16	0.95	0.05	0.30	0.70	0.00	0.70	0.00	0.85	0.00	1.00	0.11	0.13	0.36

DOI: 10.1002/aqc

exposure to gillnets (exposure level is left at 1.00). In addition, in the B3 Scenario the exposure level is increased in all areas to take into account potential non-compliance with the new regulations, as well as dolphin catches in recreational gillnets, trawl fisheries and continued commercial gillnetting permitted in some areas. For example, gillnetting continues to be legal in areas 4, 9 and parts of areas 3 and 10. Likewise, there were eight reported Hector's dolphin mortalities inside the Banks Peninsula Marine Mammal Sanctuary (part of area 12) during 1995–2005, partly because recreational gillnetting was allowed inside the sanctuary for most of the year and partly due to illegal gillnetting (DOC and MFish, 2007). These dolphin mortalities were voluntarily reported. No quantitative estimates are available from observer programmes or other systematic monitoring. Therefore, in the worst case scenario (B3) a nominal 0.10 was added to the exposure level to represent potential non-compliance with the new regulations and/or incomplete monitoring and policing. This was done for all areas except those without protection measures (e.g. area 4) or with regulations so incomplete that the exposure level was left at 1.00 (areas 5–9). A further 0.30 was added to the exposure level for areas 1–3, 0.10 for area 10 and 0.05 for area 11 to represent continued commercial gillnetting in these partially protected areas. To represent trawl bycatch 0.01 was added for area 2 (almost complete trawling ban), 0.10 for areas 1 and 10–16 (partial trawling bans) and 0.25 for the other areas (little or no protection from trawling). In addition, 0.05 is added to represent recreational bycatch for area 11, 0.10 for areas 1–3, 5, 10 and 12 and 0.20 for areas 4 and 9, reflecting the relative amounts of recreational gillnetting in those areas. For example, recreational gillnetting will be legal throughout areas 4 and 9 and for parts of areas 10 and 12. These are relatively modest increases in the level of exposure to fisheries mortality. For example, while there is no quantitative estimate for the number of dolphins caught in trawl fisheries, the number of reported catches and the level of fishing effort suggest that bycatch in trawl fisheries could be substantial (Dawson and Slooten, 2005).

Areas 4 and 9 are not included in Table 1. There is no protection in these areas, therefore the exposure level is 1.00 for all model scenarios (with increases for Scenario B3, as specified above). For areas 1–3 there are insufficient quantitative data on dolphin distribution and in particular on the distribution of fishing effort to carry out the calculations in Table 1. For these areas, qualitative predictions were made as follows. On the North Island west coast (areas 1 and 2) gillnetting will still be allowed inside the harbours. The catch rate was multiplied by 0.10 in these areas, to indicate there is still a low level of risk of entanglement in commercial gillnets. Two areas (3 and 10) are partially protected. The catch rate was multiplied by 0.25 to indicate that about a quarter of these two areas will remain unprotected.

An observer programme carried out in 2009 provides some data from after implementation of the new protection measures. The observer coverage was too low (2–10% depending on the area) to allow robust estimation of catch rate. However, a simple bootstrap analysis using the numbers of observed catches and gillnet sets is used to estimate the likelihood that catch rate is unchanged from previous years. The best information on Hector's dolphin bycatch comes from the east coast South Island. Davies *et al.* (2008) estimate that some 40 dolphins per year were caught in this area in the last few years before the new protection measures were implemented. In this year's observer programme, one dolphin was observed caught in this area. We estimated the probability of observing 0, 1, 2 etc. dolphin captures if the total number of captures is still 40 per year. In this area 320 of a total of 3444 gillnet sets were observed (9.3%).

Total protection (Option C)

The total protection option completely eliminates fishing mortality for all populations (areas 1–16). Like Scenario B1, Option C assumes that there is no mortality from recreational gillnetting or trawl fisheries and that policing and compliance are 100% effective.

For each of these management options, we estimated population size in 2050, probability of recovery and time taken to recover to 1970 population size (K) and to half of 1970 population size ($1/2K$). The latter is a performance standard specified in the US Marine Mammal Protection Act, and is used here as reference point. The US MMPA requires that populations be kept at or above $1/2K$ and that fisheries bycatch not increase the time taken for depleted populations to reach $1/2K$ by more than 10% (US Marine Mammal Protection Act; Wade, 1998).

