Characterisation of marine mammal interactions with fisheries & bycatch mitigation

Final report for INT2019-03 prepared by Dragonfly Data Science for the Conservation Services Programme, Department of Conservation.

Authors:
Laura Tremblay - Boyer
Katrin Berkenbusch

DRAGONFLY Data Science

PO Box 27535, Wellington 6141
New Zealand
dragonfly.co.nz

Cover Notes

To be cited as:

Tremblay-Boyer, Laura; Berkenbusch, Katrin (2022). Characterisation of marine mammal interactions with fisheries & bycatch mitigation, 67 pages. Final report for INT2019-03 prepared by Dragonfly Data Science for the Conservation Services Programme, Department of Conservation..

CONTENTS

EXECUTIVE SUMMARY ... 4

1 INTRODUCTION ... 5

2 METHODS ... 7

2.1 Marine mammal interactions with New Zealand fisheries ... 7

2.1.1 Observer records ... 9

2.1.2 Fisher records ... 11

2.1.3 Modelled bycatch estimates ... 12

2.2 Mitigation methods for marine mammal bycatch ... 12

3 RESULTS ... 14

3.1 Marine mammal interactions in New Zealand fisheries ... 14

3.1.1 Summary of bycatch trends across species ... 14

3.1.2 Common dolphin ... 24

3.1.3 Hector's and Māui dolphins ... 25

3.1.4 New Zealand sea lion ... 30

3.1.5 New Zealand fur seal ... 35

3.2 Bycatch mitigation for marine mammals ... 39

3.2.1 Trawling ... 40

3.2.2 Longlining ... 44

3.2.3 Set netting ... 46

3.2.4 Pots and traps ... 49

3.2.5 Purse seining ... 51

3.3 Mitigation techniques in New Zealand fisheries ... 52

4 DISCUSSION ... 53

4.1 Marine mammal interactions in New Zealand fisheries ... 53

4.2 Mitigation of marine mammal bycatch in New Zealand ... 55

5 ACKNOWLEDGMENTS ... 56

6 REFERENCES ... 57

APPENDIX A FISHERY TARGET SPECIES ... 63

APPENDIX B OBSERVER COVERAGE BY TARGET FISHERY AND GEAR ... 64

EXECUTIVE SUMMARY

Incidental captures of marine mammals in New Zealand waters have been documented for a range of commercial fisheries, including trawl, longline, set net, pots (and traps) and purse seine. The current study used existing information to characterise marine mammal interactions with these fisheries from 1992–93 to 2017–18, and reviewed potential mitigation techniques for reducing incidental captures in New Zealand waters. Additional analyses were conducted for species with significant numbers of captures or for which additional information was available; these species were common dolphin (*Delphinus delphis*), Hector's and Māui dolphins (*Cephalorhynchus hectori hectori* and *Cephalorhynchus hectori maui*), New Zealand sea lion (*Phocarctos hookeri*) and New Zealand fur seal (*Arctocephalus forsteri*).

Across fisheries, trawl had the highest number of observed captures when aggregated by species and gear, followed by surface longline. Especially within trawl fisheries, there was often high variability in observed capture rates amongst regions and target species. Post-capture survival (whether an individual was recorded as alive upon release) was the highest for surface-longline fisheries, and almost all individuals caught in these fisheries were recorded as live releases. In contrast, post-capture survival was lowest for trawl fisheries, where almost all individuals observed caught were recorded as dead.

The highest number of observed captures was pinnipeds, with New Zealand fur seal featuring the most frequently in observer records. Observed captures of this species were high in trawl fisheries and also in surface longline. New Zealand sea lion was almost exclusively caught in trawl. Common dolphin was the most frequently-recorded cetacean species in the observer data, followed by long-finned pilot whale and dusky dolphin.

The current characterisation also identified four specific associations between species and fisheries that resulted in significant numbers of captures: common dolphin and large-vessel trawl fisheries targeting jack mackerel, Hector's and Māui dolphins and set-net fisheries, New Zealand sea lion and trawl fisheries targeting squid, and New Zealand fur seal and trawl fisheries targeting southern blue whiting. Most of these fisheries have implemented mitigation measures over the study period, and reductions in observed and estimated captures were evident for all of these species in the time-series data.

The ability to assess and estimate the extent of captures relies on comprehensive observations of fishing effort *via* the fisheries observer programme. High observer coverage is crucial for the recording of captures of rare species, for which even a low number of captures can have a significant impact on the population (e.g., Māui dolphin). In addition, observer coverage needs to be adequately high to allow reliable capture estimates for species that are observed sufficiently often to inform a model in systematic bycatch assessments. The current analysis revealed that observer coverage was low overall across gears, although there were increases in some fisheries with high marine mammal capture rates in recent years. Observer coverage was particularly low in inshore trawl fisheries, which are characterised by high effort, while overlapping with the habitat of many coastal marine mammal species. This scarcity of observer data impedes a reliable assessment of interactions of marine mammal species with these fisheries.

Mitigation efforts in New Zealand and elsewhere have focused on technical and other approaches to reduce or prevent incidental captures of marine mammals in commercial

fisheries. Findings from this research highlight the challenges of testing the efficacy and effectiveness of different mitigation measures, and document the limitations of many approaches; they also show that successful mitigation techniques are often species- and fishery-specific.

Mitigation techniques for New Zealand fisheries include exclusion devices that are currently used in subantarctic trawl fisheries to mitigate the bycatch of New Zealand sea lion. Exclusion devices have also been trialled in other New Zealand trawl fisheries to reduce incidental captures of New Zealand fur seal. Although these limited trials did not indicate the suitability of exclusion devices, their effectiveness in trawl fisheries elsewhere and for New Zealand sea lion warrant further research into this mitigation technique for New Zealand fur seal.

In northern North Island trawl fisheries, acoustic deterrent devices are currently being used to prevent common dolphin bycatch. The lack of systematic data of their use and of associated operational aspects means that their effectiveness remains untested. Furthermore, the acoustic deterrent devices are used in combination with other measures in this fishery, precluding the assessment of individual measures.

For longline, set-net, pot (and trap) and purse-seine fisheries, bycatch mitigation options remain limited, and research to date has been unable to identify technical approaches and gear modifications that would have potential in a New Zealand context. Although acoustic devices have been shown to be effective in preventing bycatch of some small cetacean species in set-net fisheries, research to date does not support their use as a mitigation device for Hector's dolphin bycatch.

1. INTRODUCTION

Incidental captures of pinnipeds and cetaceans have been documented across different commercial fisheries in New Zealand waters, including trawl, longline, set-net, purse-seine and pot fisheries (e.g., see reviews in Berkenbusch et al. 2013, Laverick et al. 2017). In some of these fisheries, onboard government observers monitor the interactions between fishing operations and marine mammals (and other protected species), and thereby provide an independent record of incidental captures. The fisheries observer programme started in the 1992–93 fishing year, and is implemented differently across fishing gears and target fisheries.

Information collected by fisheries observers is used as input to studies aimed at quantifying marine mammal interactions with commercial fisheries in New Zealand. These studies include regular bycatch assessments that integrate observer records with fishing effort data to derive estimates of fishery-wide captures in New Zealand's Exclusive Economic Zone (EEZ) (see Abraham et al. 2016, Abraham & Berkenbusch 2017, Thompson et al. 2017). The most recent estimation provided capture estimates for New Zealand sea lion (*Phocarctos hookeri*) in trawl fisheries up to the 2014–15 fishing year (Abraham & Berkenbusch 2017), and for common dolphin (*Delphinus delphi*) and New Zealand fur seal in trawl and longline fisheries up to the 2017–18 fishing year (*Arctocephalus forsteri*) (Abraham et al. 2021).

In addition, observer records also support assessments that are aimed at determining the risk posed by fishery-related mortalities to marine mammal populations. Recent risk assessments include the multi-species analysis of 35 marine mammal (sub)species interacting with New Zealand's commercial fisheries (Abraham et al. 2017). As part of this risk assessment, fishing-related mortality estimates were provided for each taxon for the three-year period from 2012–13 to 2014–15. The findings showed that a few species interact relatively frequently with fisheries in New Zealand or had a high risk resulting from fisheries interactions, including common dolphin, Hector's and Māui dolphins (*Cephalorhynchus hectori hectori* and *C. hectori maui*), bottlenose dolphin (*Tursiops truncatus*), killer whale (*Orcinus orca*), New Zealand fur seal and New Zealand sea lion.

Two subsequent risk assessments have focused on a specific species, New Zealand sea lion (Large et al. 2019) and Hector's dolphin (Roberts et al. 2019). These risk analyses have followed the Spatially Explicit Fisheries Risk Assessment approach (SEFRA; Sharp 2018). Under this approach, information of the spatial distribution of the population and its overlap with fishing effort is used to derive estimates of annual mortalities from interactions with fisheries. The risk analysis for New Zealand sea lion was limited to the Auckland Islands female population, and covered the period between 1992–93 and 2016–17 (Large et al. 2019). For Hector's dolphin, the assessment considered both subspecies, Hector's and Māui dolphins, and also non-fishery threats, for the period between 1992–93 and 2016–17 (Roberts et al. 2019).

Efforts to reduce the bycatch of protected species have led to the implementation of a variety of mitigation measures that are aimed at reducing the likelihood of interactions or lessen the severity of their outcomes (e.g., see recent reviews in Leaper & Calderan 2018, Hamilton & Baker 2019). These measures include temporal and spatial fishery closures that reduce the overlap in the distributions of fishing effort and marine mammals, and also systematic changes to fishing practices, such as switching of fishing gear. Technical mitigation methods tested or implemented in New Zealand and overseas include gear modifications and changes to fishing practices (Childerhouse et al. 2013, Laverick et al. 2017). For example, captures of pinnipeds in pot fisheries in Australia have prompted the development and application of exclusion devices that allow trapped sea lions to escape (Campbell et al. 2008). In New Zealand, the high number of incidental captures of New Zealand sea lion in subantarctic trawl fisheries resulted in the adoption of Sea Lion Exclusion Devices (SLEDs) in squid and southern blue whiting target fisheries (Ministry for Primary Industries 2019).

Similar exclusion devices have also been trialled for small cetaceans in trawl fisheries, and other mitigation techniques for this group of marine mammals include acoustic devices and changes to the design and implementation of fishing gears and practices (e.g., Rowe 2007, Hamilton & Baker 2019). New Zealand examples of mitigation techniques include modifications to fishing practices in the North Island mackerel trawl fishery to reduce common dolphin bycatch, such as the use of acoustic dissuasive devices, with details outlined in the Marine Mammals Operational Procedures (MMOPs; see Deepwater Group 2018).

The current project consisted of two main components: a data analysis providing a characterisation of marine mammal interactions with New Zealand commercial fisheries, and a review of mitigation techniques for reducing incidental captures of marine mammals in these fisheries. From this review, recommendations were made on mitigation measures that are potentially suited to the fishing gears used in New Zealand.

2. METHODS

The present project included all marine mammals occurring in New Zealand waters, excepting taxa with a New Zealand threat status of "vagrant" (see Table 1). Vagrant taxa were: Antarctic fur seal (*Arctocephalus gazella*), subantarctic fur seal (*Arctocephalus tropicalis*), pygmy killer whale (*Feresa attenuata*), Weddell seal (*Leptonychotes weddellii*), crabeater seal (*Lobodon carcinophagus*), Ross seal (*Ommatophoca rossi*), killer whale (*Orcinus orca*) types B, C, D, melon-headed whale (*Peponocephala electra*) and pantropical spotted dolphin (*Stenella attenuata*) (Baker et al. 2019).

Reported interactions between fisheries and cetaceans and pinnipeds occurring in New Zealand waters include bycatch reports in trawl, surface and bottom-longline, set-net (or "gillnet"), pot and trap, and purse-seine fisheries (Berkenbusch et al. 2013, Laverick et al. 2017).

2.1 Marine mammal interactions with New Zealand fisheries

The current characterisation of marine mammal interactions with New Zealand fisheries integrated data from different sources that either directly report an interaction or represent an estimate based on statistical modelling. "Fisheries" are defined broadly as either all fishing operations using the same fishing gear (e.g., trawl fisheries) or fishing operations targeting the same species, usually with the same gear (e.g., the southern bluefin tuna surface-longline fishery). In the latter case, they are defined as "target fisheries", or the target species is included in the description (see Appendix A for information of target species).

There are different categories of interactions, which are reported or estimated across data sources in New Zealand (summarised in Table 2). Here, "interaction" was broadly defined as physical contact between an individual and fishing gear, or a modification in behaviour caused by fishing operations. Within that category, a "capture" was defined as an individual that is caught in fishing operations, so that it cannot escape the fishing gear without external assistance. Individuals that climbed onboard the vessel or that were decomposed when caught were not considered captures. Finally, the term "mortality" refers to a capture in fishing gear that resulted in mortality. This term was used here interchangeably with "death" to reflect usage in other studies.

The main source of reliable information of interactions between marine mammals and fisheries in New Zealand is the fisheries observer programme, managed by Fisheries New Zealand (and its predecessors). The programme in its current form officially started in the 1992–93 fishing year, and is implemented differently across fishing gears and target fisheries. The information collected by observers has been used as input for studies aimed at quantifying marine mammals interactions at broader scales, such as estimates of fishery-wide captures (e.g., Abraham & Berkenbusch 2017) or risk analyses (e.g., Large et al. 2019, Roberts et al. 2019) (see Table 3).

Ideally, it would be possible to estimate the number of individuals of a species that interact with fishing gear over time in each interaction category (e.g., how many New Zealand fur seal interacted with trawl fisheries, how many were captured, and how many died). In practice, general interactions (including behaviour modifications) with fishing gear are difficult to monitor over large scales, and most studies report or estimate captures or mortalities. Often, observations of captures by fisheries observers apply to a small

Table 1: Marine mammals in New Zealand, including their New Zealand threat status (Baker et al. 2019).

Grouping	Common name	Scientific name	NZ threat status
Baleen whales	Antarctic blue whale	*Balaenoptera musculus* intermedia	Data deficient
Mysticeti	Pygmy blue whale	*Balaenoptera musculus brevicauda*	Data deficient
	Antarctic minke whale	*Balaenoptera bonaerensis*	Data deficient
	Dwarf minke whale	*Balaenoptera acutorostrata* "dwarf"	Data deficient
	Bryde's whale	*Balaenoptera brydei*	Nationally critical
	Fin whale	*Balaenoptera physalus*	Data deficient
	Sei whale	*Balaenoptera borealis*	Data deficient
	Humpback whale	*Megaptera novaeangliae*	Migrant
Toothed whales	Sperm whale	*Physeter macrocephalus*	Data deficient
Odontoceti	Pygmy sperm whale	*Kogia breviceps*	Data deficient
	Killer whale	*Orcinus orca*	Nationally critical
	False killer whale	*Pseudorca crassidens*	Naturally uncommon
	Short-finned pilot whale	*Globicephala macrorhynchus*	Data deficient
	Long-finned pilot whale	*Globicephala melas*	Not threatened
	Common dolphin	*Delphinus delphis*	Not threatened
	Dusky dolphin	*Lagenorhynchus obscurus*	Not threatened
	Bottlenose dolphin	*Tursiops truncatus*	Nationally endangered
	Hector's dolphin	*Cephalorhynchus hectori hectori*	Nationally vulnerable
	Māui dolphin	*Cephalorhynchus hectori maui*	Nationally critical
	Southern right whale dolphin	*Lissodelphis peronii*	Data deficient
	Hourglass dolphin	*Lagenorhynchus cruciger*	Data deficient
	Spectacled porpoise	*Phocoena dioptrica*	Data deficient
	Striped dolphin	*Stenella coeruleoalba*	Data deficient
	Risso's dolphin	*Grampus griseus*	Data deficient
	Dwarf sperm whale	*Kogia sima*	Data deficient
	Fraser's dolphin	*Lagenodelphis hosei*	Data deficient
	Rough-toothed dolphin	*Steno bredanensis*	Data deficient
Beaked whales	Andrews' beaked whale	*Mesoplodon bowdoini*	Data deficient
	Goose-(Cuvier's)beaked whale	*Ziphius cavirostris*	Data deficient
	Dense-beaked whale	*Mesoplodon densirostris*	Data deficient
	Gray's beaked whale	*Mesoplodon grayi*	Not threatened
	Hector's beaked whale	*Mesoplodon hectori*	Data deficient
	Strap-toothed whale	*Mesoplodon layardii*	Data deficient
	Spade-toothed whale	*Mesoplodon traversii*	Data deficient
	Shepherd's beaked whale	*Tasmacetus shepherdi*	Data deficient
	Southern bottlenose whale	*Hyperoodon planifrons*	Data deficient
	Arnoux's beaked whale	*Berardius arnuxii*	Data deficient
	Ginkgo-toothed beaked whale	*Mesoplodon ginkgodens*	Data deficient
	True's beaked whale	*Mesoplodon mirus*	Data deficient
	Lesser/pygmy beaked whale	*Mesoplodon peruvianus*	Data deficient
Pinnipeds	New Zealand sea lion	*Phocarctos hookeri*	Nationally vulnerable
	New Zealand fur seal	*Arctocephalus forsteri*	Not threatened
	Southern elephant seal	*Mirounga leonina*	Nationally critical
	Leopard seal	*Hydrurga leptonyx*	Naturally uncommon

subset of fishing operations, and cannot be extrapolated to the entire fishery without a statistical model. For example, if ten fur seal were caught by surface-longline gear when 1% of the effort was observed, but capture rates were higher for some gear configurations, seasons or fishing locations, these factors need to be accounted for in the estimation of total fur seal captures in these fisheries (i.e., the total captures would not simply be 10 × 100).

Table 2: Description of key sources of information on interactions between marine mammals and commercial fisheries in New Zealand waters, the type of interaction recorded, and whether they were included in the current assessment ("Used").

Source	Description	Interaction	Used
Fisheries observer records	Captures of protected species reported by observers onboard fishing vessels.	Captures.	Yes.
Fisheries observer sightings	Sightings of protected species reported by observers onboard fishing vessels.	Potential interaction from spatial overlap with fishing operations.	No.
Fisher-reported captures	Captures of protected species reported by fishers on the Non-fish/Protected Species Catch Return (NFPSCR) form available since 2008–09.	Captures.	Yes.
Bycatch estimates	Model-based estimates from observed captures predicting bycatch numbers for the total effort of the observed fishery or gear.	Captures.	Yes.
Risk assessment estimates	Model-based estimates of total annual mortalities from a specific gear or fishery.	Mortality.	Yes.
Sightings database	Database maintained by Department of Conservation (DOC), collating information on marine mammals sightings in New Zealand from forms submitted by the public.	Potential interaction from spatial overlap with fishing operations.	No.
Strandings database	Database maintained by DOC of reported whale or dolphin strandings.	Mortality.	No.
Necropsy records	Pathology reports from necropsy investigations of marine mammals stranded or captured dead, conducted at Massey University on behalf of DOC.	Mortality.	No.

Furthermore, different studies report different categories of interactions based on the study focus. For example, mortalities are relevant in the context of population dynamics, and risk assessments generally focus on estimating mortalities. In contrast, bycatch estimates aim to characterise gear-wide captures from observer records, but not all bycaught animals die as a result of the interaction.

Because of the potentially different impact on populations, the category of interaction needs to be clearly identified when interactions are reported. In the present study, not all interaction categories were available for all species, so the focus was on the most robust or recent estimates that were available for each species, typically observed captures. An overall summary of these observer data was included for all species, in addition to a summary of captures reported by fishers. For a subset of species, observed captures were significant or recurring over multiple years, or modelled estimates of captures or mortalities were available from other studies. For these species, observed captures were further disaggregated and reported in separate species-specific sections. The focus on these individual species also included estimated captures or mortalities from modelling studies.

2.1.1 Observer records

Fisheries observers record the captures of protected species, such as marine mammals, onboard commercial fishing vessels. These independent records allowed for a comprehensive assessment of incidental captures of marine mammals across all gears

Table 3: Records of marine mammal species interacting with fisheries included in this study. Data sources were fisher-recorded captures on Non-fish/Protected Species Catch Return forms, observer records of captures ("observed") including observer data for at least five years, modelled bycatch estimates, and estimates from risk assessments (Large et al. 2019, Roberts et al. 2019).

Species	Fisher-recorded	Observed	Observed ($\geq$ 5 years)	Bycatch estimates	Risk assessment
Humpback whale	×	×			
Long-finned pilot whale	×	×	×		
Minke whale	×				
Bottlenose dolphin	×	×	×		
Common dolphin	×	×	×	×	
Dusky dolphin	×	×	×		
Hector's dolphin	×	×	×		×
Killer whale	×	×			
Elephant seal	×	×			
Leopard seal	×	×			
New Zealand fur seal	×	×	×	×	
New Zealand sea lion	×	×	×	×	×

when observers were present. The main fishing gears with observer coverage were trawl, surface longline, bottom longline, set net and purse seine.

For this analysis, all records from the Protected Species Captures (PSC) database were extracted, up to the end of the 2017–18 fishing year. This database is a version of the Centralised Observer Database maintained by the National Institute of Water and Atmospheric Research (NIWA), with the data prepared and formatted for the estimation of protected species captures (see details in Abraham & Berkenbusch 2019). The data from the PSC database are also available online (https://psc.dragonfly.co.nz/). Observers may also record sightings of protected species (including seabirds and marine mammals), but there records were not included in the current study.

The start year for the current analysis depended on the start of observer coverage for the different fishing gear: for trawl, bottom longline and surface longline, observer records started in 1992–93, for set net, they started in 1998–99, and for purse seine in 2004–05. Where relevant, fishing events were further classified into a "fishery" based on the fishing method (or gear) and the fisher-declared target species (see Appendix A, Table A-1 for a description of target species by fishery). The "fishing year" refers to the period from 1 October to 30 September the following year. This period is used by managers for most fisheries, and this format was retained here. When a single year is reported (e.g., in figures), it represents the second year in the time period (e.g., "2010" corresponds with the 2009–10 fishing year).

Observer coverage rate by year and gear (or target fishery) was calculated as the ratio of the sum of the effort when an observer was present to the total fishing effort for that gear or target fishery in that year; total fishing effort was reported by fishers in catch effort forms submitted to Fisheries New Zealand. These forms vary by gear and over time, and are collated in a database called *warehou*. Since 2017–18, data have also also been recorded electronically and stored in a separate database. Both *warehou* and the electronic reporting system database are hosted by Fisheries New Zealand, and accessible to science providers. The effort data were prepared as described in Abraham and Berkenbusch 2019. The definition of effort was based on the gear used: it was number of tows for trawl, number of hooks for bottom and surface longline, length of net (in metres) for set net, and number of sets for purse seine. To calculate effort for a specific gear or fishery, all records of fishing events were extracted for the period from 1992–93 onwards.

The first step in the present assessment was to calculate the total number of observed captures by species and gear for the entire period with observer coverage. This initial analysis led to the identification of key species that had a high number of observed captures. When possible, more detailed temporal trends from observer records were derived, including trends in observed capture rates. Observed capture rates were calculated as the ratio of observed captures to the total observed effort for a fishery and year. This ratio provided a standardised approach for examining capture trends over time; because observed captures are expected to increase with coverage, the reporting of observed captures without observer effort can be ambiguous.

A second source of fishery observer data was used in addition to the Fisheries New Zealand-led programme. In the 1997–98 fishing year, a targeted observer programme was commissioned by DOC to monitor set nets in eastern South Island, in the Pegasus Bay and Canterbury Bight areas, with the objective of assessing entanglement of Hector's dolphin (Starr & Langley 2000, see also Baird & Bradford 2000). Captures of Hector's dolphin were observed as part of this limited programme, and these records were included in the present summaries pertaining to this species. This programme also included some observer effort in inshore trawl, with the recording of a single Hector's dolphin capture in this gear. This capture was included here in the aggregated summaries of captures by gear type, including observed captures and observed capture rates of Hector's dolphin. Because of the limited temporal and spatial scope, and specific focus on Hector's dolphin, these data were not included in overall statistics of observer effort by fishing gear or target fishery.

Observed effort in net length was obtained from Starr and Langley 2000. There was a small number of sets (16) for which no effort measure was available. For these sets, the effort by set (in net length) was assumed to be the average net length for the other sets observed as part of this programme. To obtain observer effort on set nets targeting shark species only, the total effort (in net length) was multiplied by the proportion of sets reported by Starr and Langley 2000 as targeting sharks, school shark, or rig.

2.1.2 Fisher records

Since October 2008, fishers have been able to report marine mammals captures on the Non-fish/Protected Species Catch Return (NFPSCR) form, and also through electronic reporting (introduced during the 2017–18 fishing year) (Table 3). The NFPSCR form includes fields to identify the species captured and the status of captured animals (alive uninjured, alive injured, dead). To extract attributes about the fishing effort, this form can be linked to the catch effort form that was completed for the fishing trip. Using this information, captures by species (or group of species), by gear type and by status were aggregated from the 2008—09 fishing year onwards (i.e., since the introduction of the NFPSCR form). Note that some of the captures reported in the NFPSCR form are also included in observer records.

2.1.3 Modelled bycatch estimates

Two types of modelled bycatch estimates were included in this report (Table 3). These modelled estimates are captures or annual deaths at the scale of a fishery based on the observed fishing effort. The modelled estimates were used to analyse trends in captures, as observed captures are determined by observer coverage, which is often low and variable across fisheries.

The first type of model was based on a family of Generalised Linear Models (GLMs), which predict captures by unit effort (e.g., tow or set) as a function of covariates that may be indicative of capture rates such as year, season, fishing area, vessel, gear or effort attributes, distance from shore, and the use of mitigation measures. In New Zealand, these models have been applied and updated over time for marine mammal species with sufficient numbers of observed captures to allow the estimation of total captures; these species are common dolphin, New Zealand fur seal and New Zealand sea lion ((see Abraham & Berkenbusch 2017, for the most recent published estimates). These estimates were recently updated to the 2017–18 fishing year (Abraham et al. 2021).

The second type of model was from risk analyses aimed at determining the risk posed by current threats (including fishery-related mortalities) to a population. In New Zealand, risk analyses have recently followed the Spatially Explicit Fisheries Risk Assessment approach (SEFRA) (Sharp 2018). As part of this framework, annual mortalities from interactions with fisheries are estimated to quantify the risk of fishing to the population(s) under study. These estimates account for the spatial distribution of the population and its overlap with fishing effort, and also the vulnerability of individuals to different types of fishing gear (including cryptic mortality, when relevant). There have been three relevant risk analyses in New Zealand recently; the first one included all marine mammal taxa resident in New Zealand waters (Abraham et al. 2017), whereas the other two risk analyses focused on Hector's and Māui dolphins (Roberts et al. 2019), and on New Zealand sea lion (Large et al. 2019), respectively. The multi-species risk assessment by Abraham et al. (2017) was restricted to the period between 2012–13 and 2014–15. Owing to the limited time period of this risk assessment, it was not included in the present study. The other two risk analyses included the period from 1992–93 to 2016–17.

Modelled estimates from previous studies were summarised for each marine mammal species for which they were available (see overview in Table 4). For New Zealand sea lion, estimates were available from both approaches, the GLMs (Abraham & Berkenbusch 2017) and the spatial risk analysis (Large et al. 2019). The latter analysis was more recent and spanned a longer time period for a key component of the population (i.e., females), but the former predicted captures for both male and females over additional fisheries, so both estimates were included here. All the model estimates included here were generated within a Bayesian framework, using credible intervals to represent uncertainty. The 95% credible interval (95% c.i.) shows the 2.5th and the 97.5th quantiles of the distribution estimated for a given variable.

2.2 Mitigation methods for marine mammal bycatch

Continuing efforts to reduce the likelihood and impacts from incidental captures of marine mammals have led to a number of reviews of bycatch mitigation measures in New Zealand and overseas. In New Zealand, these reviews have focused on assessing

Table 4: Summary information of the most recent model estimates of captures for New Zealand marine mammals by fishing gear, including the time period of the estimates.

Species	Main gear(s)	Period	Reference
Common dolphin.	Other trawl fisheries.	1995–96 to 2014–15.	Abraham and Berkenbusch (2017).
Common dolphin.	Jack mackerel. (North Island west coast).	1995–96 to 2017–18.	Abraham et al. (2021).
Hector's and Māui dolphins.	Set net and inshore trawl.	1992–93 to 2016–17.	Roberts et al. (2019).
NZ sea lion.	Trawl (Auckland Islands population only).	1992–93 to 2016–17.	Large et al. (2019).
NZ sea lion.	Trawl.	1995–96 to 2017–15.	Abraham and Berkenbusch (2017).
NZ fur seal.	Trawl and surface longline.	1995–96 to 2017–18.	Abraham et al. (2021).

mitigation measures for marine mammals across different fisheries (Rowe 2007), and specifically for pot, trap and set-net fisheries (Childerhouse et al. 2013, Laverick et al. 2017). Internationally, relevant studies have considered bycatch mitigation measures for specific marine mammal-fishery interactions (e.g., common dolphin in the South Australian sardine purse-seine fishery, Hamer et al. 2008), and for reducing cetacean bycatch across different global fisheries (Leaper & Calderan 2018). A recent expert workshop held by the Food and Agriculture Organisation of the United Nations (FAO) assessed technical mitigation methods for a diverse range of marine mammals and fisheries, resulting in a detailed summary with an evaluation of their effectiveness (FAO 2018). Another recent comprehensive review of global bycatch mitigation for marine mammals also considered aspects pertaining to the application, effectiveness and potential costs of technical mitigation methods (Hamilton & Baker 2019).

These existing reviews formed the basis for the present study, with literature and data searches focusing on subsequent information that was not included in previous reviews. The present collation of information was aimed at technical measures and methods that may be applicable to New Zealand fisheries and marine mammal species resident in this region. Comprehensive assessments of a wide range of mitigation measures, including applications and trials that show little effectiveness are documented in previous reviews.

The literature search included primary and "grey" literature, scientific reports, conference and workshop proceedings and mitigation protocols. The emphasis of this data sourcing was on technical mitigation methods for different marine mammal species and fisheries, including operational characteristics and marine mammal bycatch mitigation devices. Mitigation through spatial and temporal closures or through systematic changes in fishing gear (e.g., switching from set netting to trawling) or fishing effort was not considered.

The search of information used internet search engines, such as Google and Google Scholar, and also focused on specific websites and organisations that provide relevant information, such as the Australian Fisheries Management Authority (https://www.afma.gov.au/sustainability-environment/bycatch-discarding/bycatch-reduction-devices) and workshop proceedings that include mitigation information (FAO 2018). The search was extended to relevant databases, such as the PSC database for New Zealand (https://psc.dragonfly.co.nz), and the international Bycatch Reduction Techniques Database (see www.bycatch.org).

Search terms included keywords that were used individually and in various combinations, such as "mammal mitigation fish*", "bycatch reduction", and included species (common and scientific) names of New Zealand pinnipeds and cetaceans.

Aspects considered in the present synthesis of information included the efficacy of mitigation measures in reducing marine mammal bycatch, impacts on fishing operations and efficiencies, limitations of measures and also of studies and trials testing them. These aspects were evaluated in a New Zealand context, focused on species and fisheries identified in the current characterisation of marine mammal interactions with fisheries.

3. RESULTS

3.1 Marine mammal interactions in New Zealand fisheries

The present analysis summarised observed captures of all marine mammal species, and then focused on species for which captures were significant or additional information was available; these species were common dolphin, Hector's and Māui dolphins, New Zealand sea lion and New Zealand fur seal.

3.1.1 Summary of bycatch trends across species

Observer coverage (defined as the proportion of effort when an observer was present on a vessel) varied across gears and over time (Figure 1, and see Appendix B, Figures B-1 to B-5 for individual target fisheries). Overall, observer coverage was low throughout the reporting period, and did generally not exceed 25% for most of the gears. Marked exceptions were jack mackerel trawl and southern blue whiting trawl, which both had particularly high observer coverage in recent years (i.e., 100% for the latter trawl fishery). Across individual fishing gears other than trawl, observer coverage was particularly low in set nets, where it varied between no coverage for most years and less than 5% of all effort in recent years. In comparison, surface longline had the highest average observer coverage at around 20%.

Although observer coverage was generally low for each gear type, it varied across target fisheries (Appendix B). For trawl gear, overall observer coverage was about 10%, but it was higher in some target fisheries in recent years (Figure B-1). The latter fisheries included hake, jack mackerel, squid and southern blue whiting targets, where at least 75% of all tows were observed in recent years; in the southern blue whiting target fishery, observer coverage was 100% in the six most recent fishing years. At the same time, observer coverage in inshore trawls and flatfish target trawls was particularly low throughout the reporting period, with average rates not exceeding 2% for either fisheries. These two fisheries combined made up 43.8% of the total effort by trawl fisheries since 1992–93; in comparison, hake, mackerel, squid and southern blue whiting target fisheries combined made up 11.4% of the total effort over the same period.

For surface-longline gear, observer coverage was generally low for most target species (about 5% of hooks), except for southern bluefin tuna (Figure B-2). For this key target fishery, observer coverage was about 40% for most of the time span of the observer programme, but it declined to below 20% in recent years (2016 to 2018). The other key target fishery for this gear, bigeye tuna, had low observer coverage throughout the study period, averaging at about 3% of all hooks.

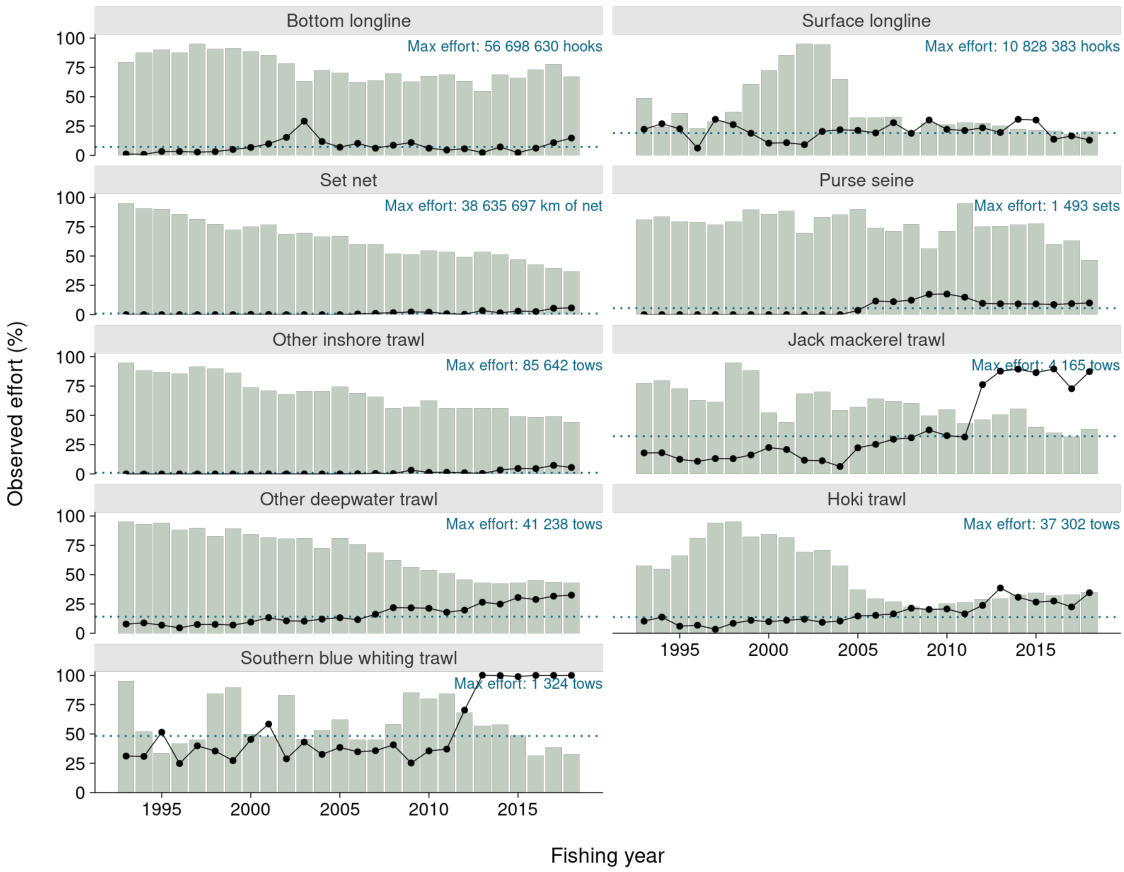

Figure 1: Fishing effort (green bars) and observer coverage (black circles and line) for the main fishing gears operating in New Zealand waters, for the period between 1992–93 and 2017–18. Other inshore trawl included gear operated by inshore and flatfish fisheries. Other deepwater trawl included gear operated by deepwater, middle depth, scampi, and squid fisheries. Observer coverage was calculated as the percentage of effort when an observer was present to total effort. Effort measures were hook number for bottom and surface longline, sets for purse seine, metres of net for set net, and number of tows for trawl. Blue dotted line indicates the average observer coverage over the period shown.

Overall observer coverage was also low (5% or less) for bottom longline, except for sets targeting ling (Figure B-3). Ling targets were the main bottom-longline fishery in terms of effort, and the corresponding observer coverage was variable across years, with an average of about 12% of sets. The highest observer coverage in the ling target fishery was in 2003–03, at about 56% of hooks, and this increase was reflected in the overall trend in observer coverage for this gear type.

For set nets, observer coverage was consistently low, varying between no coverage for most years, and increasing to less than 5% of all effort in recent years. Most of the set-net fishing effort was focused on rig and shark species, followed by minor species (Figure B-4). Observer coverage in rig and shark target fisheries showed similar trends, with an average value below 5% of net length (m) observed, but with small increases in recent years. Observer coverage for both of these target fisheries was about 10% in 2017–18.

Observer effort in purse-seine target fisheries was highest for the main target fishery, skipjack tuna, where coverage was about 20% of sets (Figure B-5). For the second largest purse-seine target fishery, mackerel, observer coverage was consistently low, with marked decreases since the late 2000s. Recent observer coverage in the purse-seine mackerel fishery was below 2%.

Considering observed captures across gear over the entire study period, trawl fisheries had the highest number of observed captures when aggregated by species and gear, followed by surface longline (Table 5). Post-capture survival (whether an individual was alive upon release) was highest for surface-longline fisheries, with almost all caught individuals recorded as alive when captured. The lowest post-capture survival was in trawl fisheries, where almost all caught individuals were recorded as dead. Although other gears, like set net and bottom longline, had higher post-capture survival than trawl fisheries, the majority of individuals was dead before being returned to sea.

New Zealand fur seal featured the most frequently in observer records, particularly in trawl, followed by surface longline (Table 5). In both gear types, observers recorded a number of multiple capture events. Mortalities of New Zealand fur seal were high in trawl fishing, with only 10% of captures being live releases. In comparison, the majority (94.4%) of observed captures in surface-longline fisheries were live releases. New Zealand sea lion was almost exclusively caught in trawl, with only one observed capture in another gear, in surface longline. There were few (three) observed leopard seal captures, and all occurred in trawl fisheries. Post-capture survival was low for all pinnipeds caught by trawl gear.

Observed captures of cetaceans were dominated by common dolphin, predominantly in trawl, with notably lower numbers of observed captures in set net and other gear types. Dusky dolphin was the second most commonly observed dolphin species with 21 captures overall across multiple gears. Hector's dolphin captures were only observed in set nets with the exception of one capture in trawl gear. There were 17 captures overall, most of them in single-capture events; three of the observed captures of Hector's dolphin were individuals that were captured alive. Other captures of toothed whales were observed infrequently, with seven captures of bottlenose dolphin and two captures of killer whale.

Table 5: Total observed marine mammal captures for the period of the fisheries observer programme from 1992–93 and 2017–18. Included are the number of observed fishing events with captures, the number of captures, and the percentage of captures that were released alive, for each taxon and fishing method.

Method	Species	Capture events	Captures	
			No.	Live (%)
Bottom longline	New Zealand fur seal	5	5	20.0
	Long-finned pilot whale	3	3	33.3
Purse seine	New Zealand fur seal	1	1	0.0
Set net	New Zealand fur seal	52	58	5.3
	Hector's dolphin	13	16	18.8
	Dusky dolphin	7	7	0.0
	Common dolphin	6	6	0.0
	Long-finned pilot whale	1	1	100.0
Surface longline	New Zealand fur seal	677	840	94.4
	Bottlenose dolphin	4	4	100.0
	Common dolphin	4	4	75.0
	Long-finned pilot whale	3	3	100.0
	Dusky dolphin	2	2	100.0
	Humpback whale	1	1	100.0
	Unidentified dolphin or toothed whale	1	1	100.0
	New Zealand sea lion	1	1	100.0
	Killer whale	1	1	100.0
Trawl	New Zealand fur seal	2 527	3 582	10.0
	New Zealand sea lion	310	349	8.0
	Common dolphin	114	253	0.8
	Long-finned pilot whale	7	27	0.0
	Dusky dolphin	11	12	0.0
	Leopard seal	3	3	0.0
	Bottlenose dolphin	3	3	0.0
	Elephant seal	1	1	0.0
	Unidentified seal or sea lion	1	1	0.0
	Killer whale	1	1	0.0
	Hector's dolphin	1	1	0.0

Observed captures of long-finned pilot whale were in four different gear types, trawl, surface longline, bottom longline and set net. There was also a single capture of a humpback whale in surface-longline fisheries, which was released alive.

In addition to observer records, capture information of marine mammals in different gear types was also available from fisher-reported data (Table 6). Since October 2008, fishers have been able to report captures of marine mammals on the NFPSCR form. Although reporting rates are unknown, these data provide some information about the species captured in the different fisheries for the period between 2008–09 and 2017–18.

When aggregating all fisher-reported captures by species and gear over this period, the patterns were similar to the observer records. That is, trawl fisheries had the highest number of reported captures, followed by surface longline. New Zealand fur seal was also prominent in fisher-reported captures, with the highest number of reported captures in trawl, followed by surface longline and set net. In addition, the diversity of species was higher in fisher records compared with observer data. For example, the former data source included a killer whale capture in pot gear. Furthermore, fisher-reported captures also included gears with no or low observer coverage, such as lobster pot and troll.

The spatial distribution of observer records showed that marine mammals captures were observed in commercial fisheries throughout New Zealand's EEZ (Figure 2). Most species were caught in a specific area, except for New Zealand fur seal, which was caught in most regions. Observed common dolphin captures were mostly on the west and south coasts of North Island. In comparison, observed captures of dusky and Hector's dolphins were on the South Island east coast. There were few observed captures of long-finned pilot whale, with most capture records of this species on the North Island west coast. All observed captures of New Zealand sea lion were in southern waters, south of South Island, particularly in subantarctic fisheries around the Auckland and Campbell island groups.

For key gears with observed marine mammal captures (trawl, surface longline and set net), the distribution of observations matched the combined distributions of fishing effort and observer coverage (Figure 3). For set net, fishing effort south of South Island was low, but rates of observer coverage were higher than in other regions, resulting in higher numbers of observed New Zealand fur seal captures. Observer coverage was also comparatively high around Canterbury Bight, and all observed captures of Hector's dolphin occurred in this region.

For surface longline, the two key fishing grounds for southern bluefin tuna had different levels of observer coverage, with the fishing ground off Fiordland having considerably higher coverage than the North Island fishing ground. Observer coverage in surface-longline fishing was particularly low around Bay of Plenty and north towards Northland, while there was relatively high surface-longline effort in this region. Observed captures of New Zealand fur seal were in both of these fishing grounds, but not in other areas, although low observer coverage in these other areas reduced the probability of observing a capture.

Table 6: Fisher-reported marine mammal captures for the period between 2008–09 and 2017–18, reported on the Non-fish/Protected Species Catch Return form (NFPSCR; introduced in October 2008) and from electronic reporting (introduced in the 2017–18 fishing year). Included are the number of fishing events with captures, the number of captures, and the percentage of individuals that were captured alive, for each taxon and fishing method. Precision harvest for trawl gear refers to vessels fishing with Precision Seafood Harvest gear.