RESULTS

Estimated current population sizes are substantially lower than 1970 levels for each regional population (Figure 2) and for all populations combined (Figure 3). Without fisheries mortality, the total population would be expected by 2050 to have recovered to around 15 000 individuals–about half of the 1970 population size (Figure 3). This is mainly driven by the two largest populations, on the east and west coast of South Island. Both are expected to decline under the past management approach (Option A, Figure 2). Under the protection measures introduced in 2008 (Option B) the west coast South Island population is predicted to decline by just over 1000 individuals between now and 2050. The east coast population is expected to recover slowly (gaining about 450 individuals). Without fisheries mortality (Option C) both populations are predicted to recover to approximately half of their 1970 population size (Figure 2). The North Island population is the most seriously depleted, and is expected to recover very slowly, even if fisheries mortality is reduced to zero. The population on the south coast of the South Island is currently close to half of its 1970 population size. This population is expected to do reasonably well under the new protection measures and shows the smallest difference between Options B and C. For all other populations, Option B performs slightly better than Option A, and Option C results in much larger 2050 population sizes than the other management options. The effectiveness of Option B would be reduced substantially if a high proportion of fishing effort from protected areas is displaced to unprotected areas and when trawling and recreational gillnetting are taken into account (Figure 3).

It is not surprising that the two largest populations make the strongest contribution to total population size and to the relative effectiveness of the management options. The west coast South Island population is not only the largest, but also has the weakest protection measures. In this area, gillnetting is illegal to 2 n.mi. offshore (about 30% of the dolphins' offshore range) for three months of summer and there are no