Method	Species	Capture events	Captures	
			No.	Live (%)
Bottom longline	Common dolphin	4	4	75.0
	New Zealand fur seal	3	3	33.3
	Unidentified pinniped	1	1	0.0
Lobster pot	Killer whale	1	1	0.0
Purse seine	Common dolphin	7	38	52.6
Set net	New Zealand fur seal	115	122	4.1
	Common dolphin	22	22	0.0
	Hector's dolphin	12	16	6.2
	Dusky dolphin	11	15	40.0
	Unidentified pinniped	8	8	0.0
	Unidentified dolphin or toothed whale	3	3	0.0
	Humpback whale	1	1	100.0
	Unidentified baleen whale	1	1	100.0
Surface longline	New Zealand fur seal	272	346	92.5
	Unidentified pinniped	63	103	83.5
	Common dolphin	6	6	66.7
	Bottlenose dolphin	4	4	100.0
	Unidentified dolphin or toothed whale	3	3	100.0
	Long-finned pilot whale	3	3	100.0
	Minke whale	2	2	100.0
	Beaked whales	1	1	100.0
	Humpback whale	1	1	100.0
	Killer whale	1	1	100.0
Trawl	New Zealand fur seal	1 615	2 026	13.5
	Common dolphin	95	161	2.5
	New Zealand sea lion	66	79	16.5
	Unidentified pinniped	55	64	20.3
	Bottlenose dolphin	9	9	0.0
	Long-finned pilot whale	4	8	0.0
	Dusky dolphin	4	6	0.0
	Unidentified dolphin or toothed whale	6	6	0.0
	Leopard seal	3	3	33.3
	Unidentified dolphin	3	3	0.0
	Elephant seal	2	2	0.0
	Hector's dolphin	1	1	0.0
Trawl (precision harvest)	New Zealand fur seal	15	15	0.0
	Common dolphin	4	5	0.0
	Unidentified pinniped	2	2	0.0
	Bottlenose dolphin	1	1	0.0
Troll	New Zealand fur seal	1	1	100.0

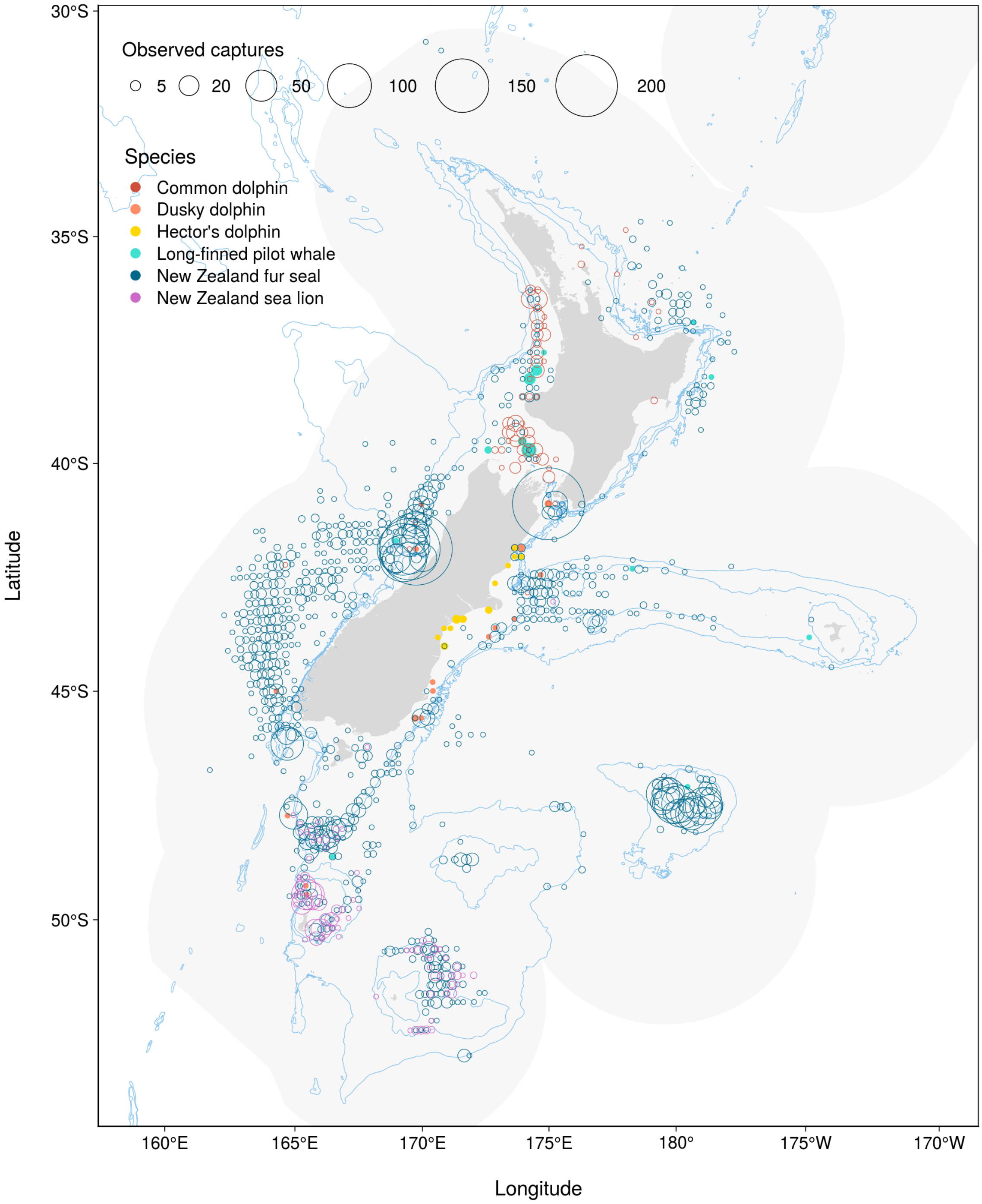

Figure 2: Observed captures of marine mammal species with at least eight captures in the study period between 2002–03 and 2017–18 in New Zealand's Exlusive Economic Zone (grey shading). Captures were aggregated into 0.2 - degree cells (but were not standardised by observer effort), with the size of the circles indicating the number of observed captures. Species with more than 50 captures by cell are shown with open circles to avoid obscuring other data. Bathymetry contours show 200, 500 and 1000 m water depth.

Observed captures in trawl fisheries were distributed throughout New Zealand's EEZ, with different capture "hotspots" depending on the marine mammal species. For common dolphin, there was a distinct area of high captures corresponding with the mackerel target fishery off the North Island west coast. For New Zealand sea lion, observed captures were high in subantarctic waters, corresponding with the squid and southern blue whiting target fisheries in this region. High numbers of observed captures of New Zealand fur seal were evident in the wider Cook Strait region, off the central South Island west coast and in waters around Bounty Islands. Other species with observed captures in trawl fisheries included long-finned pilot whale on the North Island west coast.

Observer coverage in trawl fisheries was heterogeneous, with high coverage around the Auckland and Campbell island groups, Bounty Islands and Chatham islands, and, in North island, around the North and South Taranaki bights (Figure 3). In comparison, observer coverage in trawl fisheries was low in most inshore areas, including areas where trawl effort was high.

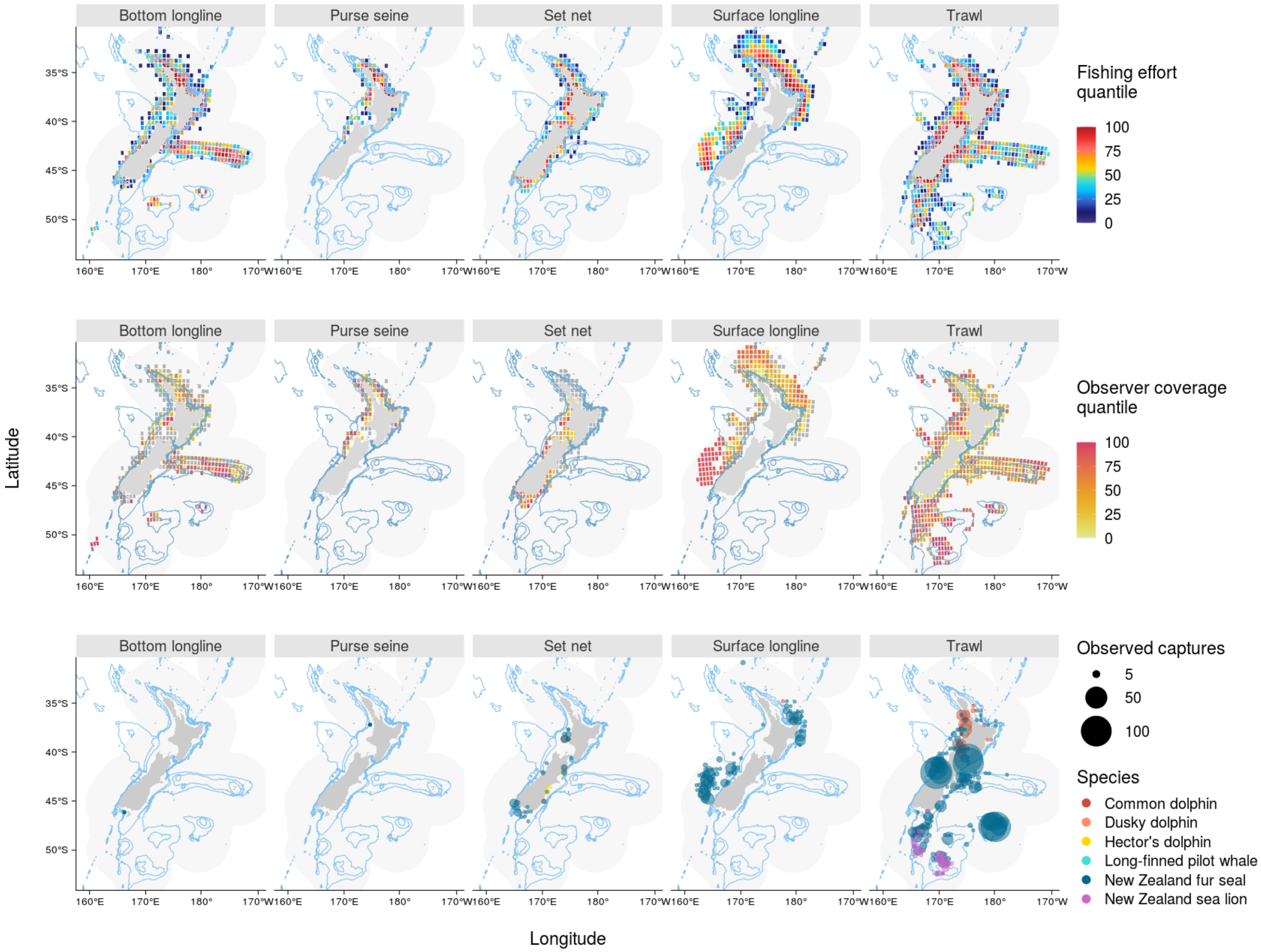

Figure 3: See caption next page.

Figure 3: Top: Distribution of fishing effort by main gear type (by 0.5 degree cell), from 2007–08 to 2017–18, the period for which effort coordinates were consistently recorded across all gears. The quantile indicates the relative value of total effort in a cell compared with all cells for that gear. Cells with effort from less than three vessels were excluded. Middle: Observer coverage by gear and 0.5 degree cell from 2007–08 to 2017–18, where the unit of effort was hook for bottom and surface longline, set for purse seine, net length for set net, and tow for trawl. Cells in grey did not have observer records over the period. Bottom: Observed captures by gear for marine mammal species over the study period between 2007–08 and 2017–18. Captures were aggregated into 0.5-degree cells, with the colour of each circle representing different species, and the size of the circle the magnitude of the observed captures in this location. (Note that captures were not standardised by observer effort.) For all panels, New Zealand's Economic Exclusive Zone is highlighted in grey, with bathymetry contours for 200, 500 and 1000 m water depth shown in blue.

3.1.2 Common dolphin

Most observed captures of common dolphin occurred in trawl fisheries, with few captures in set net and surface longline (Figures 4 and 5; data for surface longline not shown). Observed common dolphin captures in trawl were largely in the jack mackerel target fishery off the North Island west coast. Observed captures of this species in trawl fisheries varied over time, with a peak of 30 observed captures in 2013–14, corresponding with 0.23 individuals per one hundred tows; the corresponding observer coverage was 15.6% in this fishing year. Since then, there has been a notable decline in the number of observed common dolphin captures, mainly determined by the lower number of observed captures in the jack mackerel trawl fishery: there were nine observed common dolphin captures in all trawl fisheries in the three most recent fishing years, and only two of these captures were in the jack mackerel target fishery (despite high rates of observer coverage; Figure B-1). This decrease in observed common dolphin captures was also evident in the low capture rates since the late 2000s for most trawl targets, although some of these fisheries (e.g., middle-depth trawl) had little observer coverage. In 2016–17 and 2017–18, all observed captures of common dolphin were in inshore trawl fisheries.

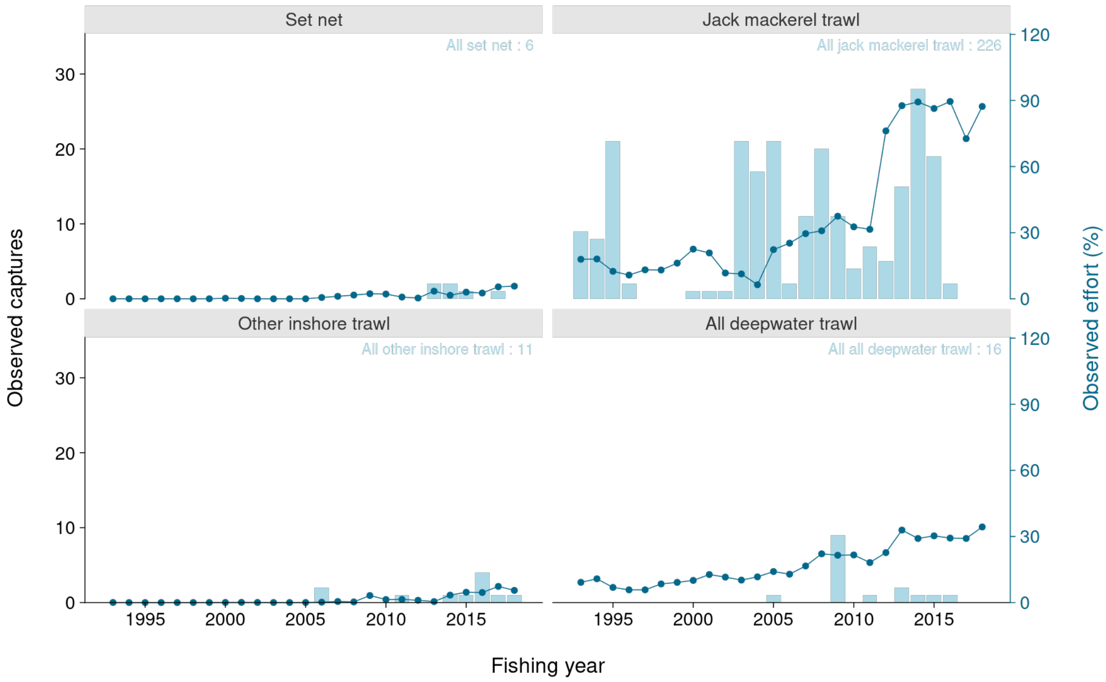

Figure 4: Number of observed captures (bars) of common dolphin in set-net and trawl fisheries, for the period between 1992–93 and 2017–18. Total number of captures are indicated in the top-right corner of each graph (only gear with at least five captures is shown). Other inshore fisheries included captures in inshore and flatfish fisheries. Observer coverage rate (blue points and line) for each fishing gear is the percentage of effort when an observer was present, with the effort measured as metres net length for set net, and number of tows for trawl. The observer coverage rate was calculated for all target fisheries using the gear.

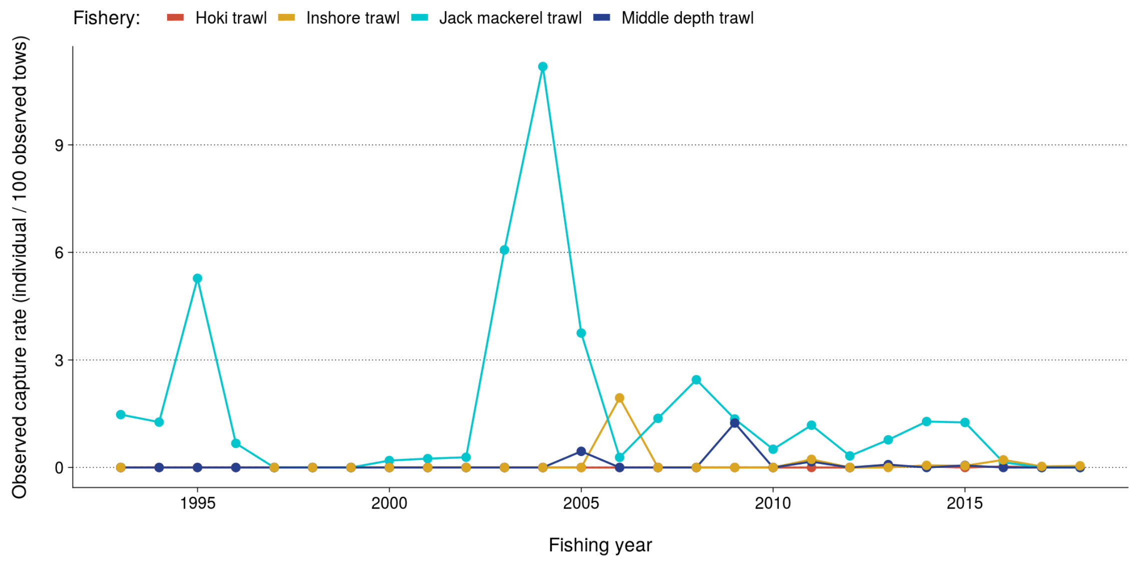

Figure 5: Observed capture rates of common dolphin in trawl, by target fishery, for the period between 1992–93 and 2017–18. Capture rates are individuals per 100 tows. Observations not occurring in consecutive years are connected by a dotted line.

Modelled bycatch estimates predicting capture rates over both observed and unobserved tows up to 2014–15 indicated a decrease in common dolphin captures in all trawl fisheries over time, and a marked decline in the jack mackerel fishery (Figure 6). The estimated capture rate was at least five times higher in the large-vessel jack mackerel fishery than in other trawl fisheries; however, because fishing effort was lower, other trawl fisheries continued to account for a high proportion of estimated common dolphin captures. This finding was in contrast to trends from the observer data alone. The initially high number of 271 (95% c.i.: 146–440) estimated captures in all trawl in 2002–03 decreased to 104 (95% c.i.: 50–190) estimated captures in 2014–15 (Figure 6). In part, this decline corresponded with a reduction in trawl fishing effort. Because observer coverage in the other trawl fisheries was considerably lower than for the jack mackerel trawl fishery, the uncertainty in the annual capture estimates was high. For the last year of the model period for combined trawl estimates (2014–15), the total number of captures was estimated to be 22 (mean; 95% c.i.: 20–29) in the jack mackerel trawl fishery, and 104 (mean; 95% c.i.: 50–189) in other trawl fisheries. The model for the jack mackerel fishery extended to the 2017–18 fishing year; for this last year of the assessment, the estimated captures were zero (mean; 95% c.i.: 0–4), compared with 130 (mean; 95% c.i.: 57–237) estimated captures in the 2002–03 fishing year.

3.1.3 Hector's and Māui dolphins

Hector's and Māui dolphins had relatively low capture rates compared with other marine mammal species in New Zealand.Observer effort for this species includes a DOC programme that took place in 1997–98, in addition to records from Fisheries New Zealand (Starr & Langley 2000). There were 17 observed Hector's dolphin captures between 1992–93 and 2017–18, and one fisher-reported capture (in trawl fisheries). There were no observer records of Māui dolphin captures.

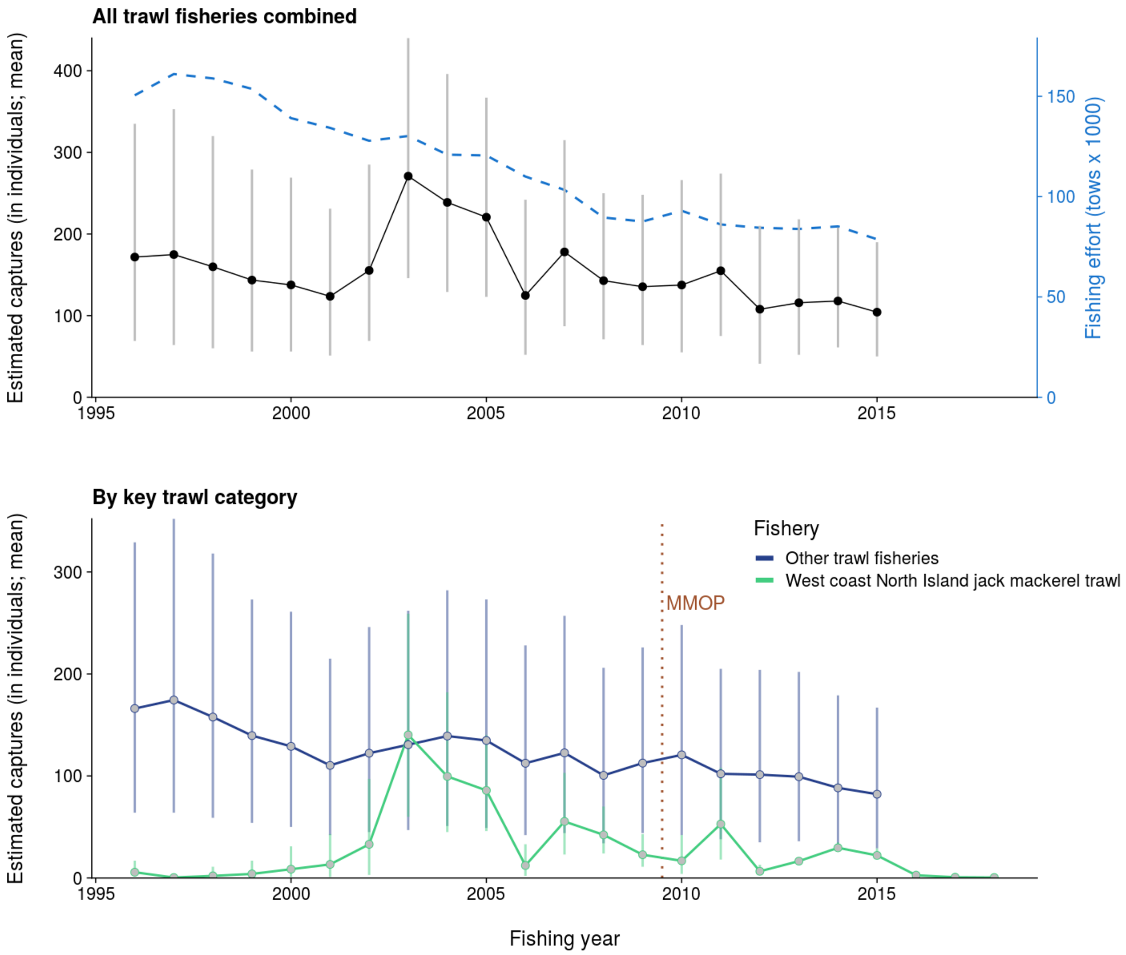

Figure 6: Top: Estimated annual captures of common dolphin for all trawl fisheries and fishing effort (number of tows; dashed blue line) between 1995–96 and 2014–15. Capture estimates were based on models of observed captures for other trawl fisheries (Abraham & Berkenbusch 2017) and for the West Coast North Island jack mackerel trawl fishery (Abraham et al. 2021), respectively. Black dots indicate the mean model prediction, grey bars span the 95% credible interval for the annual predictions. Bottom: Estimated annual captures of common dolphin for trawl fisheries targeting jack mackerel on the North Island west coast (green) and other target fisheries (blue) between 1995–96 and 2014–15 (for other trawl fisheries) or 2017–18. Estimates were based on separate models of observed captures for these two target categories (Abraham & Berkenbusch 2017, Abraham et al. 2021). Grey dots indicate the mean model prediction, vertical bars span the 95% credible interval for the annual predictions. For both graphs, the dotted vertical line indicates the introduction of Marine Mammal Operational Procedures (MMOP) by the industry body (Deepwater Group 2018).

There were 16 observed Hector's dolphin captures in set-net fisheries, and these sets were predominantly in the shark target fishery (Figure 7). The first observed captures were in 1997–98 as part of the observer programme conducted by DOC in the Pegasus Bay and Canterbury Bight areas. There was no clear trend in capture rates given the small number of years (seven) when captures were observed with long periods of time without observed captures (Figure 8). Average observed capture rates in shark set-net fisheries were low overall, with an average of 1.8 individuals per thousand km of nets observed since the first year this fishery had observer coverage (i.e., 1998–99) (not accounting for the one-year observer programme led by DOC; Starr & Langley 2000).

Although observer coverage in set-net fleets has increased over time, it remained low at about 4.5% of effort observed in the last three years (overall set-net fisheries).

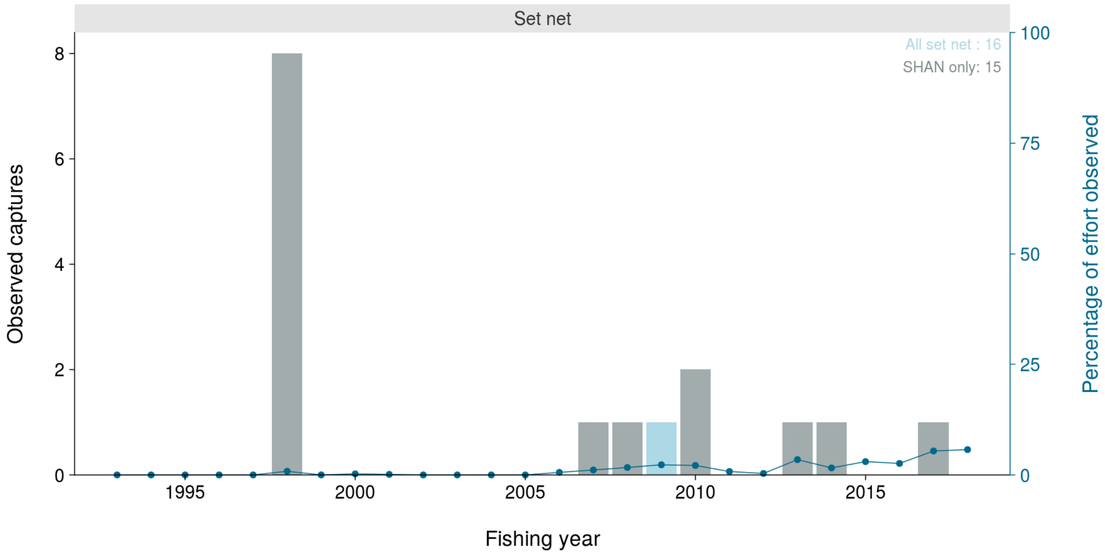

Figure 7: Number of observed captures of Hector's dolphin in set-net fisheries between 1992–93 and 2017–18. Total number of captures is indicated in the top-right corner. Observed captures in set-net fisheries include shark targets (SHAN; dark grey). Observer coverage rate is shown in blue as the percentage of effort when an observer was present, with the effort measured as metres net length. The observer coverage rate was calculated for all target fisheries using the gear. Records include both observations by Fisheries New Zealand observers and the one-year programme led by Department of Conservation in 1997–98 (see Starr & Langley 2000).

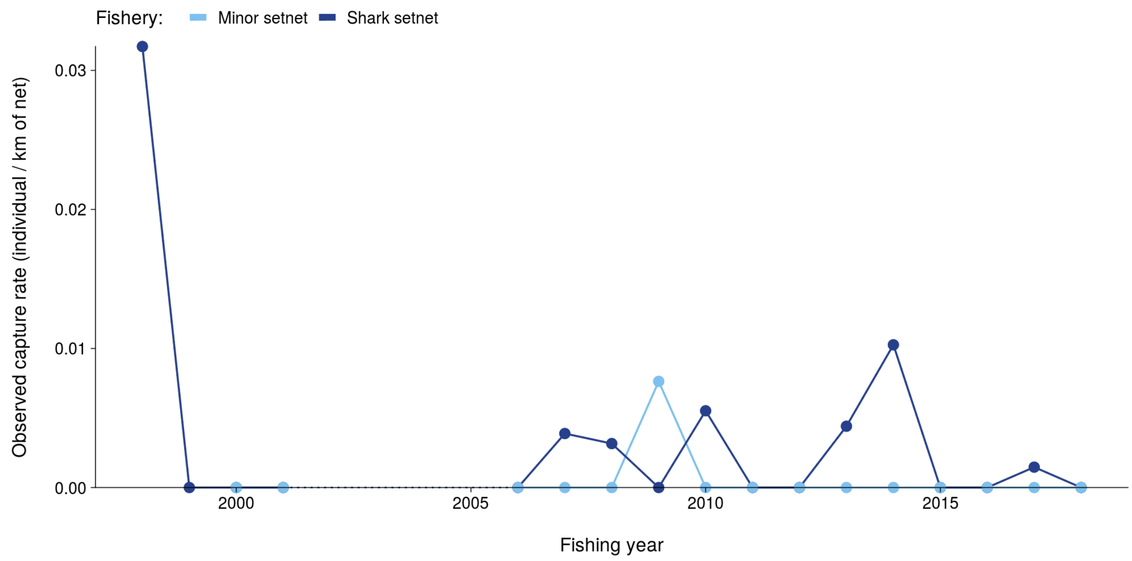

Figure 8: Observed capture rates of Hector's dolphin in set nets, by target fishery, for the period between between 1997–98 and 2017–18. Capture rates are individuals per kilometre of net. Observations not occurring in consecutive years are connected by a dotted line. Records include both observations by Fisheries New Zealand observers and the one-year programme led by Department of Conservation in 1997–98 (see Starr & Langley 2000).

Given the paucity of observer data, modelled estimates of total fisheries captures would be difficult to obtain based on observer data only, and would have high uncertainty. A recent spatial risk assessment for Hector's and Māui dolphins estimated annual deaths from fishing for each population from 1992–93 to 2016–17 (Roberts et al. 2019). This risk assessment presents the most comprehensive estimate of fleet-wide mortalities. Annual mortalities were estimated based on overlap in predicted densities from habitat modelling, the distribution of fishing effort for set-net and inshore trawl fisheries, assumptions about cryptic mortality, and the vulnerability of individuals to each fishing gear. The predictions of annual deaths for Māui dolphin were less than one individual per year, and this low number prevented an analysis of temporal trends.

For the Hector's dolphin subspecies, estimated annual mortalities were predicted to be higher in set net than in inshore trawl fisheries; they varied between 39 and 70 individuals for set net compared with 14 to 41 individuals for inshore trawl (mean prediction) (Figure 9). For both gears, annual mortalities declined over time, partly corresponding with a decrease in fishing effort and also a reduction in spatial overlap between fishing effort and the Hector's dolphin population (Roberts et al. 2019). In the three most recent years of the study period, the number of estimated annual mortalities averaged about 45 individuals for set net and 14 individuals for inshore trawl.

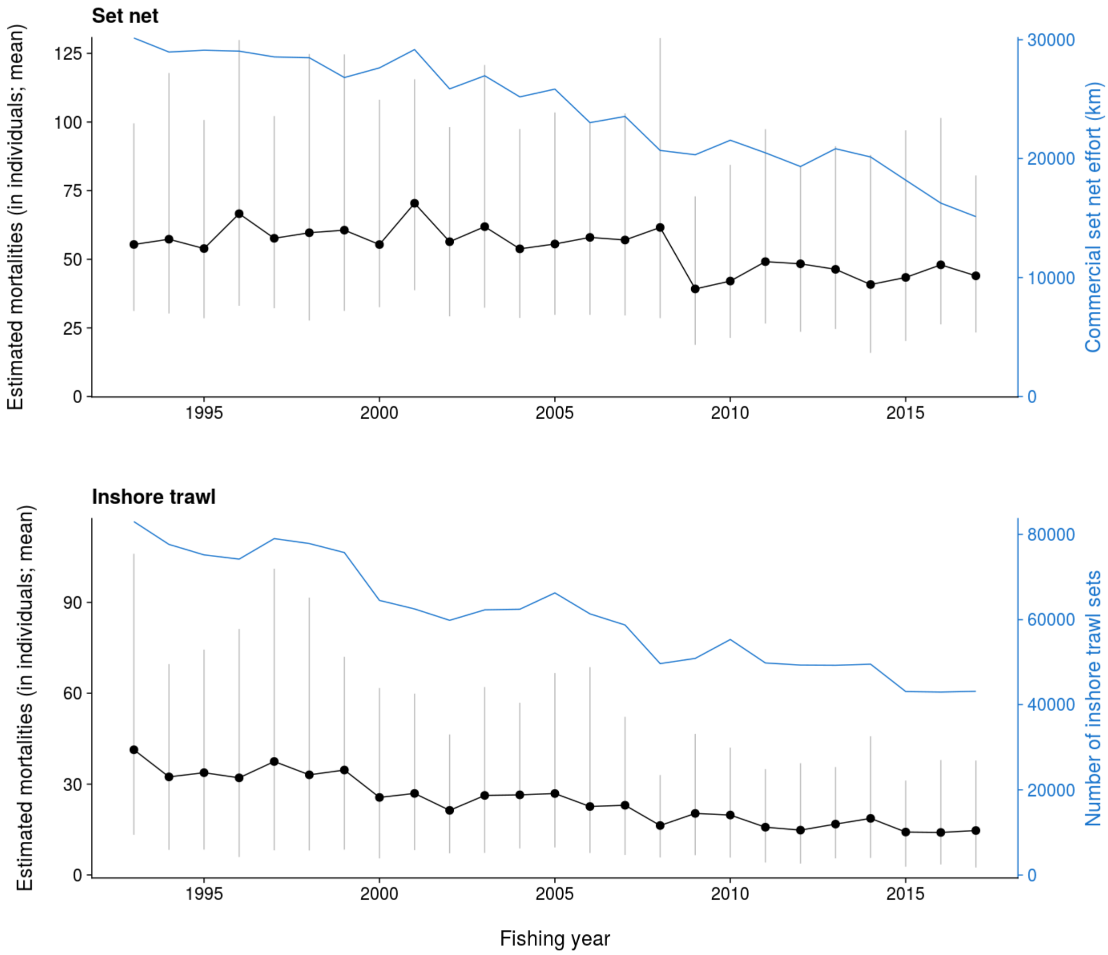

Figure 9: Estimated annual deaths of Hector's dolphin for set - net and inshore trawl fisheries between 1992–93 and 2016–17, based on a spatial risk assessment for this species (Roberts et al. 2019). Black dots indicate the mean model prediction, grey bars span the 95% credible interval for the annual predictions. Fishing effort used as input to the model is shown in blue. See Roberts et al. (2019) for the definition of spatial areas used to delineate fisheries and derive fishing effort.

3.1.4 New Zealand sea lion

Observed captures of New Zealand sea lion were almost exclusively in trawl fisheries, mainly in the squid and southern blue whiting target fisheries that occur around Auckland and Campbell islands (Figures 10 and 11). Across all trawl, the number of observed New Zealand sea lion captures decreased markedly following a peak in 2000–01. This decrease was mainly due to a decline in captures in squid trawl, following the introduction and subsequent widespread use of sea lion exclusion devices (SLEDs) in this fishery.

In contrast, in the southern blue whiting target fishery, observed capture rates of New Zealand sea lion have increased considerably since 2004–05, although observed captures have been comparatively low in recent fishing years. Since 2013, SLEDs have also been in use in this target fishery, and their use corresponded with lower capture rates documented in recent years.

Modelled estimates of captures were available for the Auckland Islands female population for the period from 1992–93 to 2016–17 (Large et al. 2019). The capture estimates were derived from a spatial risk assessment model accounting for the overlap between fishing effort and population density given foraging range and vulnerability to fishing gear (see also Abraham and Berkenbusch 2017 for a different approach for the period from 1995–96 to 2014–15). The analysis focused on females, because the species is considered to be more sensitive to female mortalities, as New Zealand sea lion are polygamous breeders, and the sex ratio in observed captures has been biased towards females in trawl fisheries (Large et al. 2019). Key trawl fisheries around Auckland Islands

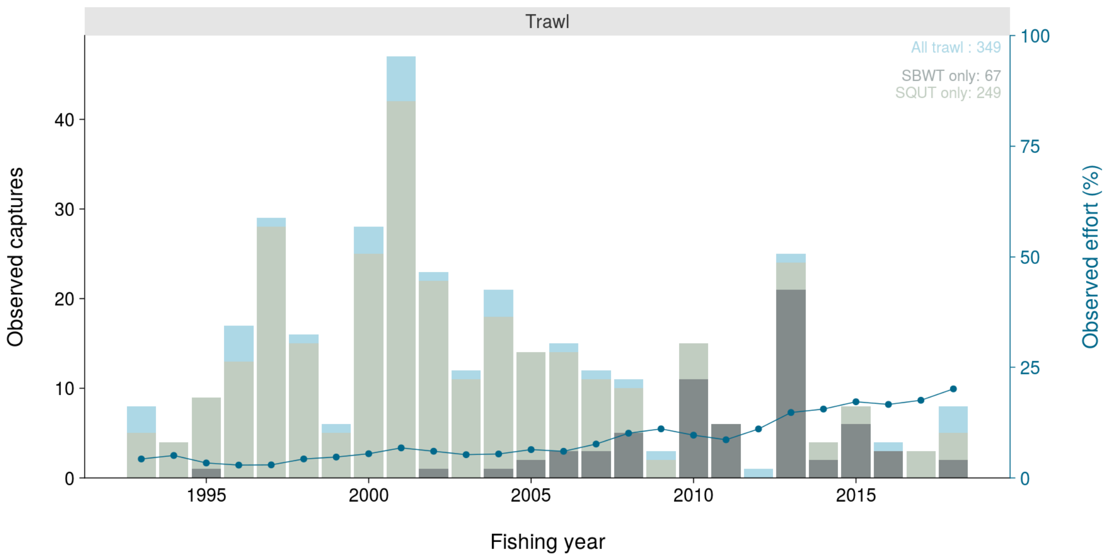

Figure 10: Number of observed captures of New Zealand sea lion in trawl fisheries between 1992–93 and 2017–18. Total number of captures is indicated in the top-right corner. Observed captures in trawl fisheries include southern blue whiting (SBWT; dark grey) and squid (SQUT; light grey) targets. Observer coverage rate is shown with the blue line as the percentage of effort when an observer was present, with the effort measured in number of tows. The observer coverage rate was calculated for all target fisheries using the gear.

target squid and scampi; effort targeting southern blue whiting in this area was low and not included as a dedicated fishery in the study by Large et al. 2019.

Estimated annual female mortalities in all trawl fisheries declined from an initial peak of 96 (95% c.i.: 68–129) females in 1993–94 to relatively low numbers in recent years—mortalities were less than ten females per year for the period from 2011–12 to 2016–17 (Figure 12). In 2016–17, there were predicted to be eight (median; 95% c.i.: 3–16) annual mortalities of females.

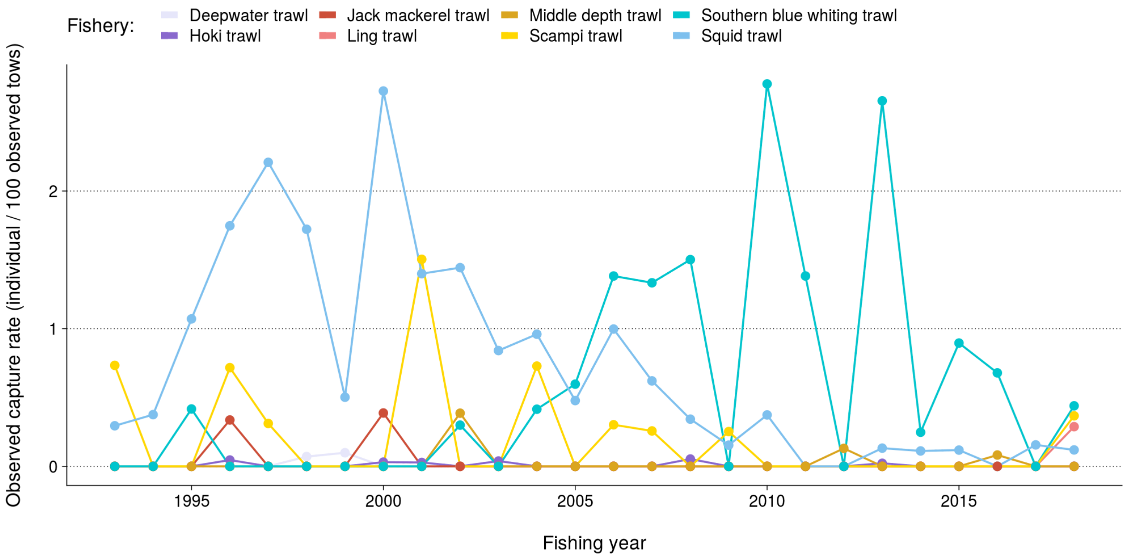

Figure 11: Observed capture rates of New Zealand sea lion in trawl, by target fishery, for the period between 1992–93 and 2017–18. Capture rates are individuals per 100 tows. Observations not occurring in consecutive years are connected by a dotted line.

In this recent risk assessment, the squid trawl fishery was split by depth category (bottom versus midwater trawl) and SLED use (no SLEDs, non-standardised SLEDs during a transition period, standardised SLEDs from 2008–09 onwards) (Figure 12, bottom). The modelled estimates of annual mortalities predicted the highest mortality for tows without SLEDs, compared with almost no mortalities on tows with standardised SLEDs. At the same time, midwater trawls were predicted to have higher annual mortalities than bottom trawl for most years in the study period. In comparison, the scampi target fishery had lower numbers of estimated annual mortalities for most of the assessment period, but had the highest annual mortalities recently, in the period from 2010–11 to 2016–17. The variability in the predicted mortalities also corresponded in part with the fishing effort, with an initially lower number of predicted annual deaths determined by low fishing effort in 1992–93; the overall trends also corresponded with fishing effort until use of standardised SLEDs became widespread in squid trawl fisheries.

Another source of modelled capture estimates for both male and female New Zealand sea lion was also available for trawl fisheries near Auckland Islands targeting squid, the southern blue whiting target fishery near Campbell Islands, and other trawl fisheries (including scampi) operating near Auckland Islands and on the southern end of the Stewart-Snares shelf (Abraham & Berkenbusch 2017). This model predicted capture rates based on observer data from 1995–96 and 2014–15, and was not developed as part of a spatial risk assessment. Based on this approach, the squid trawl fishery was predicted to have the most captures with the highest estimate of 140 (mean; 95% c.i.: 92–208) individuals in 1997 and a steady decline since then (Figure 13). Estimated captures for the last year of the model period (2014–15) were one (mean; 95% c.i.: 1–3) individual.

Captures in the southern blue whiting trawl fishery were considerably more variable over the study period, including in recent years. Estimated captures peaked in 2009–10, with an estimate of 24 (mean; 95% c.i.: 15–37) captures. There was almost complete observer coverage in the three most recent years of the model period (2012–13 to 2014–15), and there were no predicted captures for the unobserved trawl sets; observers recorded six individual captures in 2014–15. The scale of captures was estimated to be the lowest for scampi and other trawl fisheries, with the highest prediction of captures in 2000–2001 with 20 (mean; 95% c.i.: 12–29) individuals, and a consistent subsequent decrease, partly corresponding with a decline in effort. The predicted captures for scampi and other targets in 2014–15 were five (mean; 95% c.i.: 1–10) individuals.

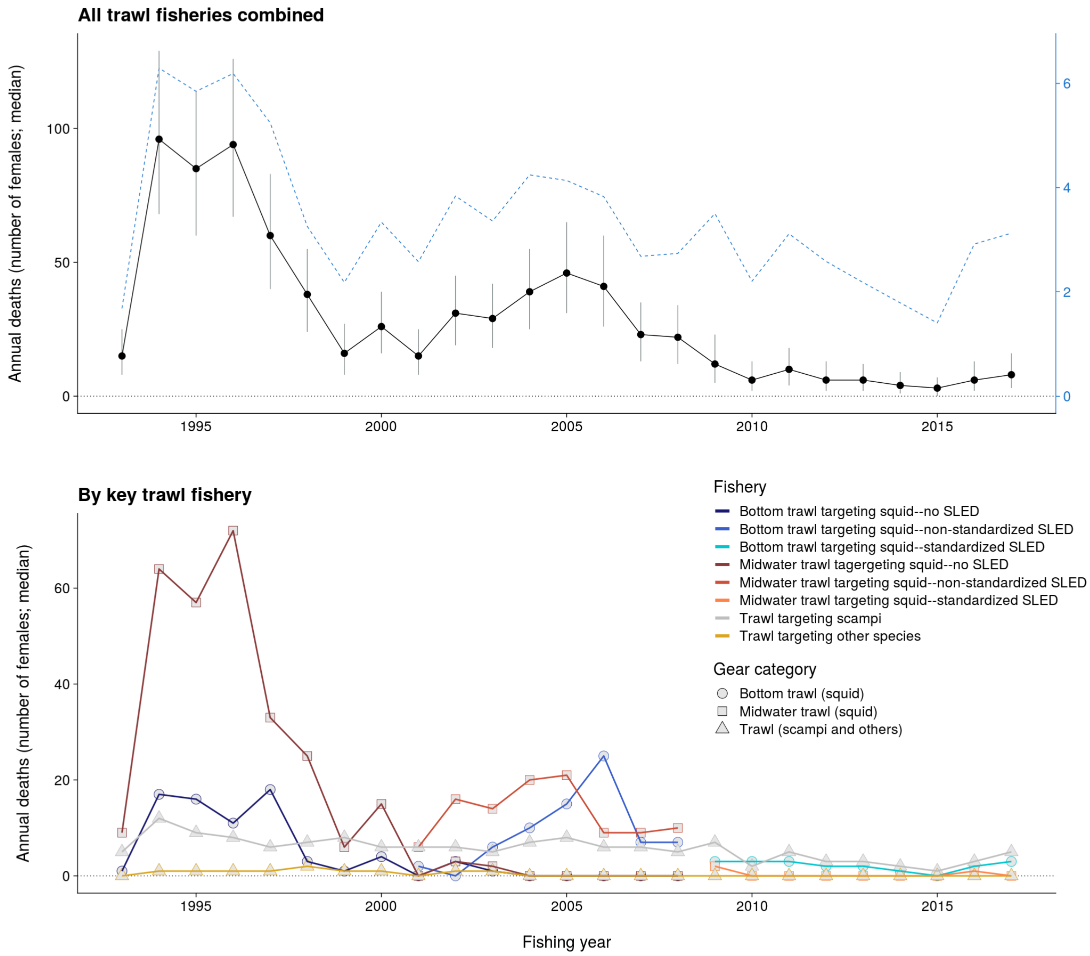

Figure 12: Top: Estimated annual deaths of female New Zealand sea lion for Auckland Islands trawl fisheries between 1992–93 and 2016–17, based on a spatial risk assessment for this species (Large et al. 2019). Blue dots indicate the median model prediction, grey bars span the 95% credible interval for the annual predictions. Fishing effort used as input to the model is shown as a blue dashed line. Bottom: Estimated annual deaths by trawl fishery. Trawl fisheries are distinguished by target fishery and use of Sea Lion Exclusion Devices (SLEDs) in bottom and midwater trawl targeting squid, as defined in the model (none, non-standardised and standardised). Only median model predictions are shown; the 95% credible intervals were omitted for clarity.