DOI: 10.1002/aqc

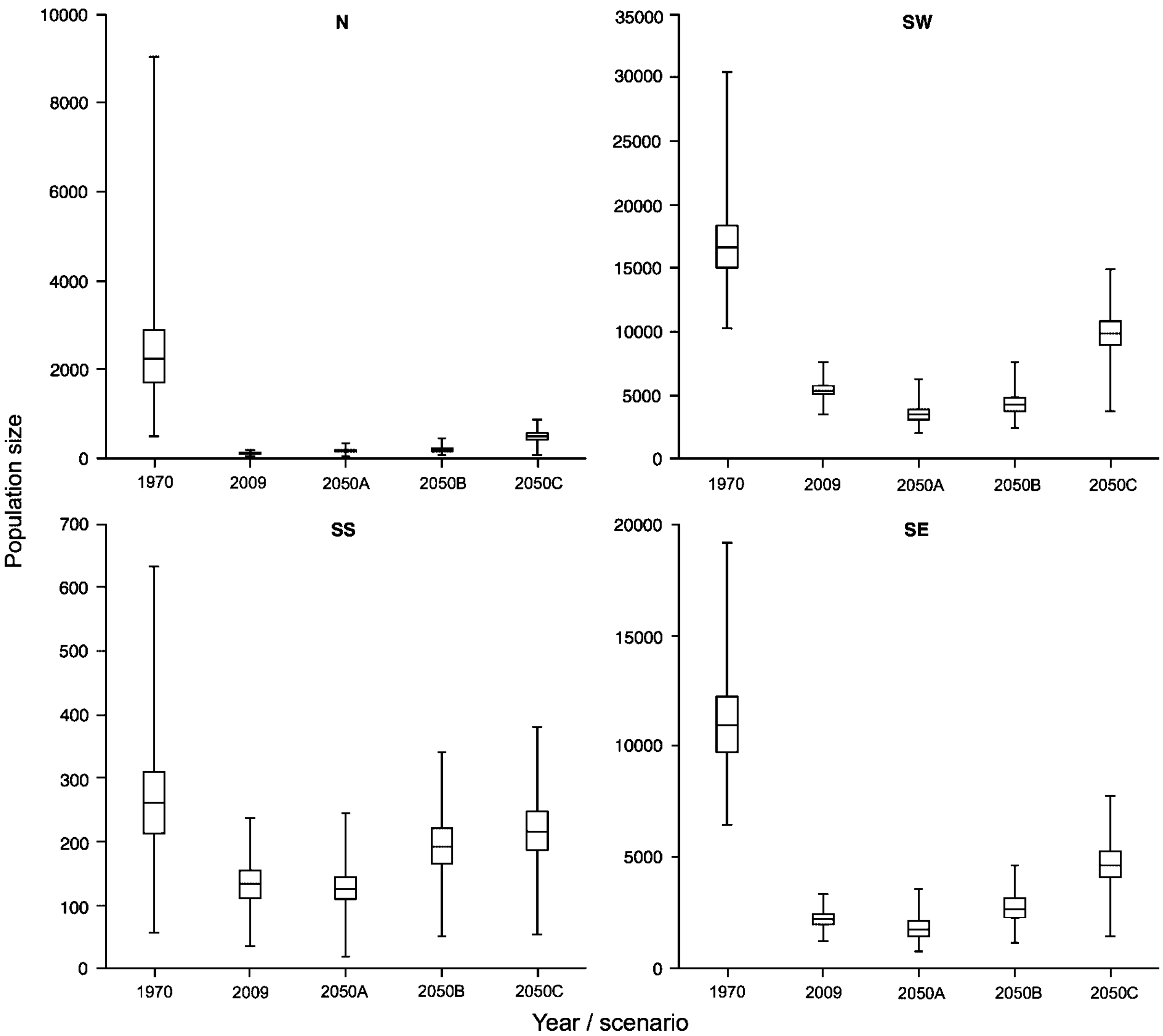

Figure 2. Estimated population sizes in 1970, 2009 and 2050 for four regional populations. Clockwise from top left: North Island (N: areas 1–4 in Figure 1), South Island west (SW: areas 5–8), east (SE: areas 9–13) and south coasts (SS: areas 14–16). Population size estimates for 2050 are shown for three management options: A. Past management, B. New protection measures and C. No fisheries mortality. Boxes indicate upper and lower quartiles (25th and 75th percentile), the line inside each box is the median (50th percentile) and the whiskers indicate the range of the 5000 population size estimates resulting from each simulation.

restrictions on trawl fisheries. The overall reduction in fishing effort in this area is expected to be relatively small and most of the past fishing effort from 0–2 n.mi is likely to be displaced further offshore.

Option B is most effective if all fishing effort is removed from protected areas (Scenario B1, Figure 3). Protection is less effective if half of the fishing effort is displaced to adjacent, unprotected areas (Scenario B2). Further population declines are expected if all fishing effort is displaced and the potential impact of trawl fisheries, recreational gillnetting, and incomplete policing and compliance is taken into account (Scenario B3, Figure 3). Over or under-estimating the catch rate by 25% has a substantial effect on the estimate of 1970 population size but relatively little effect on conclusions with regard to 2050 population sizes and the potential for population recovery (Figure 4).

We estimated the probability and time taken to recover to 1970 population size and to half of that level (Table 2). For the species as a whole, recovery did not occur in any of the model runs for Option A and Scenario B3. Recovery occurred in 20% of model runs for Scenario B1, 8% for Scenario B2 and always took >1000 years. By contrast, under Option C the total population always recovered. Recovery to $1/2K$ always occurred within 1000 years and on average took 39 years (CV 0.34). Estimated delays in recovery to $1/2K$ and K were substantial for Options A and B (Table 2). For example, without fisheries mortality (Option C) predicted recovery time to $1/2K$ was 39 years. A 10% delay in recovery time would mean recovery within 43 years. Estimated delays were substantially longer, with the total population taking more than 1000 years to reach $1/2K$ (20% of runs for Scenario B1, 8% for B2, no recovery for B3) or declining (80% of runs for B1, 92% for B2, 100% for B3). Recovery was also delayed by more than 10% for each of the regional populations. For example, under Scenario B1 recovery to $1/2K$ was estimated to take more than 19, 217, 306 and 1000 years, respectively, for the regional populations, and exceeded the time to recovery for Option C by much more than 10%. Under- and

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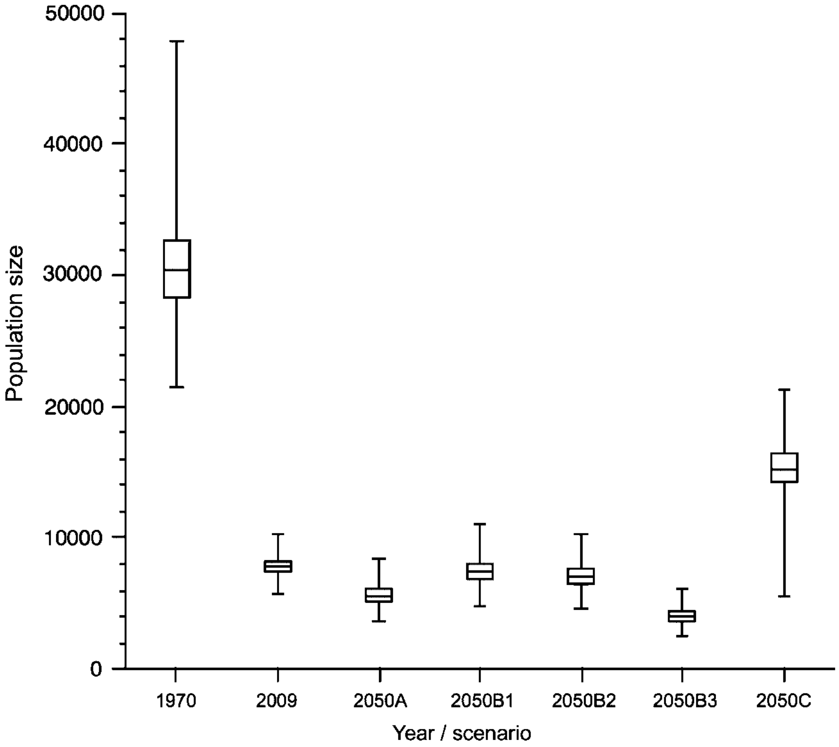