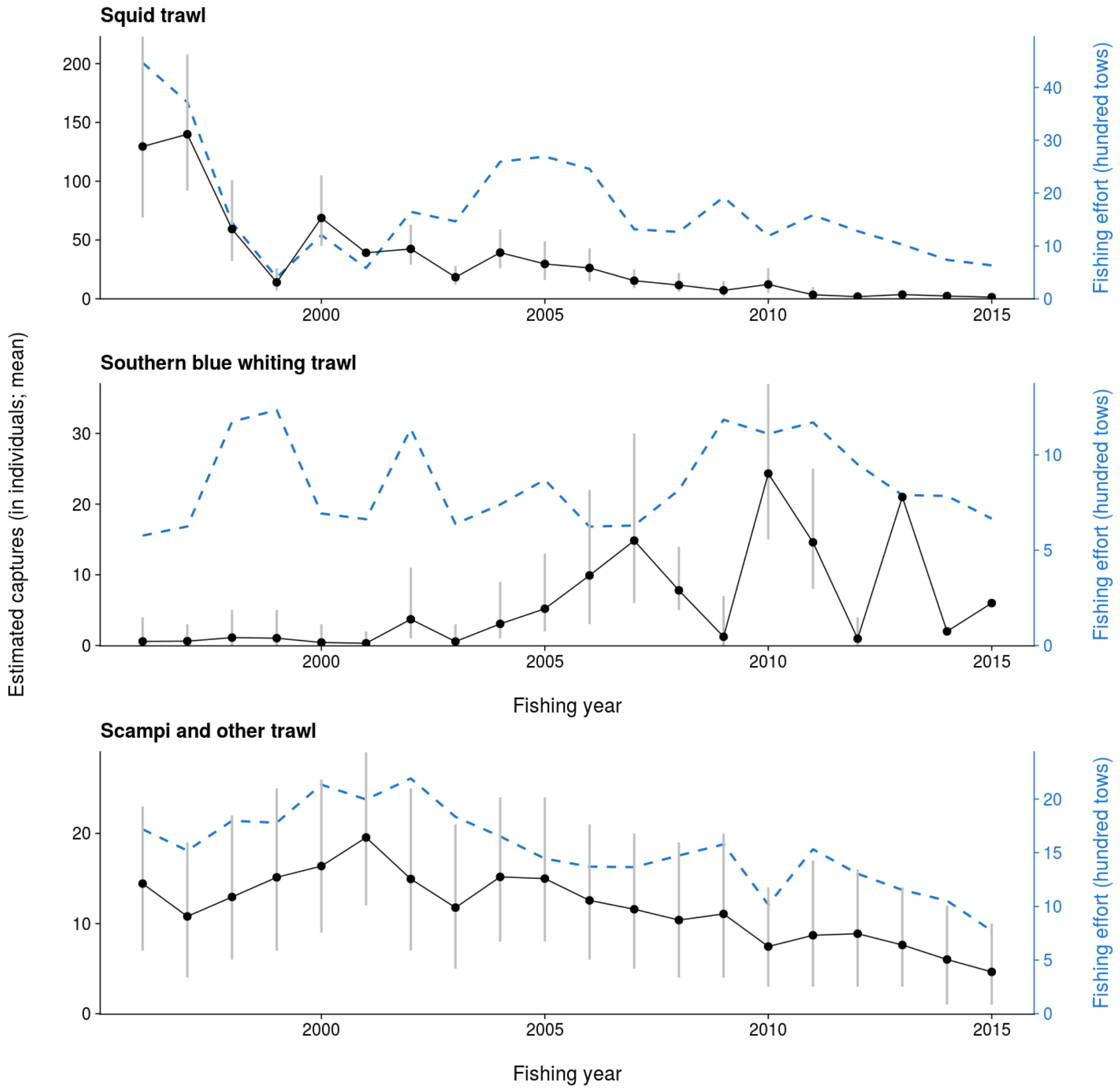

Figure 13: Estimated annual captures of New Zealand sea lion for squid trawl fishery near Auckland Islands (top), southern blue whiting trawl fishery near Campbell Islands, and other trawl fisheries including scampi trawl, between 1995–96 and 2014–15, based on models of observed captures (Abraham & Berkenbusch 2017). Blue dots indicate the mean model prediction, vertical bars span the 95% credible interval for the annual predictions. Fishing effort used as input to the model is shown as blue dashed line.

3.1.5 New Zealand fur seal

New Zealand fur seal is the marine mammal species that featured most frequently in observer records in New Zealand fisheries between 1992–93 and 2017–18. The highest number of observed captures was in trawl fisheries, followed by surface longline (Figure 14). There were fewer observed captures in set net, bottom longline and purse seine.

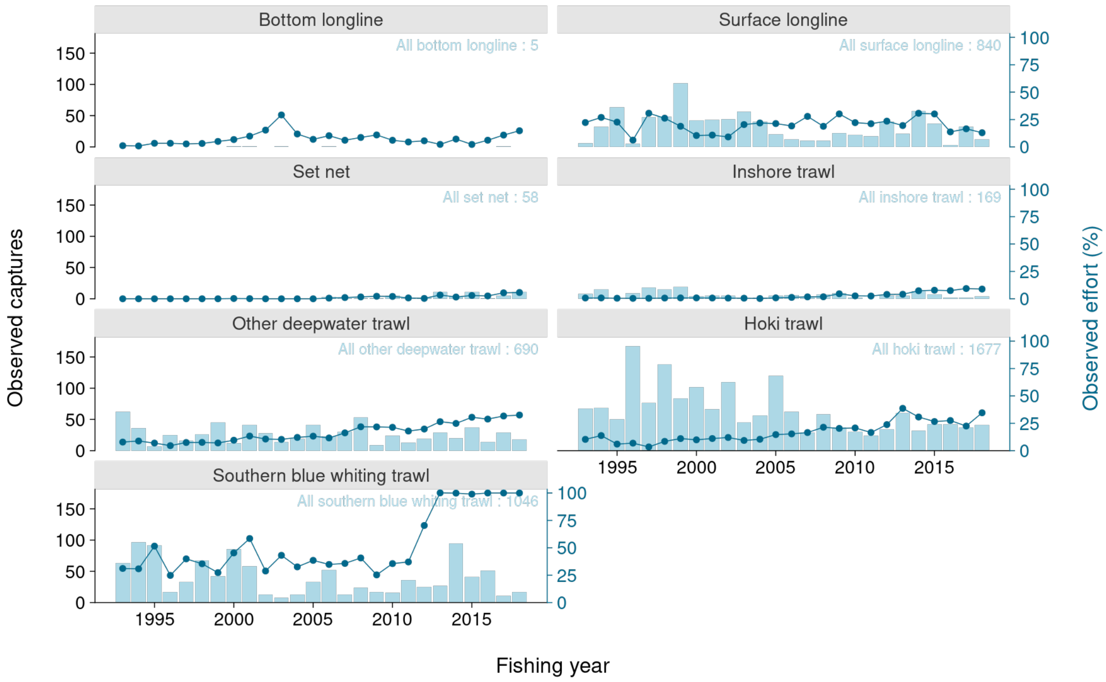

Figure 14: Number of observed captures (bars) of New Zealand fur seal in commercial fisheries between 1992–93 and 2017–18. Total number of captures are indicated in the top-right corner of each graph. Observer coverage rate (blue points and line) for each fishery is the percentage of effort when an observer was present, with the effort measured as number of hooks for bottom and surface longline, sets for purse seine, metres net length for set net, and number of tows for trawl. The observer coverage rate was calculated for all target fisheries using the gear. Other deepwater trawl includes gear operated by deepwater, middle depth, scampi, and squid fisheries.

Within trawl fisheries, observed captures were highest in trawl targeting hoki (Figure 14), whereas observed capture rates were particularly high for the southern blue whiting target fishery (Figure 15). Although capture rates for this fishery declined over time, they remained markedly higher than capture rates of other target fisheries. For surface-longline effort, observed captures were highest for southern bluefin tuna targets. For all surface longlining, observed capture rates varied over time, and were relatively high in recent years (Figure 16).

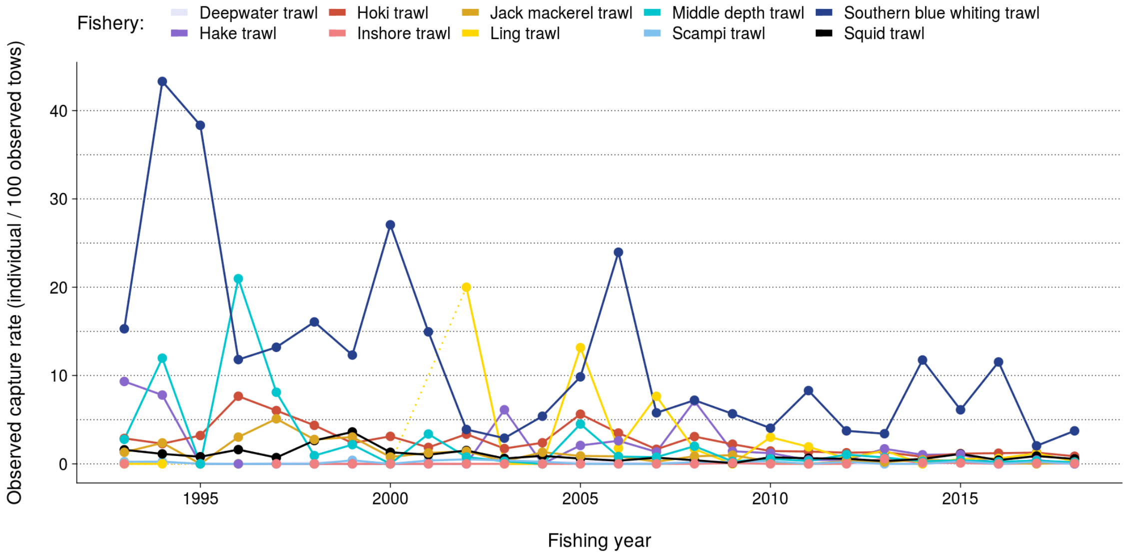

Figure 15: Observed capture rates of New Zealand fur seal in trawl, by target fishery, for the period between 2002–03 and 2017–18. Capture rates are individuals per 100 tows. Observations not occurring in consecutive years are connected by a dotted line.

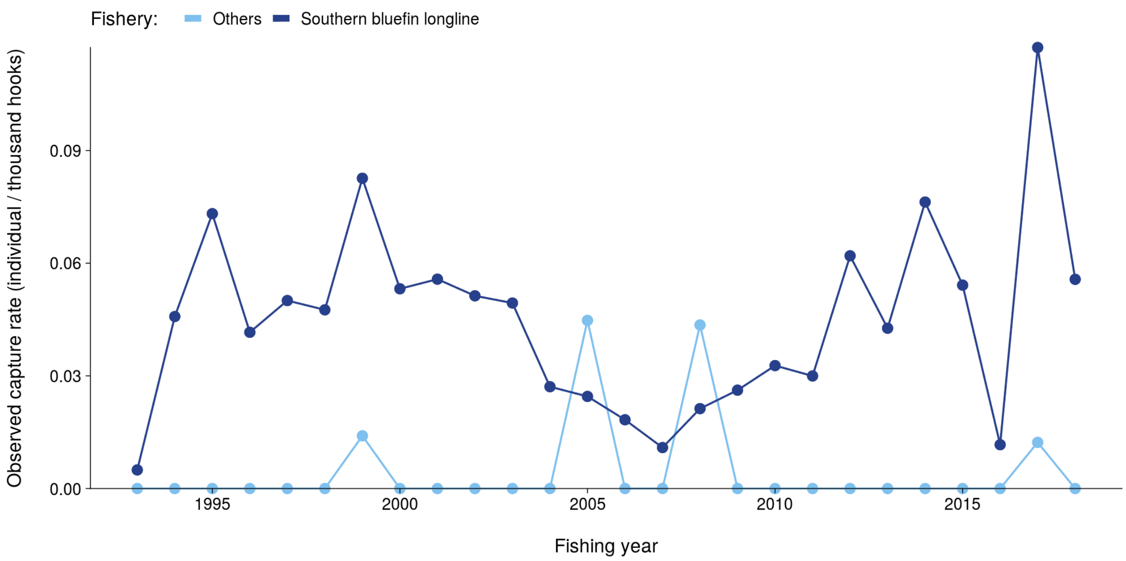

Figure 16: Observed capture rates of New Zealand fur seal in surface-longline fisheries, by target fishery, for the period between 1992–93 and 2017–18. Capture rates are individuals per thousand hooks. Observations not occurring in consecutive years are connected by a dotted line.

The spatial distribution of observed captures differed between the two main gears catching New Zealand fur seal (Figure 17). Trawl fisheries had high numbers of observed captures in Cook Strait, off the central West Coast and around Bounty Islands, corresponding with target fisheries for hoki, hake and hoki, and southern blue whiting, respectively. Observed capture rates in Bounty Islands waters were particularly high with values approaching 0.3 individuals per tow. In contrast, observed captures in surface-longline gear were in Bay of Plenty and the central part of the east coast of North Island, and also offshore of Fiordland. These areas are fishing grounds for southern bluefin tuna. While observed capture rates offshore Fiordland were generally lower than in North Island, the higher rate of observer coverage resulted in a high number of observed captures. Both of these areas, particularly offshore Fiordland, had high fishing effort for surface longline compared with other areas in New Zealand (Figure 3).

Modelled estimates of fleet-wide captures of New Zealand fur seal were available for trawl and surface-longline fisheries for the period between 2002–03 and 2017–18 (Abraham et al. 2021). Trawl fisheries overall were predicted to capture higher numbers of New Zealand fur seal than surface-longline fisheries (Figure 18). For trawl fisheries, estimated annual captures declined following a high number of estimated captures in 2004–05 (mean: 1700 individuals; 95% c.i.: 1254–2313). The decline in captures was determined in part by a steady decrease in trawl fishing effort over the study period.

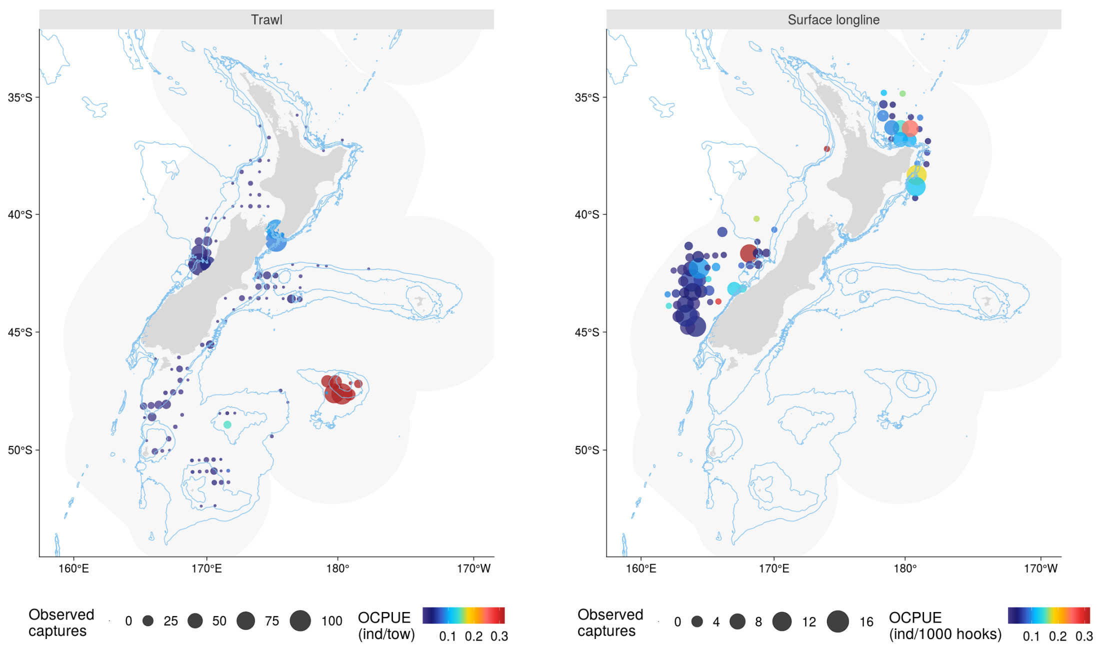

Figure 17: Spatial distribution of observed captures for New Zealand fur seals for trawl and surface longline fisheries, the main gears with observed captures for this species. The size of the circle indicates the magnitude of observed captures aggregated by 0.2 degree cell, its colour indicates the observed capture rate. Captures are aggregated for the period from 2007–08 to 2017–18. Capture rates are in individuals per thousand hooks for surface longline and individuals per tow for trawl.

For surface-longline fisheries, the number of estimated annual captures declined from 403 to 58 (mean prediction) over the model period, corresponding with a decline in fishing effort. Fishing effort has remained relatively similar since 2008–09, but captures of New Zealand fur seal were generally predicted to increase over this later time period, with some fluctuation (Abraham et al. 2021).

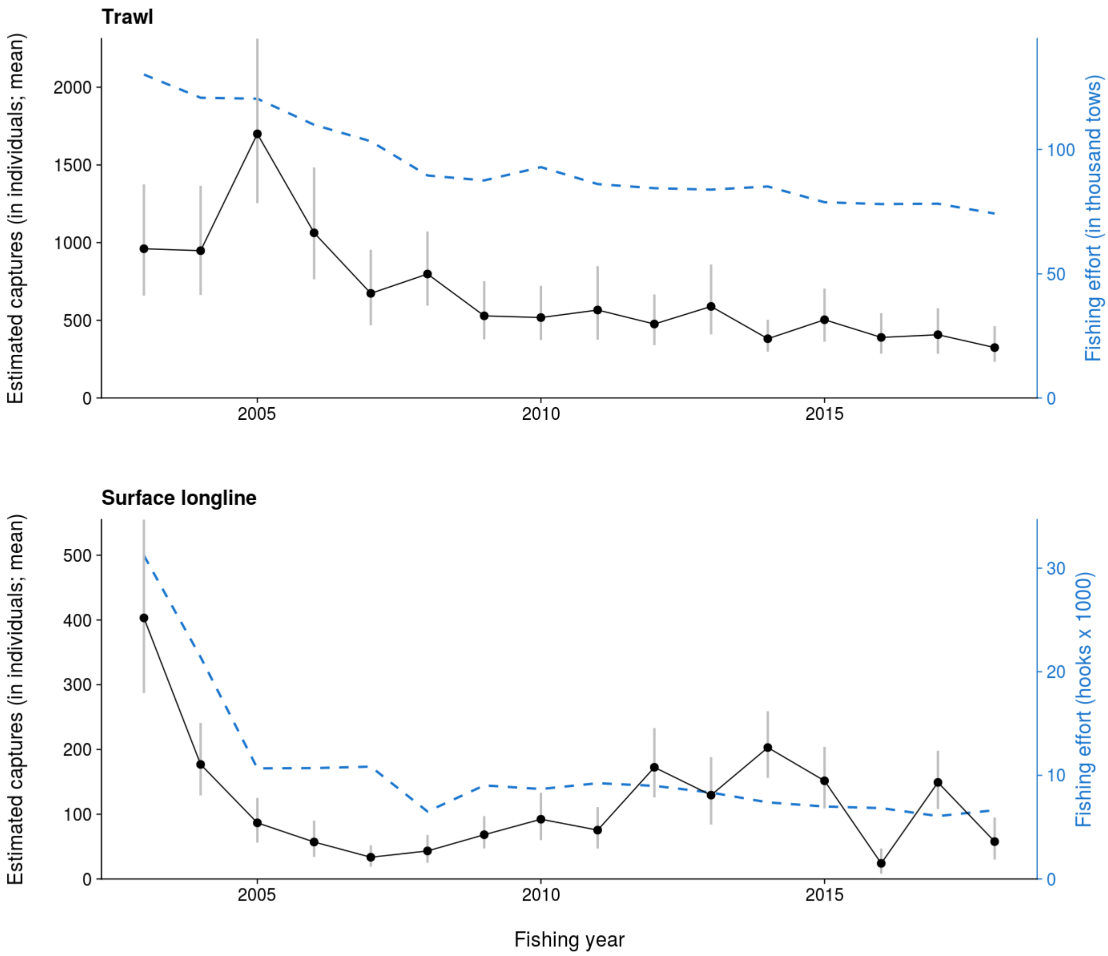

Figure 18: Estimated annual captures of New Zealand fur seal for trawl (top) and surface longline (bottom) between 2002–03 and 2017–18, based on models of observed captures (Abraham et al. 2021). Blue dots indicate the mean model prediction, vertical bars span the 95% credible interval for the annual predictions. Fishing effort used as input to the model is shown as a blue dashed line.

3.2 Bycatch mitigation for marine mammals

The widespread occurrence of incidental captures of marine mammals has led to a number of mitigation trials and studies in different fisheries and regions (e.g., Northridge et al. 2003, Mooney et al. 2007, Van der Hoop et al. 2012). Research into mitigation has focused on reducing the likelihood of interactions (e.g., acoustic deterrents) and also on lessening the severity of outcomes (e.g., trawl net alterations to allow captured animals to escape). Throughout this research, rigorous testing of the efficacy of mitigation techniques has been challenging, as studies are often limited by low interaction rates and by difficulties achieving direct comparisons between trial and control conditions (Leaper & Calderan 2018). Furthermore, when mitigation techniques are trialled in combination with other measures, or are implemented concomitantly with systematic changes in fishery characteristics (e.g., gear switching or reductions in fishing effort), it is difficult to determine the effectiveness of a particular mitigation technique compared with other changes or measures that were implemented at the same time.

Several recent reviews have examined a comprehensive range of mitigation techniques aimed at reducing marine mammal bycatch, including their efficacy (Werner et al. 2015, FAO 2018, Leaper & Calderan 2018, Hamilton & Baker 2019). These assessments include a recent (2018) FAO expert workshop of global mitigation measures, providing a detailed assessment of technical approaches that may prevent or ameliorate marine mammal interactions with different commercial fisheries (FAO 2018). Similarly, Hamilton and Baker (2019) provide a detailed assessment of mitigation measures for cetaceans and pinnipeds, including evidence supporting their efficacy, and recommendations for further trials and research. In the context of New Zealand fisheries, studies have focused on reviewing mitigation options for different New Zealand fisheries (Rowe 2007), and also specifically for set netting (Childerhouse et al. 2013), and for cetacean entanglements (Laverick et al. 2017).

In appraising the different mitigation techniques, these reviews highlight universal approaches across different species and fisheries are difficult to achieve, and effective mitigation techniques are usually specific to a particular fishery and marine mammal species combination (e.g., see Childerhouse et al. 2013, Hamilton & Baker 2019). In addition, these studies highlight the importance of observer coverage to monitor the application and outcomes of mitigation techniques in different fisheries.

Trials and experiments of marine mammal mitigation measures in New Zealand fisheries have focused on acoustic devices (for Hector's dolphin; Stone et al. 2000) and on adding escape mechanisms in the form of exclusion devices to trawl nets (for New Zealand sea lion and New Zealand fur seal; Cleal et al. 2009a, Ministry for Primary Industries 2019). Sea lion exclusion devices (SLEDs) have been adopted as a specific measure for mitigating captures of New Zealand sea lion in subantarctic trawl fisheries targeting squid (Auckland Islands, SQU 6T) and southern blue whiting (Campbell Islands, SBW 6I), prompted by high numbers of New Zealand sea lion captures in these fisheries. In addition, measures aimed at reducing common dolphin bycatch include the use of acoustic deterrent devices in northern North Island mackerel trawl fisheries.

3.2.1 Trawling

Incidental captures of marine mammals in trawl fisheries occur during the deployment (“shooting”) and hauling of gear, and also during towing (Lyle & Wilcox 2008). Bycatch records from trawl fisheries are generally dominated by small-sized cetaceans and pinnipeds, although there have been documented captures of large cetaceans, including in New Zealand (Berkenbusch et al. 2013, Laverick et al. 2017). The former two groups are particularly vulnerable to capture as many species share target prey with fisheries, leading to spatial overlap between their distributions and fishing effort. In addition, a number of delphinid and pinniped species are actively attracted to fishing vessels and deliberately swim in and out of nets to forage on caught target species (Jaiteh et al. 2012, Lyle et al. 2016). Pinnipeds, such as fur seals, in particular, have been shown to be adept at foraging on captured fish within the nets, including during towing.

Mitigation techniques trialled or used in trawl fisheries include acoustic (deterrent) devices, exclusion devices (of different designs), the barring of access to the net through net binding or entrance barriers, and changes to the net colour (Table 7). In addition to these specific mitigation techniques, improvements to the deployment of trawl gear (e.g, auto-trawl systems to maintain the net opening and increasing the stability of trawl gear) have also been proposed (Wakefield et al. 2017, Santana-Garcon et al. 2018).

Acoustic devices (pingers) – trawling
Acoustic devices or pingers emit acoustic signals that are aimed at alerting marine mammal to the presence of fishing gear or deterring them from interacting with it. They vary in design, such as output volume, frequency and amplitude, and include units that emit loud sounds, such as Dolphin Dissuasive Devices®. Acoustic devices have been trialled in different trawl (and other) fisheries to prevent pinnipeds and small cetaceans from interacting with the net, and trial outcomes have been dependent on the devices used, and the fishery and species involved (see FAO 2018, Hamilton & Baker 2019). For example, the use of acoustic deterrents in mid-water pair-trawl fisheries in United Kingdom corresponded with a reduction in common dolphin bycatch (Northridge et al. 2011); however, the same species exhibited no notable response to acoustic devices during experimental trials in a behavioural study (Berrow et al. 2008). Similarly, responses of bottlenose dolphin to pingers in trawl fishery trials have also been inconsistent (Leeney et al. 2007, Santana-Garcon et al. 2018).

For pinnipeds, experiments with acoustic deterrent devices and also with other loud noises, such as “seal scarers” and seal predator sounds (e.g., killer whale), were not effective in displacing fur seals from the vicinity of trawl nets, including in New Zealand’s hoki trawl fishery (Baird 2004).

In New Zealand, Dolphin Dissuasion Devices® are used in the jack mackerel trawl fishery on the northern North Island west coast to deter common dolphin from interacting with the net (Deepwater Group 2018). In this region, particularly in the area north of 39° 18′S, a considerable proportion of observed common dolphin captures have been in the trawl fishery targeting jack mackerel (Thompson et al. 2013). The significant number of captures in this fishery led to the adoption of practices that include mitigation techniques, aimed at reducing the likelihood of common dolphin bycatch, as outlined in the Marine Mammal Operational Procedures by the industry body (Deepwater Group 2018). The operational procedures apply to trawlers over 28 m length, and measures for cetaceans, specifically for common dolphin, include the requirement to use Dolphin

Table 7: Summary of potential mitigation techniques for trawl fisheries, aimed at reducing the bycatch of cetaceans and pinnipeds.

Mitigation method	Cetaceans	Pinnipeds
Acoustic device	Effectiveness is unclear as studies and trials to date are inconclusive. Potential value for small cetaceans, but requires fishery-specific trials. Dolphin Dissuasive Devices® are used in NZ jack mackerel trawl fishery, but their effectiveness has not been formally tested.	Shown to be ineffective.
Exclusion device	Limited trials indicate potential for small cetaceans, but requires further research including design and effectiveness.	Considered effective, depending on design. Mandatory in Falkland Islands squid trawl fishery. Required to be used in NZ subantarctic trawl fisheries (squid and southern blue whiting) to mitigate NZ sea lion bycatch. Limited trials for NZ fur seal captures in hoki trawl fishery.
Net binding	Not formally tested. Interactions during tow and haul not mitigated.	Used in Australia: considered to be effective, but quantitative data lacking. Interactions during tow and haul not mitigated.
Net entrance barrier	Only limited trials, but indicating potential; further research required.	Not formally tested.
Net colour	Not formally tested. Ineffective in poor visibility and for cetaceans that actively enter the net to feed on catch.	Not formally tested. Ineffective in poor visibility and for pinnipeds that actively enter the net to feed on catch.

Dissuasion Devices® on every tow in fisheries management area JMA 7 north of 40°30′ S. For the use of these devices, the operational procedures include specific instructions, such as the minimum number (four) of functioning units to be carried on each vessel and their placement on trawl gear.

Observed common dolphin captures in this fishery have markedly declined in recent years (see Section 3.1.2), but the efficacy of the Dolphin Dissuasion Devices® in this trawl fishery remains unknown, as the acoustic devices are used in combination with other mitigation methods and protocols.

Overall, there is currently no strong evidence to suggest that acoustic devices provide a mechanism for reducing marine mammal bycatch in trawl fisheries (FAO 2018, Hamilton & Baker 2019). On the basis of existing trials, the FAO expert workshop recognised the potential of pingers as a mitigation method for trawl fisheries that warrants further testing (FAO 2018). The recent review of global mitigation techniques reached a similar conclusion, recommending further testing of loud pingers, including operational aspects that may affect their efficacy (Hamilton & Baker 2019). These trials would also need to address potential disadvantages associated with the use of pingers, such as noise pollution, habitat displacement and habituation (e.g., Omeyer et al. 2020).

Exclusion devices – trawling
In contrast to acoustic devices that are aimed at displacing marine mammals from the vicinity of trawl nets, exclusion devices are designed to allow marine mammals to escape from the net after entering it (Hamilton & Baker 2019). Exclusion devices consist of a grid or similar guide that allows target species to pass through, while guiding marine mammals towards a net opening through which they can exit. A critical aspect of the grid is the spacing of the bars, which needs to be sufficiently wide to allow target catch but not marine mammals (or other non-target species) to pass through; similarly important, the angle of the grid or guide, and the size and placement of the opening (top versus bottom of the net) must warrant the escape of marine mammals without significant loss of target catch. The development of exclusion devices has focused on different designs regarding the rigidity, bar spacing and orientation of the grid, and the placement and specifications of the escape opening (e.g., see Tilzey et al. 2006, Hamilton & Baker 2015a, Lyle et al. 2016).

In New Zealand, the use of Sea Lion Exclusion Devices (SLEDs) is required in subantarctic trawl fisheries targeting squid (Auckland Islands, SQU 6T) and southern blue whiting (Campbell Islands, SBW 6I) for mitigating bycatch of New Zealand sea lion (Ministry for Primary Industries 2019). Each vessel in these fisheries must carry at least two approved and certified SLEDs, and a SLED must be used on each tow (Deepwater Group 2018).

The SLEDs approved for New Zealand trawl fisheries have a top-opening escape hole, which includes a forward-facing hood and floats to maintain the net opening and ensure that only actively-swimming animals are leaving the net (Hamilton & Baker 2015a, 2015b). In spite of this feature, criticisms of SLEDs have included concerns that sea lion that fail to exit the net may drop out of the devices before the net is brought onboard the vessel (Robertson 2015). The loss of carcasses has been documented for trawl nets that contained exclusion devices with bottom-opening escapes, and this loss was only ascertained through underwater video footage (e.g., Lyle et al. 2016). In addition, there have also been concerns about potential (head) injuries, incurred during interactions with the grid, which may subsequently affect sea lions even if they succeed in escaping from the net (Robertson 2015).

As any "cryptic mortalities" are not recorded, they may lead to underestimates of fishery-related sea lion mortalities. Cryptic mortalities also include sea lion that escape the net, but are unable to reach the surface within their dive limit (Ministry for Primary Industries 2019). Some of these concerns were considered in a recent assessment of available data for the specific SLED design used in New Zealand (Hamilton & Baker 2015a, 2015b). This assessment concluded that trapped animals are unlikely to be lost through the top-opening SLEDs with a forward-facing hood, and that the majority of New Zealand sea lion would survive interactions with the grid after exiting the trawl net via the SLED.

Exclusion devices have also been trialled in New Zealand hoki trawl fisheries to reduce New Zealand fur seal bycatch, with a couple of at-sea trials using underwater cameras to assess the performance of the Seal Exclusion Device (SED) during fishing operations (Cleal et al. 2009a). The SED design was based on SLEDs with changes to the bar spacing of the grid to reflect the smaller size of New Zealand fur seal compared with New Zealand sea lion. The first trial was conducted during the hoki spawning season, targeting hoki aggregations in Cook Strait, with the second trial outside the spawning season reflecting lower fish catches. Although several New Zealand fur seal were frequently present around the vessels and feeding from the codend during hauling, no incidental captures were recorded during the trials. Underwater footage showed that the SEDs were operating, but also documented the loss of target fish through the escape hole, partly caused by a considerable aggregation of fish stuck on the bars of the grid. The physical impact of hoki hitting the grid also caused concerns about the possible reduction in flesh quality and value of hoki. Based on these trials, the SEDs were not considered suitable for bulk fisheries characterised by high fish densities and catch rates.

In Australia, different designs of SEDs were trialled over several fishing seasons in the mid-water hoki (blue grenadier) trawl fishery (Tilzey et al. 2006). Early designs were characterised by substantial fish loss and fish blocking the grid, while bycatch data indicated that fur seal entered nets fitted with SEDs through the top-opening escape. Subsequent trials compared bottom- and top-opening SEDs, and SEDs without escape openings, but found that low fur seal abundance and bycatch hampered some of the comparisons. Nevertheless, forward-facing, top-opening SEDs were found to significantly reduce bycatch mortality of fur seal, leading to their recommendation for use on mid-water trawls in the winter fishing season.

In the Patagonian squid trawl fishery in Falkland Islands waters, intensive testing of different SEDs designs over a short timeframe was prompted by a sudden marked increase in interactions and bycatch mortalities of seals and sea lions in this fishery (Iriarte et al. 2020). Although pinniped interactions had previously been low, bycatch incidents and mortalities of both pinnipeds species increased notably in 2015–16, apparently related to changes in habitat use. By 2017, significant numbers of seals (>100 individuals at times) were following the trawl vessels, approaching the nets during shooting and hauling, and scavenging from the nets. As the number of pinniped mortalities increased in spite of a temporary exclusion zone, the entire fishery was temporarily closed for the trialling of modified fishing gear, including several SED designs. The trials were accompanied by 100% observer coverage to monitor the efficiency of the SEDs. The trials resulted in the approval of three different types of SEDs that accommodated different vessel characteristics, and became mandatory in September 2017. All of the SEDs contained hard grids with top-opening escapes.

Exclusion devices (e.g., ”Bycatch Reduction Devices”, BRD) have also been trialled for reducing the bycatch mortality of small cetaceans, including designs with a bottom- or top-opening escape hole (FAO 2018, Hamilton & Baker 2019). Results from these trials have been variable, with underwater footage indicating that dolphins successfully navigated to the top opening of the trawl net via the exclusion grid (van Marlen 2019), but also that they failed to detect the escape opening or attempted to swim upstream out of the net, after perceiving the grid as a barrier rather than a guide to the net opening (Stephenson & Wells 2008, Wakefield et al. 2017).

In Western Australia, the initial reduction in bottlenose dolphin bycatch mortality in demersal trawl nets fitted with bottom-opening BRDs led to their mandatory introduction in 2006, although bycatch rates have not further declined since then (Allen et al. 2014). This finding led to the recommendation to trial top-opening BRDs, in association with increased observer coverage. The need for further research into the design and effectiveness of exclusion devices for preventing dolphin mortalities was also highlighted in recent mitigation reviews (FAO 2018, Hamilton & Baker 2019).

Net binding & entrance barrier – trawling
Another approach for reducing fishery-related mortalities of marine mammals in trawl fisheries is preventing access to the inside of nets—either by keeping the entrance temporarily closed (i.e., when it is at or near the surface during shooting) or through some form of entrance barrier that allows target catch but not marine mammals to pass through (see reviews in FAO 2018, Hamilton & Baker 2019).

Temporarily closing the entrance of the net during shooting (net binding) is intended to prevent incidental captures during the deployment of the net, with the bindings breaking under increasing pressure from the trawl doors as they spread. Net binding has been trialled in hoki trawl fisheries in New Zealand and Australia to mitigate the bycatch of seabirds and fur seals (*A. pusillus* and *A. forsteri*), respectively (Cleal et al. 2009b, FAO 2018). For the two pinniped species, the trials in Australian trawl fisheries seemed to indicate that this method reduces the bycatch of fur seals, but quantitative data of this research are not currently available (see Hamilton & Baker 2019). Furthermore, any successful mitigation through net binding would need to be used in combination with other techniques, to ensure that interactions are not only reduced during net shooting, but also during towing and hauling.

Preventing access to the inside of trawl nets has also been trialled with different types and configurations of net entrance barriers, including ropes vertically hung within the net, different shapes of mesh barriers, and designs with and without associated escape holes (van Marlen 2019). Some of the designs were deemed unsuitable based on initial trials (e.g., causing significant loss of target catch), whereas other types of barrier seemed to have potential but would require further testing as a mitigation device for dolphin bycatch. Further trials were also recommended by the expert workshop for mitigating bycatch considering this mitigation technique (FAO 2018).

Net colour – trawling
Changes in net colour have also been proposed as another potential mitigation option for reducing cetacean bycatch, by increasing the visibility of nets and making them more easily detectable (Hamilton & Baker 2019). There have been no targeted trials of this gear modification, and its potential efficacy remains untested. An obvious weakness of this approach is its limited value in poor visibility and the loss of colour at depth. Furthermore, for pinnipeds and cetaceans that enter and interact with nets to opportunistically feed on target catch, changing the net colour does not represent a disincentive deterring this behaviour.

3.2.2 Longlining

Interactions of marine mammals with demersal and pelagic (surface- and bottom-) longline fisheries have been reported for a range of cetacean and pinniped species, with the type of interactions generally distinguished as either hooking or entanglement (Hamer et al. 2012, Werner et al. 2015). Bycatch records in longline fisheries include direct observations (e.g., by fishers and fisheries observers) and also entanglements in fishing gear that implicate longline fisheries (Laverick et al. 2017). In New Zealand waters, bycatch records in longline fisheries most frequently feature New Zealand fur seal in surface longlining, with few records of other marine mammals and in bottom-longline fisheries (Section 3.1.1 and Abraham & Berkenbusch 2017).

The widespread occurrence of marine mammal bycatch in longline fisheries worldwide was recognised at an international workshop in 2013 that assessed mitigation measures in demersal and pelagic longline fisheries (Werner et al. 2015). Participants in this workshop reviewed the current state of knowledge of different mitigation measures, and provided a ranking of each method. The ranking was based on a set of criteria, such as the efficacy of potential methods, associated risks, impact on target catch, and technological and practical aspects of their application (where relevant). By eliciting expert knowledge and opinion, the workshop also provided priorities for future research efforts. Most of the identified methods were ranked "medium" or "low" regarding their mitigation potential and research priority, with only terminal gear modifications (i.e., weakened hooks) receiving a high ranking.

The main technical mitigation measures identified for longline fisheries are acoustic devices, terminal gear modifications or weakened hooks and catch protection (Table 8); however, the efficacy of these measures is largely unknown (Werner et al. 2015, FAO 2018, Hamilton & Baker 2019).

Table 8: Summary of potential mitigation techniques for longline fisheries, aimed at reducing the bycatch of cetaceans and pinnipeds.

Mitigation method	Cetaceans	Pinnipeds
Acoustic devices	Ineffective (i.e., no data to demonstrate efficacy).	Ineffective (i.e., no data to demonstrate efficacy).
Weakened hooks	Potentially effective, but needs further research, including injury and post-escape survival of hooked animals.	Not formally tested.
Catch protection devices	Potentially effective, depending on the design and fishery, but needs further research.	Potentially effective, depending on the design and fishery, but needs further research.

Acoustic devices – longlining
The use of acoustic deterrent devices in longline fisheries includes both passive and active devices, but studies to date have not provided sufficient evidence for this mitigation technique to be recommended in recent bycatch mitigation reviews (e.g., Werner et al. 2015, FAO 2018, Hamilton & Baker 2019). Werner et al. (2015) highlighted the challenge of testing the efficacy of acoustic devices in pelagic longline fisheries. They also noted that a number of longline fisheries have adopted this mitigation approach even though its efficacy remains untested, and the devices have been shown to be ineffective in some situations.

Weakened hooks – longlining
Weakened hooks are aimed at lessening the severity of interaction outcomes, by reducing the bending strength of the hooks. This weakening enables marine mammals to free themselves, but without risking the release of target catch (Werner et al. 2015). Although this method does not prevent interactions, its potential as a mitigation technique was

ranked “high” in the recent expert workshop of longline mitigation methods, especially for situations where other mitigation options may not be available. Nevertheless, the expert panel acknowledged that further research is needed, especially regarding injury and subsequent survival of hooked animals.

Catch protection devices – longlining
Catch protection devices of various designs have been trialled in longline fisheries exposed to considerable depredation by odontocetes and pinnipeds, such as the Patagonian toothfish fishery (Purves & Agnew 2004). The underlying principle of this technique is that once the devices are triggered, the catch is covered on the line, preventing depredation from marine mammals (and seabirds). To date, different catch protection devices have been trialled in demersal and pelagic longline fisheries, but their assessment has been hampered by low interaction rates and small sample sizes (FAO 2018). Nevertheless, catch protection devices are considered to be potentially effective in reducing depredation by cetaceans and pinnipeds, warranting further research (Werner et al. 2015, FAO 2018). For example, in the Chilean longline fishery targeting toothfish, the development of a kind of “net sleeve” (or “cachalotera”) seemed to have led to marked reductions in depredation by sperm whale and South American sea lion (*Otaria flavescens*) (Moreno et al. 2008). In this demersal fishery, the device is triggered when the line is being hauled.

In surface-longline fisheries, trials of this mitigation technique have focused on triggered catch protection devices that are activated by the hooking of fish, with different designs requiring further testing and improvements to determine their adequate functioning and efficacy as a mitigation device (Werner et al. 2015, Hamilton & Baker 2019). Further research is also needed to address operational limitations, such as increased drag during hauling and the need for additional crew to deploy some of the mitigation devices (see Hamer et al. 2015).

3.2.3 Set netting

Interactions with set-net fisheries frequently result in mortality of small cetaceans and pinnipeds, as their small body sizes mean that they are unable to free themselves, resulting in drowning. In comparison, large-size cetaceans may be able to free themselves, but their interactions with fishing gear may lead to severe injuries and subsequent mortality (Cassoff et al. 2011, Moore et al. 2012). For coastal species and populations with low abundances, these mortalities can pose a significant threat, as the removal of even a small number of individuals can severely impact on the sustainability of the population. Examples from New Zealand include Hector’s dolphin, particularly the nationally critical subspecies Māui dolphin, which has been impacted by mortalities in set nets (Baird & Bradford 2000, Currey et al. 2012).

A preference for mitigation measures that prevent interactions with set-net fisheries was highlighted in a recent review of mitigation options for New Zealand set-net fisheries, which appraised different gear modifications (and other measures) for reducing marine mammal bycatch in these fisheries (Childerhouse et al. 2013). The study concluded that spatial and temporal closures are currently the most effective measure for reducing incidental captures and mortalities in New Zealand set-net fisheries. Existing fishery closures are currently implemented in different coastal North Island and South Island areas, such as the Banks Peninsula Marine Mammal Sanctuary and Te Waewae Bay

Sanctuary, in addition to fishing restrictions in different parts of the New Zealand coastline (Dawson & Slooten 1993, Department of Internal Affairs 2008, Ministry for Primary Industries 2019).

Entanglement records from Department of Conservation's incident and sightings databases also implicate larger-sized cetaceans in interactions with set-net fishing gear in New Zealand waters, including southern right whale, dwarf minke whale, humpback whale and killer whale (Laverick et al. 2017). Although these records frequently lack information that allows the distinction between recreational and commercial set-net fisheries, they confirm the potential risk of set-net fisheries to these species.

Gear modifications for set-net fisheries include acoustic devices, and changes to the visual and acoustic properties of nets and the net material (Table 9). Similar to mitigation techniques trialled for other fisheries, studies into the suitability of these modifications highlight the difficulty of finding a universal measure that is effective across different set-netting operations and for different marine mammal species interacting with these fisheries. In addition, studies and trials are often limited by small sample sizes that preclude rigorous testing of the findings (FAO 2018, Hamilton & Baker 2019).

Table 9: Summary of potential mitigation techniques for set-net fisheries, aimed at reducing the bycatch of cetaceans and pinnipeds.

Mitigation method	Cetaceans	Pinnipeds
Acoustic devices	Effective for some (non-NZ) small cetacean species, but not for Hector's dolphin; requires further research.	Not formally tested, unlikely to be effective. Potentially acting as an attractant.
"Acoustic" nets	Limited trials with variable findings; further research required. Potentially only effective if cetaceans are actively echolocating when they encounter the nets.	Ineffective.
Visual changes to net	Limited trials, but potentially effective (light-emitting diodes added to nets).	Not tested, but potentially an attractant.
Weakened gear	Limited trials, effectiveness unclear. Weakened rope strength may allow large cetaceans to free themselves; requires further research.	Limited trials, effectiveness unclear.

Acoustic devices (pingers) – set netting

A number of mitigation studies have focused on pingers in set-net fisheries, with trials in New Zealand assessing the responses of Hector's dolphin (Stone et al. 1997, Stone et al. 2000, and see review in Dawson et al. 2013). Pingers have also been used in New Zealand set-net fisheries, but their application has been limited to few vessels and corresponding observer records, which lack information about their effectiveness (e.g., Ramm 2010).

Pingers have been found to be an effective mitigation technique for deterring interactions of some cetacean species with set-net fisheries, such as harbour porpoise *Phocoena phocoena* (Dawson et al. 2013). Nevertheless, their efficacy overall seems to be species- and fishery-specific, with only few species showing clear and consistent displacement responses (FAO 2018, Hamilton & Baker 2019).

In addition, potential negative effects associated with the use of pingers include habituation, noise pollution and adverse effects from restricting access or excluding species from critical habitat.

For Hector's (and Māui) dolphin, data to date do not support the efficacy of acoustic devices for preventing interactions with set nets, and further research is needed to assess their efficacy (Dawson & Lusseau 2005, Childerhouse et al. 2013, Dawson et al. 2013). Future research would also need to focus on other cetacean species, and include technical aspects such as the minimum number and spacing of pingers on set nets.

For pinnipeds, the addition of acoustic devices has not been demonstrated to have long-term benefits of reducing bycatch in set nets, with concerns that the acoustic signals may attract some pinniped species to the enhanced food availability in the nets (FAO 2018, Hamilton & Baker 2019).

Changes to net characteristics – set netting

A number of mitigation studies in set-net fisheries have focused on changes to net properties, such as increasing the visibility or acoustic reflectivity of nets so that they are more easily detected by marine mammals (see review in Hamilton & Baker 2019). A potential disadvantage of this approach is that species with a propensity to feed opportunistically on net-captured fish (e.g., small odontocetes, pinnipeds) are alerted to the net's presence.

Increasing the visibility of nets can be achieved by adding light sources, or by using specific colours or panels with different patterns (Leaper & Calderan 2018, Hamilton & Baker 2019)). In general, these net modifications have received little research attention, but a recent study assessed the effect of light-emitting diodes (LEDs) on floatlines of bottom-set and drift nets in a small-vessel South American fishery (Bielli et al. 2020a). This study found a marked reduction in the number of bycaught cetaceans (and sea turtles and seabirds) in gillnets that contained LEDs, indicating the potential value of this method as a mitigation technique. Nevertheless, subsequent criticisms of the study design and analysis questioned the robustness of the findings (Authier & Caurant 2020, Bielli et al. 2020b). Although the authors addressed the criticisms raised, they recommended further testing of this method, especially in view of limited research of this method to date.

A different approach for increasing the detectability of set-netting gear to echolocating cetaceans is enhancing the acoustic reflectivity of nets (Leaper & Calderan 2018). The latter can be achieved by adding reflective materials, metal oxide or barium sulphate, with the latter additions also increasing the stiffness of nets. Limited trials revealed inconsistent outcomes, with suggestions that bycatch reductions were due to the stiffness of the net, which also caused substantial loss of target catch. For this reason, further development and testing would be required to improve the method in terms of loss of target catch and its efficacy.