Figure 3. Estimated total population size for Hector's dolphin in 1970, 2009 and 2050. Population size estimates for 2050 are shown for five management options: A. Past management, B. New protection measures: B1. All fishing effort from protected areas is removed from the fishery, B2. Half of the fishing effort from protected areas is displaced to unprotected areas, B3. All fishing effort is displaced and dolphin mortality in trawl and recreational gillnet fisheries is included in the analysis and C. No fisheries mortality. Boxes indicate upper and lower quartiles (25th and 75th percentile), the line inside each box is the median (50th percentile) and the whiskers indicate the range of the 5000 population size estimates resulting from each simulation.

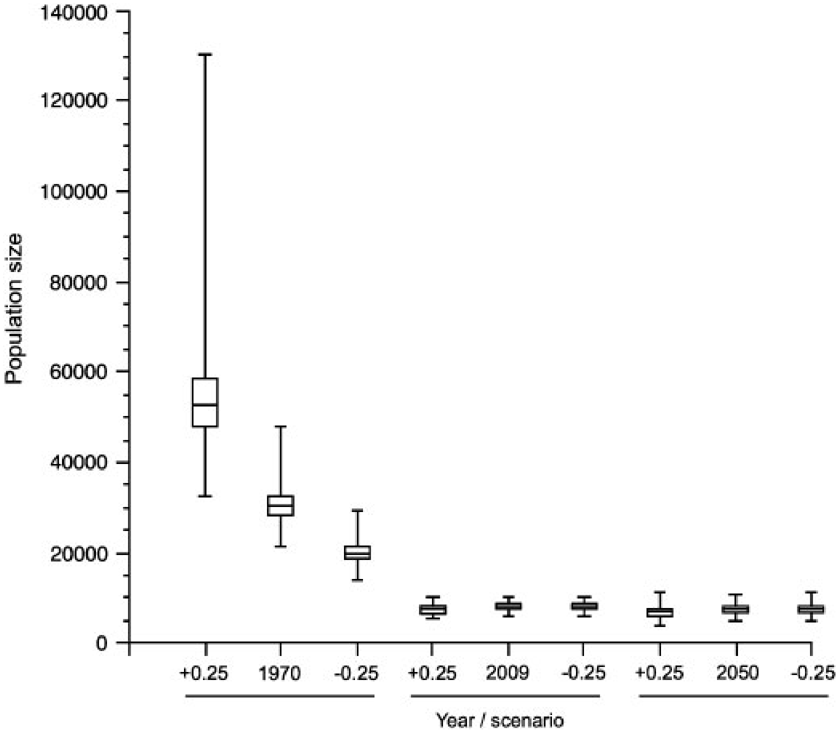

Figure 4. Sensitivity analysis showing the effect of over- and under-estimating catch rate on estimated total population size under management Scenario B1. Population sizes for 1970, 2009 and 2050, estimated using the catch rate estimated in an observer programme or plus and minus 0.25 of that catch rate to reflect potential under- and overestimation. Boxes indicate upper and lower quartiles (25th and 75th percentile), the line inside each box is the median (50th percentile) and the whiskers indicate the range of the 5000 population size estimates resulting from each simulation.

DOI: 10.1002/aqc

Table 2. Recovery to (a) population size in 1970, (b) half that level. Estimates presented for each regional area and scenario: Recovery: proportion of 5000 model runs in which the population recovers. <1000 years: proportion of runs in which the population recovered in <1000 years. Average: average number of years to recovery (and CV), only for those runs where recovery took <1000 years