Weakened gear – set netting

Attempts of lessening the severity of marine mammal interactions with set nets (and also lobster pots) include ways of weakening fishing gear, such as ropes and netting, so that animals are able to free themselves (Leaper & Calderan 2018, Hamilton & Baker 2019). Disadvantages of this method are that marine mammals may escape, but remain entangled in parts of the fishing gear, impacting on their subsequent survival. Net modifications in the form of weakened monofilament netting were trialled in net fisheries targeting skate in United Kingdom, comparing bycatch data from thin twined (0.4 mm) and standard (0.6 mm) monofilament nets (Northridge et al. 2003). This dedicated trial documented substantially lower seal and harbour porpoise bycatch in the thin twined nets, but the authors were uncertain if the result was due to captured marine mammals escaping more easily or was caused by higher cryptic mortality as carcasses dropped out of the weaker nets.

Weakened links that connect the line to buoys on anchored set nets have also been documented to be ineffective in reducing cetacean bycatch (Van der Hoop et al. 2012, Laverick et al. 2017). In addition, they make the disentangling of captured animals more difficult as the latter are more mobile. A related study of the breaking strength of rope retrieved from entangled whales suggested that a reduction in the strength of rope would allow larger-sized individuals to free themselves (Knowlton et al. 2016). Although this modification would not reduce the likelihood of interactions and still affect smaller-sized cetaceans, including juveniles, the authors thought it could potentially mitigate a large proportion of bycatch of North Atlantic right whale and humpback whale. This finding prompted the recommendation for the development and testing of ropes with lower breaking strength for set-net and pot fisheries.

3.2.4 Pots and traps

Bycatch of marine mammals in pot and trap fisheries is distinguished by either entanglement in rope or direct capture in pots or traps that lead to fishery-related injury and mortality. Bycatch records associated with pot fisheries in New Zealand document cetacean entanglements in rope, particularly of medium- and large-sized species; for example, entanglements attributed to (recreational or commercial) rock lobster fisheries in New Zealand waters include southern right whale, humpback whale, killer whale and an unknown baleen whale species (e.g., see Laverick et al. 2017).

Fishery-related mortalities of pinnipeds have been reported from lobster fisheries elsewhere, caused by depredation behaviour (e.g., in Australia, Campbell et al. 2008); however, pinnipeds do not generally feature in documented interactions with pot fisheries in New Zealand.

Proposed and trialled mitigation techniques for reducing entanglements of cetaceans in pot (and trap) fisheries include acoustic devices, sinking ground lines, changes to the rope and rope-less systems (Table 10). Similar to mitigation methods in other fisheries, available data for these techniques are generally too limited to confirm their efficacy, but indicate their potential for species-specific or fishery-specific mitigation (FAO 2018, Hamilton & Baker 2019).

Examples of the development of a systematic mitigation approach include the western rock lobster fishery in Australia, where the increasing number of whale entanglements (and to a lesser extent in the octopus fishery) led to a number of initiatives to mitigate these interactions (How et al. 2015, Leaper & Calderan 2018). Initial research was focused on the identification of potential mitigation measures, followed by an assessment of gear modifications (How et al. 2015). The assessment included an industry-led workshop focused on the costs and practicalities of potential measures, and subsequent industry-wide trials of selected gear modifications. The trials were focused on adding negatively buoyant components to the rope, and reductions in rope length and in the number of floats. Resulting mitigation measures currently implemented in this fishery include these gear modifications, such as reducing the amount of rope on vertical lines and the number of floats, and removing surface rope when fishing in deeper water (>20 m depth) (Leaper & Calderan 2018).

Similar practices, recommended by the New Zealand Rock Lobster Industry Council, were highlighted as potential mitigation measures in a recent review of cetacean entanglement in pot, trap and set-net fishing gear in New Zealand waters (see Laverick et al. 2017). The recommended practices include avoidance of excess rope and of multiple-pot clusters, retrieval of unused pots from the sea, and the regular monitoring of active fishing gear.

Similar to pot (and trap) fisheries elsewhere, the low number of marine mammal interactions with these fisheries in New Zealand waters means that the systematic testing of different mitigation techniques is difficult to achieve (Laverick et al. 2017).

Table 10: Summary of potential mitigation techniques for pot (and trap) fisheries, aimed at reducing the bycatch of cetaceans (not considering pinnipeds, N/A). Techniques were considered in the context of New Zealand fisheries.

Mitigation method	Cetaceans	Pinnipeds
Acoustic devices	Insufficient evidence to date, requires further research.	N/A.
Weighting of ground line	No demonstrated effect.	N/A.
Reduction in rope length	Considered effective in Western Australian rock lobster fishery.	N/A.
Rope-less systems	Technical systems need further trial, costs likely prohibit uptake.	N/A.
Rope colour	Insufficient testing.	
Rope strength	Potential, but requires further research.	
Weakened gear	Insufficient evidence to date.	
Rope stiffness	Proposed but untested.	N/A.

Acoustic devices – pots/traps

Available data to date do not provide clear support for the use of acoustic devices as a bycatch reduction technique for pot fisheries, as experimental studies have been limited and shown variable results. For example, behavioural studies of humpback whales migrating off Australia showed inconsistent responses to acoustic signals, which seemed to be related to the direction of their migration (Dunlop et al. 2013, Pirotta et al. 2016). The lack of existing evidence and need for further research into this technique was also highlighted in recent bycatch mitigation reviews (FAO 2018, Hamilton & Baker 2019).

Reduction of rope – pots/traps
Attempts to reduce entanglements by reducing the amount of rope used during pot or trap fishing operations have been focused on potential changes in fishing practice and gear modifications (Laverick et al. 2017, Leaper & Calderan 2018). Examples include mechanical devices that ensure lines are under constant tension while pots are deployed (i.e., avoiding any surplus rope), and also the weighting of ground lines to prevent rope from floating in the water. The latter approach has been used in the Western Atlantic Ocean, where high numbers of interactions with static fishing have led to considerable impacts on resident northern right whale (*Eubalaena glacialis*) populations; however, this mitigation technique has not resulted in a discernible reduction of northern right whale entanglements (Knowlton et al. 2012).

A reduction in rope can also be achieved by limiting the number of buoy lines (e.g., one pot or trap per buoy) and specific requirements about the rope length on each line (Leaper & Calderan 2018). In the Western Australian rock lobster fishery, efforts to reduce the length of rope on each vertical line include requirements to minimise or eliminate surface rope depending on the overall length of rope and water depth; these efforts are considered to be effective in reducing whale entanglements (How et al. 2015).

Rope-less systems – pots/traps
Ways to reduce the amount of rope in the water also include the use of technology to fish rope-less pots and traps. Retrieval of gear set on the bottom would rely on timed or acoustic releases, but these systems need further development and trials, and associated costs may prohibit their widespread uptake (Laverick et al. 2017).

Changes to rope & weakened gear – pots/traps
Proposed changes to rope characteristics that may mitigate entanglements in pot and trap fisheries include increases to the detectability of rope by using colours that are more visible to cetaceans, decreasing rope strength, increasing rope stiffness and the use of weak links that connect the vertical line to the buoy system (see review in Hamilton & Baker 2019). None of these gear modifications have been formally tested, but an assessment of the breaking strength of rope suggested that ropes with lower breaking strength would markedly reduce large cetacean entanglements in the North Atlantic Ocean (Knowlton et al. 2016).

3.2.5 Purse seining

Mitigation measures applied to purse-seine fisheries are aimed at reducing the fishing-related mortality of dolphins that are specifically targeted in the herding of fishery species (see FAO 2018). These types of purse-seine fisheries do not exist in New Zealand waters; therefore, mitigation techniques such as backdown maneuvres and the use of dolphin gates do not apply to New Zealand purse-seine fisheries.

3.3 Mitigation techniques in New Zealand fisheries

Current mitigation techniques for reducing marine mammal bycatch in New Zealand trawl fisheries are Dolphin Dissuasion Devices® in the northern North Island mackerel target fishery (in JMA 7) and SLEDs in subantarctic fisheries targeting squid and southern blue whiting. Both mitigation measures are required to be used in these fisheries, as stipulated by the industry body (Deepwater Group 2018).

For Dolphin Dissuasion Devices®, there is currently no systematic data collection regarding the use and operational details associated with these mitigation devices. Although common dolphin captures in the north-western North Island mackerel trawl fishery have declined in recent years, the lack of mitigation data preclude a formal assessment of this trend in relation to the use of the acoustic deterrent devices. This aspect is particularly relevant in view of the regular bycatch assessments that are being carried out for this fishery (e.g., Abraham & Berkenbusch 2017), and which could incorporate mitigation data in the analysis. For this reason, it is recommended that data on the use of acoustic deterrent devices are systematically recorded, and stored in a consistent format, so that they are available for future analyses.

The use of SLEDs in subantarctic trawl fisheries has received considerable research attention and scrutiny, including studies relating to the post-escape survival and cryptic mortality of New Zealand sea lion (Hamilton & Baker 2015a, 2015b, Robertson 2015, Meyer 2019). Regarding the latter aspects, knowledge of the efficiency of SLEDs could be improved by the acquisition of additional underwater footage during deployment; however, poor visibility and the need for equipment to withstand the rigour of these fisheries, make the use of underwater cameras a considerable challenge. At the same time, the high observer coverage in these fisheries (usually between 80 and 100%) means that other relevant information pertaining to SLEDs is recorded.

The use of exclusion devices in New Zealand trawl fisheries has been restricted to the mitigation of sea lion bycatch in subantarctic fisheries, with limited trials focused on New Zealand fur seal in hoki fisheries (see Cleal et al. 2009a). The findings of these trials indicated that exclusion devices are unsuitable for these fisheries, owing to the impact on target catch and quality. In view of the low number of trials and the possibility of improvements to the specifications of the exclusion device used, further research into this technical mitigation measure is recommended. The benefits of intensive testing of exclusion devices including design changes and consideration of different vessel characteristics were recently highlighted in the Falkland Islands squid trawl fishery (Iriarte et al. 2020). Although there are distinct differences between this fishery and New Zealand's hoki fishery, such as characteristics of the target species and the number of pinniped interactions, the Falkland Islands study demonstrates the value of repeated trials, accompanied by observer coverage, to achieve desired mitigation outcomes.

For New Zealand set-net fisheries, a previous review of mitigation options suggested further research into the use of acoustic devices (Childerhouse et al. 2013). This recommendation was based on studies that document the effectiveness of this method (e.g., for harbour porpoise), even though research to date has shown pingers to be ineffective for Hector's dolphin (Dawson et al. 2013). For the Hector's dolphin subspecies Māui dolphin, even a small number of fishing-related mortalities (i.e., one individual) is likely to affect the sustainability of its population. For this reason, spatial and temporal closures that prevent the likelihood of interactions with fisheries are considered to be the most effective mitigation measure for this subspecies (Childerhouse et al. 2013).

Recent fishery trials with light-emitting diodes highlighted the potential value of this mitigation approach for set-net fisheries (Bielli et al. 2020a). This technique may be worth considering in New Zealand set-net fisheries to reduce interactions with marine mammal species (i.e., cetaceans) that are not attracted to set nets.

Based on mitigation measures used in the Western Australian rock lobster fishery (see How et al. 2015), potential gear modifications for New Zealand pot (and trap) fisheries could focus on an overall reduction of rope (at the surface and in vertical lines). A recent analysis of cetacean entanglements in New Zealand considered the reduction of rope in the water a preferred mitigation option for lobster fishing, as other measures (e.g., spatial closures) are potentially too restrictive, especially in view of the low number of documented cetacean entanglements (Laverick et al. 2017). The latter aspect also means that any trialling of mitigation techniques would be challenging owing to the low number of marine mammal interactions with pot (and trap) fishing gear.

4. DISCUSSION

4.1 Marine mammal interactions in New Zealand fisheries

Analysis of existing information on interactions showed that marine mammals across all species groups interact with fisheries in New Zealand, including whales, dolphins and pinnipeds. The main interaction type that can be measured and tracked is capture by a fishery, with some captures resulting in mortality.

Species that were most frequently observed as bycatch were New Zealand fur seal, New Zealand sea lion and common dolphin. For these species, observed captures have declined over time, even though observer coverage has increased in key fisheries implicated in marine mammal captures. For most of the other species, there were only few capture records available capture, and these records were often anecdotal. For some of these species, the low number of anecdotal captures may still impact on the population; e.g., Hector's and Māui dolphins and bottlenose dolphin.

In general, there were specific associations between species and fisheries that resulted in relatively high or significant numbers of captures. These associations were common dolphin and large-vessel trawl fisheries targeting jack mackerel, Hector's and Māui dolphins and set-net fisheries, New Zealand sea lion and trawl fisheries targeting squid, and New Zealand fur seal and trawl fisheries targeting southern blue-whiting. For most of these fisheries, a reduction in captures was evident in the time series, both in observed and modelled captures.

Annual captures of marine mammals by fishery were broadly determined by three main factors: the amount of fishing effort within the species' range, the local population abundance of the species, and changes in the species' vulnerability to the fishing gear. These factors have influenced marine mammal captures over time for all key species and fisheries in New Zealand.

For common dolphin, the introduction of the MMOPs appears to have resulted in a recent decline in captures. Nevertheless, the lack of data on the use of different mitigation measures within the operational procedures prevented an exploration of this trends in relation to mitigation measures. For New Zealand sea lion, captures in subantarctic trawl fisheries targeting squid and southern blue whiting have declined over time. Fishing effort in these fisheries has also declined, but marked reductions in captures of this species also followed the introduction of SLEDs in these fisheries. A steady decline in observed capture rates since the early 2000s was evident in squid-target fisheries especially.

For Hector's and Māui dolphins, spatial and temporal closures aimed at reducing incidental captures have reduced the overlap between fishing effort and their habitat. The low number of captures overall, and the small population sizes of these subspecies, makes the detection of trends difficult.

For most fishing gear, captures resulted in the mortality of the bycaught individual. The fishing gear with the most observed captures, trawl, also had the high rates of mortality across species. For New Zealand sea lion, this fishing-related mortality has been reduced, indicated by the decline in captures.

New Zealand fur seal had the highest number of interactions with fishing gear, with an associated high rate of mortality. This species is classified as "Not threatened" under the New Zealand threat classification system (Baker et al. 2019), and there has been comparatively little effort directed at reducing the bycatch of this species. Similarly, there has been no dedicated research to reduce incidental captures of dusky dolphin or long-finned pilot whale, even though multiple instances of captures have been recorded by observers across different years.

Information from fisher-reported captures supports the collection of marine mammal bycatch data, particularly for species and fisheries with low observer coverage. Nevertheless, the use of the NFPSCR form for the reporting of interactions by fishers since 2017–18 does not improve the assessment of overall captures, as reporting rates and the extent to which they vary across fishing gear, target fisheries and vessel are unknown. In addition, the identification of some species can be difficult. Nevertheless, the introduction of the NFPSCR form has increased the probability of detecting interactions with species that are not recorded in observer data, while also broadening the spatial and temporal coverage of capture records.

Species that were reported by fishers but absent from observer records included minke and beaked whales, and elephant seal. In addition, the NFPSCR form provides information on captures for gears that are otherwise seldom observed, such as lobster pot and troll. As reporting by fishers becomes better understood, it may become possible to incorporate the data collected on the NFPSCR form in more formal assessments of species interactions.

The ability to assess and estimate the extent of captures relies on comprehensive observations of fishing effort, which is achieved through the fisheries observer programme. High observer coverage is particularly vital for the recording of captures of rare species, for which even a low number of captures can have a significant impact on the population (e.g., Māui dolphin). Observer coverage is also needed to improve the quality of capture estimates (i.e., reduce associated uncertainty) for species that are caught sufficiently often to inform a model. For example, the relatively high number of estimated captures for common dolphin for trawl fisheries other than mackerel targets were mainly determined by a single fishing trip with a high capture rate. The low observer coverage (less than 0.1% in most years) in the small-vessel trawl fishery associated with this fishing trip resulted in capture estimates with high uncertainty bounds for predictions made at the scale of the fishery. Estimates with this level of uncertainty are of limited value for understanding marine mammal bycatch and informing management measures. The low observer coverage in inshore trawl fisheries is concomitant with high effort in these fisheries. In addition, inshore trawl fisheries overlap with habitat of many coastal marine species. The lack of coverage impedes a reliable assessment of interactions of this fishery with marine mammal species.

4.2 Mitigation of marine mammal bycatch in New Zealand

Ongoing efforts to reduce or prevent fishery-related mortalities of marine mammals have focused on technical and other solutions to mitigate the bycatch of pinnipeds and cetaceans. These efforts include research studies, fishery trials and expert workshops and reviews, focused on changes to fishing gear and practices in New Zealand and overseas (e.g., see Childerhouse et al. 2013, Laverick et al. 2017, FAO 2018, Hamilton & Baker 2019). Findings from this research highlight the challenges of testing the efficacy and effectiveness of different mitigation measures. They also document the limitations of many approaches, and that successful mitigation techniques are often species- and fishery-specific.

Where trials have been successful in testing mitigation measures, they have frequently included close collaborations of researchers with industry bodies and fishers (e.g., see How et al. 2015, Iriarte et al. 2020). Examples from New Zealand include the development of SLEDs for subantarctic trawl fisheries and trials of seal exclusion devices in the hoki trawl fishery (Cleal et al. 2009a, Ministry for Primary Industries 2019). For SLEDs, the development and standardisation of the design included an industry-led auditing process, leading to the certification of approved SLEDs (Ministry for Primary Industries 2019).

Another important aspect for the testing and use of mitigation techniques is the implementation of concomitant observer coverage that ensures the collection of data on the use and operational aspects of deployed mitigation gear (Allen et al. 2014). The importance of observer coverage was recognised in the recent mandatory introduction of exclusion devices in the Falkland Islands trawl fishery, which are monitored by fisheries observers covering 100% of the fishing effort (Iriarte et al. 2020).

For common dolphin captures in mackerel trawl fisheries, bycatch mitigation gear (i.e., Dolphin Dissuasion Devices®) are currently implemented with other practices, as outlined in the MMOPs (Deepwater Group 2018). Common dolphin captures in this target fishery have been low in recent years (e.g., see Figure 6), but the lack of data regarding these mitigation measures prevents a systematic assessment of their effectiveness. Furthermore, the simultaneous use of a combination of mitigation measures in this fishery further hampers the assessment of individual measures included in these operational procedures (FAO 2018).

In their review of mitigation measures for set-net fisheries, Childerhouse et al. (2013) considered the importance of explicit management goals to have a way of measuring the performance of mitigation measures. The consideration of management goals was outside the scope of the present assessment, but in view of the current status of nationally critical Māui dolphin, measures aimed at mitigating its bycatch need to prevent, rather than reduce, interactions with fishing gear.

The current characterisation of marine mammal interactions with commercial fisheries documented the high number of New Zealand fur seal mortalities in hoki trawl. This finding warrants further research into fur seal mitigation techniques for these fisheries, such as further trialling of exclusion devices. For surface-longline fisheries, trials of mitigation techniques have not led to the identification of potential mitigation options. At the same time, interactions of this species with longline gear in New Zealand frequently resulted in live releases; e.g., of a total 870 observed captures in surface longline between 1992–93 and 2017–18, 677 records were live captures (see Table 5). In view of this finding, and considering the limited trials of mitigation techniques to date, research efforts could be focused on the post-escape condition and survival of fur seals released from surface longlines.

The current study characterised marine mammal interactions with fisheries in New Zealand waters, and included a review of mitigation options. While the present assessment was restricted to commercial fisheries, incidental captures of cetaceans and pinnipeds also occur in recreational fisheries, including in New Zealand (Abraham et al. 2010). The bycatch in the latter fisheries can be significant; for example, bycatch in recreational set nets contributed considerably to documented fishery-related mortalities of Hector's dolphin (Dawson 1991). For this reason, inclusive bycatch mitigation approaches would focus on both commercial and recreational fisheries to reduce incidental captures of marine mammals in fishing gear.

5. ACKNOWLEDGMENTS

This study was funded by the Department of Conservation, project code INT2019-03. The authors would like to thank Jim Roberts, Darcy Webber and Kath Large for assistance with the results from their risk analyses for Hector's and Māui dolphins and New Zealand sea lion which were included in this report. We thank Karen Middlemiss (DOC) for comments and suggestions on earlier drafts.

Many thanks to Kath Large for updating some of the figures.

6. REFERENCES

Abraham, E. R. & Berkenbusch, K. (2017). Estimated captures of New Zealand fur seal, New Zealand sea lion, common dolphin and turtles in New Zealand commercial fisheries, 1995–96 to 2014–15. *New Zealand Aquatic Environment and Biodiversity Report No. 188*. 66 p. Retrieved from http://fs.fish.govt.nz/Page.aspx?pk=113&dk=24557

Abraham, E. R. & Berkenbusch, K. (2019). Preparation of data for protected species capture estimation, updated to 2017–18. *New Zealand Aquatic Environment and Biodiversity Report No. 234*. 49 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=24767

Abraham, E. R.; Berkenbusch, K. N., & Richard, Y. (2010). The capture of seabirds and marine mammals in New Zealand non-commercial fisheries. *New Zealand Aquatic Environment and Biodiversity Report No. 64*. 52 p.

Abraham, E. R.; Neubauer, P.; Berkenbusch, K., & Richard, Y. (2017). Assessment of the risk to New Zealand marine mammals from commercial fisheries. *New Zealand Aquatic Environment and Biodiversity Report No. 189*. 123 p. Retrieved from http://fs.fish.govt.nz/Page.aspx?pk=113&dk=24554

Abraham, E. R.; Richard, Y.; Berkenbusch, K., & Thompson, F. (2016). Summary of the capture of seabirds, marine mammals, and turtles in New Zealand commercial fisheries, 2002–03 to 2012–13. *New Zealand Aquatic Environment and Biodiversity Report No. 169*. 205 p. Retrieved from http://mpi.govt.nz/document-vault/12180

Abraham, E. R.; Tremblay-Boyer, L., & Berkenbusch, K. (2021). Estimated captures of New Zealand fur seal, common dolphin, and turtles in New Zealand commercial fisheries, to 2017–18. *New Zealand Aquatic Environment and Biodiversity Report No. 258*. 94 p.

Allen, S. J.; Tyne, J. A.; Kobryn, H. T.; Bejder, L.; Pollock, K. H., & Loneragan, N. R. (2014). Patterns of dolphin bycatch in a north-western Australian trawl fishery. *PLOS One*, *9*(4).

Authier, M. & Caurant, F. (2020). Design issues adumbrate conclusions on LED-mediated bycatch risk reduction of cetaceans and turtles in fishing nets: A comment on Bielli et al.(2020). *Biological Conservation*, *243*, 108488.

Baird, S. J. (2004). *Paper for the hoki fishery management company environmental steering group discussion on possible approaches to mitigating fur seal bycatch in the hoki fishery*. Unpublished report. Retrieved from https://www.doc.govt.nz/globalassets/documents/conservation/marine-and-coastal/fishing/twg/fur-seal-mitigation-niwa-review-04-app1.pdf

Baird, S. J. & Bradford, E. (2000). Estimation of Hector's dolphin bycatch from inshore fisheries, 1997/98 fishing year. Retrieved from http://www.doc.govt.nz/upload/documents/science-and-technical/CSL3024.PDF

Baker, C. S.; Boren, L.; Childerhouse, S.; Constantine, R.; van Helden, A.; Lundquist, D.; Rayment, W., & Rolfe, J. R. (2019). Conservation status of New Zealand marine mammals, 2019. *New Zealand Threat Classification Series 29*. 18 p.