		North Is	South Is E	South Is W	South Is S	Total
(a)						
A	Recovery	0.88	0.00	0.00	0.03	0.00
	<1000 yrs	0.00			0.00	
	Average					
B1	Recovery	1.00	0.82	0.01	1.00	0.20
	<1000 yrs	0.00	0.00	0.00	0.11	0.00
	Average				249 (1.25)	
B2	Recovery	0.00	0.71	0.01	1.00	0.08
	<1000 yrs		0.00	0.00	0.05	0.00
	Average				296 (1.09)	
B3	Recovery	0.00	0.00	0.00	0.09	0.00
	<1000 yrs				0.00	
	Average					
C	Recovery	1.00	1.00	1.00	1.00	1.00
	<1000 yrs	0.19	0.00	0.00	0.59	0.00
	Average	191 (0.94)			142 (1.38)	
+0.25	Recovery	1.00	0.99	0.00	1.00	0.58
	<1000 yrs	0.00	0.00		0.14	0.00
	Average				238 (1.07)	
−0.25	Recovery	1.00	0.99	0.00	0.99	0.07
	<1000 yrs	0.00	0.00		0.09	0.00
	Average				263 (1.21)	
(b)						
A	Recovery	0.88	0.00	0.00	0.03	0.00
	<1000 yrs	0.00			0.00	
	Average					
B1	Recovery	1.00	0.82	0.01	1.00	0.20
	<1000 yrs	0.03	0.03	0.00	1.00	0.00
	Average	217 (0.75)	306 (0.86)		19 (2.96)	
B2	Recovery	0.00	0.71	0.01	1.00	0.08
	<1000 yrs		0.00	0.00	0.34	0.00
	Average				24 (4.90)	
B3	Recovery	0.00	0.00	0.00	0.09	0.00
	<1000 yrs				0.01	
	Average				207 (1.52)	
C	Recovery	1.00	1.00	1.00	1.00	1.00
	<1000 yrs	0.96	1.00	0.94	1.00	1.00
	Average	88 (0.71)	25 (0.44)	72 (0.88)	4 (5.04)	39 (0.34)
+0.25	Recovery	1.00	0.99	0.00	1.00	0.58
	<1000 yrs	0.00	0.01		0.99	0.00
	Average		367 (0.68)		27 (2.26)	
−0.25	Recovery	1.00	0.99	0.01	0.99	0.07
	<1000 yrs	0.45	0.12	0.00	1.00	0.00
	Average	147 (1.16)	127 (1.67)		42 (3.62)	

Scenarios in Table 2: Management Option A: past management, B: new protection measures announced in 2008, assuming complete removal of fishing effort from protected areas (B1), half of the removed fishing effort displaced offshore (B2) or all fishing effort displaced plus allowance for continued legal and illegal fishing (B3), C: total protection. Sensitivity analyses on the catch rate (+0.25 and–0.25) were carried out for Scenario B1.

overestimation of the catch rate (+0.25 and −0.25 scenarios) had little effect on these conclusions. In all cases, recovery was delayed by much more than 10%.

The probability of recovery to 1970 population levels (K) was relatively low for all scenarios. The strongest potential for recovery was seen in the South Island south coast population, which is already close to $1/2K$ and predicted to recover to that level in just a few years. This population recovered to K in <1000 years in 59% of runs, with an average time to recovery of 142 years for those runs. The new protection measures were predicted to reduce the probability of recovery substantially (from 59% to 11% of the runs for Scenario B1) with recovery time increasing to 249 years for the 11% of runs in which recovery occurs in <1000 years. The only other population with the potential to recover to K in <1000 years was the North Island population. Without fisheries mortality, this population recovered to K in 19% of the runs, with an average recovery time of 191 years in those runs. Under the new protection measures, this population always took >1000 years to recover. For the species as a whole, recovery to K took more than 1000 years in all scenarios.

The observer programme carried out in 2009 provides some limited information on the effectiveness of the new protection measures. Case is needed in comparing the catch rate observed in 2009 with the earlier catch rate estimate. The 1997/98 observer programme focused on the central east coast where Hector's dolphin densities are highest and had much higher observer coverage, especially in spring and early summer when a high proportion of dolphins is caught. Hence the earlier observer programme would be expected to have a higher catch rate. Even so, the bootstrapping results provide no indication that the number of dolphins caught was significantly lower in

DOI: 10.1002/aqc

2009 (0.12 probability of observing 0 or 1 catch, if a total of 40 dolphins were caught). Likewise, the binomial confidence intervals of the two catch rate estimates overlap considerably (2009 95% CI = 0−0.017; 1997/98 95% CI = 0.01−0.06; Baird and Bradford (2000)).

DISCUSSION

The results indicate that between 1970 and 2009 Hector's dolphin populations declined throughout the geographic range of the species. Continuation of past management (Option A) would be expected to result in further population decline. Total protection (Option C) would result in substantial population recovery with the total population reaching just over half of the 1970 population size by 2050. The new protection measures (Option B) result in recovery for some populations and continued declines for others. For the species as a whole, the new protection measures would come close to halting population declines but are unlikely to result in recovery. As expected, the prognosis is worse if some or all of the fishing effort in newly protected areas is displaced rather than removed from the fishery. Under past management as well as the new protection measures, all but one of the populations are expected to be well below half of their 1970 population size in 2050. Eliminating fisheries mortality for all areas where Hector's dolphins are found (Option C) would result in substantial population increases, although several areas would still have relatively low population numbers in 2050.

We have attempted to match the complexity of this modelling approach to the available data and to the objectives of this analysis. The stochastic model incorporates uncertainty in the input parameters and sensitivity analyses have been carried out to explore the potential effect of bias in input parameters that are highly uncertain and/or potentially biased. For example, fishing effort is known to be under-reported in some areas. In addition to addressing these uncertainties within the model, these results are compared with other analysis approaches, some simpler and some more complex than this approach.

The sensitivity analysis for fishing effort displacement shows that the new protection measures would be substantially less effective if a relatively high proportion of fishing effort is displaced rather than removed from the fishery. Scenario B1 assumes that gillnetters would change to other fishing methods, or leave the industry, rather than moving their gillnetting effort from a protected to an unprotected area. Any illegal fishing, or displacement of gillnet and trawl fisheries from protected areas to adjacent areas where Hector's dolphins are found, would result in less optimistic outcomes as seen in Scenarios B2 and B3. Clearly, monitoring and policing will be very important. Intensive observer programmes will be needed to help answer the question of what proportion of fishing effort is displaced to other areas, how many dolphins continue to be caught in areas left unprotected and to improve estimates of the entanglement rate. Monitoring illegal fishing is becoming easier with automated vessel monitoring systems (Grech *et al*., 2008).

Model predictions were less sensitive to potential bias in the catch rate estimate than to effort displacement. The estimated population size in 1970 was relatively sensitive to changes in the catch rate. However, over- or underestimating the catch rate had very little effect on conclusions with regard to 2050 population sizes and the potential for population recovery. Further sensitivity analyses on catch rate, fishing effort and other parameters have been presented by Martien *et al.* (1999), Burkhart and Slooten (2003) and Slooten (2007). Unfortunately no quantitative data are available on how catch rate might vary from one area to another or how the rate at which dolphins encounter nets relates to dolphin abundance. At this time a successful observer programme, resulting in a quantitative estimate of bycatch, has been carried out only in area 12. Therefore all studies to date, including the Bayesian model constructed by Davies *et al.* (2008) have had to assume that the catch rate (per unit of fishing effort, per dolphin in the population) is similar throughout the range of the species. Data from video monitoring (McElderry *et al*., 2007), years with some but very low observer coverage (Dawson and Slooten, 2005), beachcast carcasses and interviews with fishermen in this and other areas (Dawson, 1991; Dawson *et al*., 2001) are consistent with the estimated catch rate and suggest that our assumption that catch rate does not vary substantially from one area to another is reasonable. Quantitative data on how catch rate varies with fishing effort, dolphin density, from area to area and from year to year may become available in future. Government agencies have indicated that they would like to increase the amount and geographical range of observer coverage. However, at this stage, coverage is still very low (2–10%) and there is no quantitative evidence that the catch rate has declined as a result of the new protection measures.

By reducing population size in some areas more than others, fisheries mortality may have played a role in shaping the current distribution of Hector's dolphin. For example, the areas linking North Island and South Island (areas 4, 5 and 9, Figure 1) have relatively high levels of fishing effort and low dolphin numbers. The much lower level of protection on the west coast South Island (areas 5–8) and the lack of protection for areas 4, 9 and parts of areas 3 and 10 may lead to further population fragmentation. Previous analyses have shown that higher rates of movement from one population to another would reduce the potential for fragmentation, but would lead to worse outcomes for the species as a whole (Martien *et al*., 1999; Slooten, 2007).

We chose to construct a model rather than using a PVA package like Vortex. Different software packages vary in their structure and in how processes such as environmental and demographic variation are modelled (Lindenmayer *et al*., 1995; Brook *et al*., 1997, 1999; Hanski, 2002). Brook *et al*. (1999) found that different PVA packages often produce different predictions, and found a large, statistically significant difference between two versions of Vortex, due to the way breeding was modelled. Pre-packaged programs make PVA more accessible. However, an analysis approach that is tailored specifically to the requirements of the particular species and/or management problem is generally preferable (Lindenmayer *et al*., 1995). Also, unless an exceptional amount of data is available, parsimony favours the use of relatively simple models, with fewer unverified assumptions and with properly estimated parameter values (Hanski, 2002). Simple models are necessarily simplifications, but require fewer questionable assumptions than more complex models. In addition, while these simplifications can be critical for absolute predictions (e.g. of extinction time) they rarely alter conclusions from comparative analyses (e.g. comparing the relative effectiveness of several management options).

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A simple logistic model was used, similar to the one used in the USA in determining sustainable levels of marine mammal bycatch, the Potential Biological Removals (PBR) method (Wade, 1998; Taylor *et al*., 2000). For marine mammals the maximum net productivity level (MNPL) is thought to be at or above $1/2K$ (likely range 0.5–0.85K, e.g. Taylor and de Master, 1993). A range of MNPL values were explored in simulation testing of the PBR method as well as potential biases in estimates of population size, catch rate and other inputs for the model, based on experience with fisheries in the USA (Wade, 1998). Small decreases in MNPL had a moderately strong effect on population size, causing depletion in each case. Moderate increases in MNPL allowed populations to do relatively better, but were not sufficient to compensate for potential underestimation of catch rates. Most methods of monitoring marine mammal bycatch tend to underestimate the catch rate. A simple logistic model (theta = 1, MNPL = 0.5K) was chosen as a suitable trade-off between possible over- and underestimation of the potential for density-dependent compensation (Wade, 1998). Like the PBR method, the model results in relatively optimistic predictions because it does not include Allee effects (declines in population growth rate at small population sizes).

A range of approaches, ranging from fairly simple (e.g. the PBR approach) to extremely complex (Davies *et al*., 2008) have been used to assess population viability in Hector's dolphin. Reassuringly, all of the analyses carried out to date have resulted in consistent predictions. For example, estimated bycatch during 2000–2006 was an order of magnitude higher than PBR levels (Slooten and Dawson, 2008) indicating a high probability of population decline. The PBR model used 'default' values for productivity, based on other whale and dolphin species. The population size estimates are the only data in common between this analysis and the PBR calculations (Slooten and Dawson, 2008). A stochastic Leslie Matrix model for the Banks Peninsula population (area 12) predicted population declines consistent with those in the analysis presented here (Slooten *et al*., 2000). The Leslie Matrix model used survival rates for the Banks Peninsula population based on mark–recapture analysis of photographic-identification data and the most optimistic estimate of reproductive rate. The model was not density dependent and did not involve backcalculation of past population size or depletion level relative to original population size (Slooten *et al*., 2000). Likewise, earlier versions of the model presented here included extensive sensitivity testing and resulted in consistent conclusions (Martien *et al*., 1999; Burkhart and Slooten, 2003; Slooten, 2007). In addition, these predictions were very similar to those from an integrated Bayesian model developed by the National Institute of Water and Atmosphere (Davies *et al*., 2008). Davies *et al*. (2008) estimated that by 2050 populations would decline to 5631 without the new protection measures and recover to 14 379 if fisheries mortalities are reduced to zero (with productivity in middle of plausible range at 1.5%). The corresponding estimates from the model presented here are 5605 and 15 291. In summary, all analyses carried out to date indicate that Hector's dolphin populations have been substantially depleted and that without fisheries mortality, populations would recover fairly rapidly.

'Integrated' Bayesian models, in which many parameters are estimated at the same time, on the basis of for example a time series of catch and/or abundance data are becoming popular in the fisheries literature (e.g. Punt and Hilborn, 1997). Problems with this approach include the sensitivity of complex Bayesian models to the level of data availability and quality (Kelly and Codling, 2006). To efficiently run these models requires data that are reasonably precise, accurate and high contrast, including data from a wide range of system states. For example, data from high and low population levels are required in order to estimate productivity, or how population growth rates change over a wide range of population sizes. Attempts to estimate productivity without a detailed time series of estimates, covering a wide range of population sizes, tend not to be very successful. For example, both Breen *et al*. (2003) in their model of New Zealand sealion and Davies *et al*. (2008) in their Hector's dolphin model obtained estimates of maximum population growth rate that were unrealistically low (close to zero in the case of the sealion model). In both cases, more biologically realistic estimates were eventually obtained by using highly informative priors and/or penalties external to the prior to bring the productivity estimate closer to the range of estimates for other marine mammals. In general, the more complex the model and the more data it requires, the more sensitive its results will be to missing or unreliable data (Kelly and Codling, 2006; Punt, 1997). Fisheries models have been criticized for developing to a level of complexity that is too great relative to the amount of reliable observational data that are available (Schnute and Richards, 2001). Fisheries biologists have repeatedly warned about building models so complex that the underlying biology is lost sight of, and many have pointed in the direction of simpler analysis approaches (Francis, 1980; Beverton, 1998; Schnute and Richards, 2001; Longhurst, 2006).

National and international standards provide a context for evaluating the new protection measures. For example, the New Zealand Marine Mammals Protection Act (1978) states that fisheries mortality should be managed to ensure that threatened species 'achieve non-threatened status as soon as reasonably practicable, and in any event within a period not exceeding 20 years'. Additionally, the New Zealand Marine Mammal Action Plan includes the following goals for Hector's dolphin: 'self-sustaining populations throughout the species natural range' and 'reduce bycatch to near zero'. The plan also recommends that a recovery group be set up, and a recovery plan be developed with more specific management goals for Hector's dolphin.

Management goals under US legislation include: (1) Maintaining populations above their Optimum Sustainable Population (OSP) level. OSP is defined as a population size exceeding the level at which the population has its maximum net productivity (thought to be 50–85% of the original pre-impact population for marine mammals, Taylor and de Master (1993)). (2) If a population is endangered or threatened, bycatch levels should be negligible and in no case should bycatch delay recovery of endangered species by more than 10% of the estimated recovery time in the absence of human impact. (3) Populations should not be permitted to diminish below the point at which they cease to be a significant functioning element in the ecosystem of which they are a part. Goals 1 and 3 are specified in the US Marine Mammal Protection Act and goal 2 is included in the guidelines for preparing marine mammal stock assessments (Barlow *et al*., 1995). The US requirement that fisheries bycatch not delay the rate of recovery by more than 10% means that Hector's dolphin should take less than 43 years to recover to $1/2K$.

DOI: 10.1002/aqc

Options A and B both fall well short of this target with the total population either declining or taking more than 1000 years to reach $1/2K$. This conclusion holds for each of the regional populations also.

The proposed new protection measures do not yet meet any of these national or international goals for marine mammal conservation. As the Scientific Committee of the International Whaling Commission pointed out 'The proposed protection measures are a major step forward, substantially reducing the overlap between gillnets and Hector's dolphins' However, 'additional measures are likely to be required to ensure recovery of the species' (IWC, 2008). Despite this, it is important to acknowledge that the proposed new measures represent significant progress. In particular:

1. Amateur gillnetting has been banned off most open coasts where Hector's dolphins are found.
2. Hector's dolphin populations on the open east and south coasts of the South Island are now much better protected, with a ban on gillnetting out to 4 n.mi. throughout most of this area.
3. Maui's dolphins (North Island Hector's dolphins) are now protected further offshore, to 7 n.mi., and better protected in the harbours, with gillnet bans in all harbour entrances.
4. Government has increased the budget available for observer programmes to NZ$6M. This is close to the annual gross income of the coastal gillnet fishery ($7.4M before deducting the cost of boats, fuel, labour, etc.; Penny *et al*., 2007).

Further progress, however, is needed; particularly in the following areas:

(a) Hector's dolphins off Banks Peninsula are still unprotected beyond 4 n.mi. from shore. This is unexpected, since there are extensive research data showing their distribution in this predominantly shallow region extends to 20 n.mi. offshore (Rayment *et al*., 2009).
(b) Hector's dolphins inside the Banks Peninsula Marine Mammal Sanctuary are still vulnerable to gillnetting in the flounder fishing areas. This is also unexpected, since there are extensive passive acoustic monitoring data showing the dolphins use harbours throughout the year including 12 months of monitoring in Akaroa Harbour (Slooten and Dawson, in press).
(c) There is no protection for Maui's dolphins off Taranaki (area 4), immediately south of the protected area. This used to be an area of regular Maui's dolphin presence, and they are only very occasionally seen there now (Slooten *et al*., 2005). High gillnetting effort in this area will make it difficult for Maui's dolphin to recover in this and immediately adjacent areas.
(d) While the added protection for Maui's dolphins in harbour entrances is welcomed, most of the west coast harbour habitat is still left unprotected.
(e) Protection for west coast South Island dolphins is inadequate. This population, which is a major stronghold for the species is predicted to continue to decline.
(f) There is very little protection for the Cook Strait area, between North and South Island. This is likely to further increase population fragmentation.
(g) The new protection measures offer little protection from trawling, and assume that trawling for flounder represents a negligible risk. There is no empirical evidence to support this assumption.

In summary, the new protection measures implemented in 2008 are a substantial improvement over previous protection for Hector's dolphin. However, they fall short of ensuring the species' recovery and meeting national and international management goals for marine mammal conservation.

ACKNOWLEDGEMENTS

We would like to thank Barbara Taylor (US National Marine Fisheries Service), Karen Martien (US National Marine Fisheries Service) and Stephanie Burkhart (Marine Protected Resources, US Coast Guard) for contributions to earlier versions of this population model. Discussions with these and other researchers using population viability analysis have led to the approach in this paper in including parameter uncertainty and environmental variability explicitly in the model. Discussions at 'stakeholder' meetings with representatives from the fishing industry, government departments and non-government organisations have contributed to further improvements in the approach. We are very grateful to the following sponsors for helping fund the costs of gathering the input data for the models presented here: Ministry of Fisheries, Department of Conservation, University of Otago, Auckland Regional Authority, Care for the Wild International, Whale and Dolphin Conservation Society, NZ Whale and Dolphin Trust, WWF NZ, the Royal Forest and Bird Protection Society, Black Cat Cruises. We would also like to thank the Royal Society of New Zealand whose Sir Charles Fleming Award enabled a nationwide lecture tour. Discussions at these meetings were very constructive and helpful in the development of the work reported here.

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DOI: 10.1002/aqc