Berkenbusch, K.; Abraham, E. R., & Torres, L. G. (2013). New Zealand marine mammals and commercial fisheries. *New Zealand Aquatic Environment and Biodiversity Report No. 119*. 104 p.

Berrow, S.; Cosgrove, R.; Leeney, R. H.; O'Brien, J.; McGrath, D.; Dalgarde, J., & Le Gall, Y. (2008). Effect of acoustic deterrents on the behaviour of common dolphins (*Delphinus delphis*). *Journal of Cetacean Research and Management*, *10*, 227–233.

Bielli, A.; Alfaro-Shigueto, J.; Doherty, P.; Godley, B.; Ortiz, C.; Pasara, A.; Wang, J., & Mangel, J. (2020a). An illuminating idea to reduce bycatch in the Peruvian small-scale gillnet fishery. *Biological Conservation*, *241*, 108277.

Bielli, A.; Alfaro-Shigueto, J.; Doherty, P.; Godley, B.; Wang, J., & Mangel, J. (2020b). Response to "Design issues adumbrate conclusions on LED-mediated bycatch risk reduction of cetaceans and turtles in fishing nets: a comment on Bielli et al.(2020)". *Biological Conservation*, *243*, 108493.

Campbell, R.; Holley, D.; Christianopoulos, D.; Caputi, N., & Gales, N. (2008). Mitigation of incidental mortality of Australian sea lions in the west coast rock lobster fishery. *Endangered Species Research*, *5*, 345–358.

Cassoff, R. M.; Moore, K. M.; McLellan, W. A.; Barco, S. G.; Rotstein, D. S., & Moore, M. J. (2011). Lethal entanglement in baleen whales. *Diseases of Aquatic Organisms*, *96*, 175–185.

Childerhouse, S.; Miller, E., & Steptoe, V. (2013). *Review of mitigation techniques for set net fisheries and applicability to New Zealand fisheries*. Unpublished report by Blue Planet Marine, BPM-13-DoC-New Zealand setnet mitigation review-1.0. 39 p.

Cleal, J.; Clement, G., & Wells, R. (2009a). *Mitigating incidental captures of fur seals in trawl fisheries*. A report commissioned by Department of Conservation. Project MIT 2006/09. 45 p. Wellington, New Zealand: Department of Conservation.

Cleal, J.; Clement, G., & Wells, R. (2009b). *Mitigating seabird interactions with trawl nets*. A report commissioned by Department of Conservation. Project MIT 2006/02. 70 p. Wellington, New Zealand: Department of Conservation.

Currey, R. J. C.; Boren, L. J.; Sharp, B. R., & Peterson, D. (2012). *A risk assessment of threats to Maui's dolphins*. 51 p. Wellington, New Zealand: Ministry for Primary Industries and Department of Conservation. Retrieved from http://www.fish.govt.nz/en-nz/Consultations/Hector+and+Mauis+Dolphins+Threat+Management+Plan/default.html

Dawson, S. M. (1991). Incidental catch of Hector's dolphin in inshore gillnets. *Marine Mammal Science*, *7*, 283–295.

Dawson, S. M. & Slooten, E. (1993). Conservation of Hector's dolphins: The case and process which led to establishment of the Banks Peninsula Marine Mammal Sanctuary. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *3*, 207–221.

Dawson, S.; Northridge, S.; Waples, D., & Read, A. J. (2013). To ping or not to ping: The use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. *Endangered Species Research*, *19*, 201–221.

Dawson, S. M. & Lusseau, D. (2005). Pseudoreplication problems in studies of dolphin and porpoise reactions to pingers. *Marine Mammal Science*, *21*, 175–176.

Deepwater Group (2018). *Marine mammals, operational procedures*. Version 9.0. 23 p. Retrieved from https://deepwatergroup.org/wp-content/uploads/2018/11/MMOP-Version-9-2.pdf

Department of Internal Affairs (2008). Marine Mammals Protection (Te Waewae Bay Sanctuary) Notice 2008/331. *New Zealand Gazette*, 14.

Dunlop, R. A.; Noad, M. J.; Cato, D. H.; Kniest, E.; Miller, P. J.; Smith, J. N., & Stokes, M. D. (2013). Multivariate analysis of behavioural response experiments in humpback whales (*Megaptera novaeangliae*). *Journal of Experimental Biology*, *216*, 759–770.

FAO (2018). Expert workshop on means and methods for reducing marine mammal mortality in fishing and aquaculture operations. FAO Fisheries and Aquaculture Report No. 1231, Food and Agriculture Organization of the United Nations, Rome. 124 p. Retrieved from http://www.fao.org/3/I9993EN/i9993en.pdf

Hamer, D. J.; Childerhouse, S. J., & Gales, N. J. (2012). Odontocete bycatch and depredation in longline fisheries: A review of available literature and of potential solutions. *Marine Mammal Science*, *28*(4), E345–E374.

Hamer, D. J.; Ward, T. M., & McGarvey, R. (2008). Measurement, management and mitigation of operational interactions between the South Australian Sardine Fishery and short-beaked common dolphins (*Delphinus delphis*). *Biological Conservation*, *141*(11), 2865–2878.

Hamer, D. J.; Childerhouse, S. J.; McKinlay, J. P.; Double, M. C., & Gales, N. J. (2015). Two devices for mitigating odontocete bycatch and depredation at the hook in tropical pelagic longline fisheries. *ICES Journal of Marine Science*, *72*, 1691–1705.

Hamilton, S. & Baker, G. B. (2019). Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. *Reviews in Fish Biology and Fisheries*, 1–25.

Hamilton, S. & Baker, G. B. (2015a). Review of research and assessments on the efficacy of sea lion exclusion devices in reducing the incidental mortality of New Zealand sea lions *Phocarctos hookeri* in the Auckland Islands squid trawl fishery. *Fisheries Research*, *161*, 200–206.

Hamilton, S. & Baker, G. B. (2015b). Review of research and assessments on the efficacy of sea lion exclusion devices in reducing the incidental mortality of New Zealand sea lions *Phocarctos hookeri* in the Auckland Islands squid trawl fishery: Reply to Robertson (2015). *Fisheries Research*, *165*, 130–132.

How, J.; Coughran, D.; Smith, J.; Double, M.; Harrison, J.; McMath, J.; Hebiton, B., & Denham, A. (2015). Effectiveness of mitigation measures to reduce interactions between commercial fishing gear and whales. *Fisheries Research Report No. 267. Department of Fisheries, Western Australia*. 120 p.

Iriarte, V.; Arkhipkin, A., & Blake, D. (2020). Implementation of exclusion devices to mitigate seal (*Arctocephalus australis*, *Otaria flavescens*) incidental mortalities during bottom-trawling in the Falkland Islands (Southwest Atlantic). *Fisheries Research*, *227*, 105537.

Jaiteh, V. F.; Allen, S. J.; Meeuwig, J. J., & Loneragan, N. R. (2012). Subsurface behavior of bottlenose dolphins (*Tursiops truncatus*) interacting with fish trawl nets in northwestern Australia: implications for bycatch mitigation. *Marine Mammal Science*, *29*, E266–E281.

Knowlton, A. R.; Hamilton, P. K.; Marx, M. K.; Pettis, H. M., & Kraus, S. D. (2012). Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. *Marine Ecology Progress Series*, *466*, 293–302.

Knowlton, A. R.; Robbins, J.; Landry, S.; McKenna, H. A.; Kraus, S. D., & Werner, T. B. (2016). Effects of fishing rope strength on the severity of large whale entanglements. *Conservation Biology*, *30*, 318–328.

Large, K.; Roberts, J.; Francis, M., & Webber, D. (2019). Spatial assessment of fisheries risk for New Zealand sea lions at the Auckland Islands. *New Zealand Aquatic Environment and Biodiversity Report No. 224*. 85 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=24724

Laverick, S.; Douglas, L.; Childerhouse, S., & Burns, D. (2017). *Entanglement of cetaceans in pot/trap lines and set nets and a review of potential mitigation methods*. Unpublished report by Blue Planet Marine, BPM-17-DOC-New Zealand entanglement mitigation review-v1.1. 23/07/2017. 75 p.

Leaper, R. & Calderan, S. (2018). Review of methods used to reduce risks of cetacean bycatch and entanglements. In *12th meeting of the conference of the parties, Manila,* *Philippines, 23–28 October 2017, UNEP/CMS/COP12/Inf. 15*. UNEP/Convention on the Conservation of Migratory Species of Wild Animals (CMS) Secretariat, Bonn, Germany.

Leeney, R. H.; Berrow, S.; McGrath, D.; O'Brien, J.; Cosgrove, R., & Godley, B. J. (2007). Effects of pingers on the behaviour of bottlenose dolphins. *Journal of the Marine Biological Association of the United Kingdom*, *87*, 129–133.

Lyle, J. M. & Wilcox, S. T. (2008). *Dolphin and seal interactions with mid-water trawling in the commonwealth small pelagic fishery, including an assessment of bycatch mitigation strategies*. Final report project R05/0996, The Tasmanian Aquaculture and Fisheries Institute, Hobart.

Lyle, J. M.; Willcox, S. T., & Hartmann, K. (2016). Underwater observations of seal–fishery interactions and the effectiveness of an exclusion device in reducing bycatch in a midwater trawl fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, *73*, 436–444.

Meyer, S. (2019). Desktop estimation of pinniped cryptic mortality in trawls using SLEDs. *New Zealand Aquatic Environment and Biodiversity Report No. 222*. 25 p.

Ministry for Primary Industries (2019). *Aquatic Environment and Biodiversity Annual Review 2018*. Wellington, New Zealand: Compiled by the Fisheries Science Team, Ministry for Primary Industries. 704 p.

Mooney, T. A.; Au, W. W. L.; Nachtigall, P. E., & Trippel, E. A. (2007). Acoustic and stiffness properties of gillnets as they relate to small cetacean bycatch. *ICES Journal of Marine Science: Journal du Conseil*, *64*(7), 1324–1332.

Moore, M.; Andrews, R.; Austin, T.; Bailey, J.; Costidis, A.; George, C.; Jackson, K.; Pitchford, T.; Landry, S.; Ligon, A.; McLellan, W.; Morin, D.; Smith, J.; Rotstein, D.; Rowles, T.; Slay, C., & Walsh, M. (2012). Rope trauma, sedation, disentanglement, and monitoring-tag associated lesions in a terminally entangled North Atlantic right whale (*Eubalaena glacialis*). *Marine Mammal Science*, E98–E113.

Moreno, C.; Castro, R.; Mújica, L., & Reyes, P. (2008). Significant conservation benefits obtained from the use of a new fishing gear in the Chilean Patagonian toothfish fishery. *CCAMLR Science*, *15*, 79–91.

Northridge, S.; Kingston, A.; Mackay, A., & Lonergan, M. (2011). *Bycatch of vulnerable species: Understanding the process and mitigating the impacts*. Final report to Defra Marine and Fisheries Science Unit, project no. MF1003. University of St Andrews, United Kingdom: Department for Environment, Food and Rural Affairs.

Northridge, S.; Sanderson, J. D.; Mackay, A., & Hammond, P. (2003). *Analysis and mitigation of cetacean bycatch in UK fisheries*. Final report to Defra Marine and Fisheries Science Unit, project no. MF0726. University of St Andrews, United Kingdom: Department for Environment, Food and Rural Affairs.

Omeyer, L.; Doherty, P. D.; Dolman, S.; Enever, R.; Reese, A.; Tregenza, N.; Williams, R., & Godley, B. J. (2020). Assessing the effects of banana pingers as a bycatch mitigation device for harbour porpoises (*Phocoena phocoena*). *Frontiers in Marine Science*, *7*, 285.

Pirotta, V.; Slip, D.; Jonsen, I. D.; Peddemors, V. M.; Cato, D. H.; Ross, G., & Harcourt, R. (2016). Migrating humpback whales show no detectable response to whale alarms off Sydney, Australia. *Endangered Species Research*, *29*, 201–209.

Purves, M. & Agnew, D. (2004). Killer whale (*Orcinus orca*) and sperm whale (*Physeter macrocephalus*) interactions with longline vessels in the Patagonian toothfish fishery at South Georgia, South Atlantic. *CCAMLR Science*, *11*, 111–126.

Ramm, K. (2010). Conservation services programme observer report, 1 july 2008 to 30 june 2009. Final Report, Department of Conservation, Wellington, New Zealand.

Roberts, J.; Webber, D.; Roe, W.; Edwards, C., & Doonan, I. (2019). Spatial risk assessment of threats to Hector's and Māui dolphins (*Cephalorhynchus hectori)*. *New Zealand Aquatic Environment and Biodiversity Report No. 214*. 168 p. Retrieved from https://www.mpi.govt.nz/dmsdocument/35007/direct

Robertson, B. C. (2015). Comment on "Review of research and assessments on the efficacy of sea lion exclusion devices in reducing the incidental mortality of New Zealand sea lions *Phocarctos hookeri* in the Auckland Islands squid trawl fishery". *Fisheries Research*, *165*, 127–129.

Rowe, S. J. (2007). A review of methodologies for mitigating incidental catch of protected marine mammals. *DoC Research & Development Series 282*. Department of Conservation, Wellington, New Zealand. 48 p.

Santana-Garcon, J.; Wakefield, C. B.; Dorman, S. R.; Denham, A.; Blight, S.; Molony, B. W., & Newman, S. J. (2018). Risk versus reward: Interactions, depredation rates, and bycatch mitigation of dolphins in demersal fish trawls. *Canadian Journal of Fisheries and Aquatic Sciences*, *75*(12), 2233–2240.

Sharp, B. R. (2018). Spatially Explicit Fisheries Risk Assessment (SEFRA): A framework for quantifying and managing incidental commercial fisheries impacts on non-target species and habitats. Chapter 3. In *Aquatic Environment and Biodiversity Annual Review 2018*. 38 p. Wellington, New Zealand: Compiled by the Fisheries Management Science Team, Ministry for Primary Industries.

Starr, P. & Langley, A. (2000). *Inshore fishery observer programme for Hector's dolphin in Pegasus Bay, Canterbury Bight, 1997/98*. Wellington, New Zealand: Department of Conservation. Retrieved from http://www.doc.govt.nz/upload/documents/science-and-technical/CSL3020.PDF

Stephenson, P. & Wells, S. (2008). Evaluation of the effectiveness of reducing dolphin catches with pingers and exclusion grids in the pilbara trawl fishery. *Final FRDC Report No. 173, Project 2004/068*. Fisheries Research Division, Western Australia. 44 p.

Stone, G. S.; Cavagnaro, L.; Hutt, A.; Kraus, S.; Baldwin, K., & Brown, J. (2000). *Reactions of Hector's dolphins to acoustic gillnet pingers*. Published report on contract 3071, funded by Conservation Services Levy. 29 p. Retrieved from https://www.doc.govt.nz/globalassets/documents/science-and-technical/csl3071.pdf

Stone, G.; Kraus, S.; Hutt, A.; Martin, S., et al. (1997). Reducing by-catch: Can acoustic pingers keep Hector's dolphins out of fishing nets? *Marine Technology Society Journal*, *31*, 3.

Thompson, F. N.; Abraham, E. R., & Berkenbusch, K. (2013). Common dolphin (*Delphinus delphis*) bycatch in New Zealand commercial trawl fisheries. *PLoS ONE*, *8*, e64438. doi:10.1371/journal.pone.0064438

Thompson, F. N.; Abraham, E. R., & Berkenbusch, K. (2017). Preparation of data on observed protected species captures, 2002–03 to 2014–15. *New Zealand Aquatic Environment and Biodiversity Report No. 192*. 24 p.

Tilzey, R.; Goldsworthy, S.; Cawthorn, M.; Calvert, N.; Hamer, D.; Russel, S., & Stewardson, C. (2006). *Seal-fishery interactions in the winter blue grenadier fishery off west Tasmania and the development of fishing practices and Seal Exclusion Devices to mitigate seal bycatch by factory trawlers*. Project no 2001/008. 78 p. Fisheries Research and Development Corporation, Deakin West, ACT, Australia.

Van der Hoop, J. M.; Moore, M. J.; Barco, S. G.; Cole, T. V. N.; Daoust, P.-Y.; Henry, A. G.; McAlpine, D. F.; McLellan, W. A.; Wimmer, T., & Solow, A. R. (2012). Assessment of management to mitigate anthropogenic effects on large whales. *Conservation Biology*, *27*(1), 121–133.

van Marlen, B. (2019). *NEphrops and CEtacean Species Selection Information and TechnologY*. Wageningen, The Netherlands: NECESSITY, contract 501605, final publishable activity report. IMARES. 69 p.

Wakefield, C. B.; Santana-Garcon, J.; Dorman, S. R.; Blight, S.; Denham, A.; Wakeford, J.; Molony, B. W., & Newman, S. J. (2017). Performance of bycatch reduction devices varies for chondrichthyan, reptile, and cetacean mitigation in demersal fish trawls: Assimilating subsurface interactions and unaccounted mortality. *ICES Journal of Marine Science*, *74*, 343–358.

Werner, T. B.; Northridge, S.; Press, K. M., & Young, N. (2015). Mitigating bycatch and depredation of marine mammals in longline fisheries. *ICES Journal of Marine Science*, *72*, 1576–1586.

APPENDIX A: Fishery target species

Table A-1: Definition for the New Zealand target fisheries referred to in the current study of marine mammal captures.

Method	Target fishery	Target species
Set net	Flat fish	Flatfish, black flounder, flounder, New Zealand sole, greenback flounder, lemon sole, sand flounder, yellow-belly flounder, brill, turbot.
	Minor species	Tarakihi, trevally, butterfish, snapper, ling, common warehou, kahawai, monk fish, hapuku and bass, gurnard, bluenose.
	Shark	Shark, rig, school shark, spiny dogfish, elephant fish.
Trawl	Squid	Squid.
	Hoki	Hoki.
	Deepwater	Orange roughy, oreos, cardinalfish, Patagonian toothfish.
	Southern blue whiting	Southern blue whiting.
	Mackerel	Jack mackerel, blue mackerel.
	Scampi	Scampi.
	Middle depth	Barracouta, warehou, hake, alfonsino, ling, gemfish, bluenose, sea perch, ghost shark, spiny dogfish, rubyfish, frostfish.
	Inshore	Tarakihi, snapper, gurnard, red cod, trevally, John dory, giant stargazer, elephantfish, queen scallop, leatherjacket, school shark, blue moki, blue cod, rig, hāpuku & bass.
	Flatfish	Flatfish, lemon sole, sand flounder, New Zealand sole, yellow-belly flounder, flounder, greenback flounder, turbot, brill, black flounder.
Bottom longline	Ling	Ling.
	Snapper	Snapper.
	Bluenose	Bluenose.
	Other	Hāpuku & bass, school shark, gurnard, blue cod, ribaldo, Patagonian toothfish, tarakihi, trumpeter, silver warehou, red snapper, gemfish.
Surface longline	Bigeye	Bigeye tuna.
	Southern bluefin	Southern bluefin tuna.
	Albacore	Albacore tuna.
	Swordfish	Swordfish.
	Other	Yellowfin tuna, Pacific bluefin tuna, snapper, Northern bluefin tuna.

APPENDIX B: Observer coverage by target fishery and gear

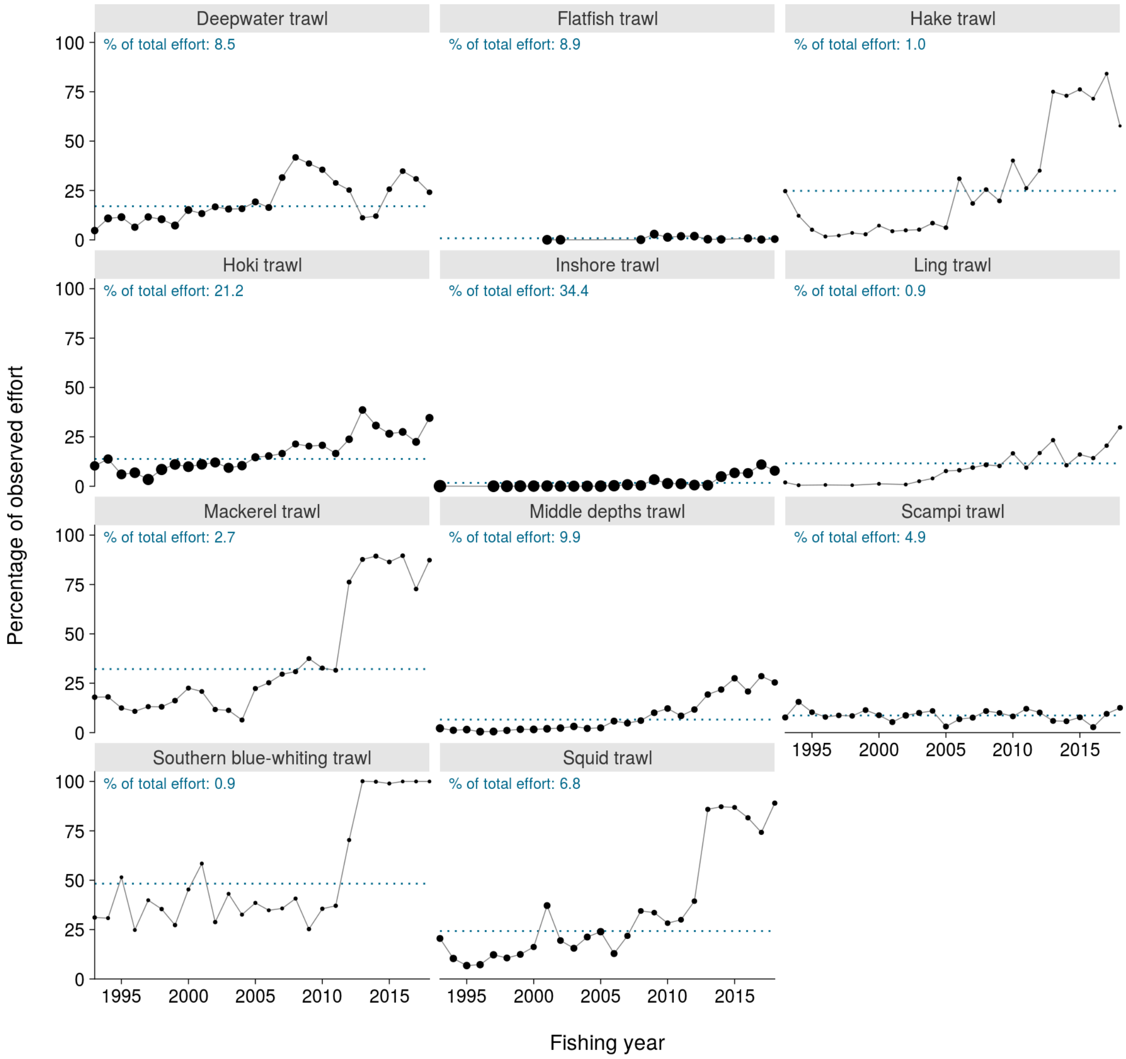

Figure B-1: Observer coverage for trawl fisheries by target species, for the period between 1992–93 and 2017–18. Observer coverage was calculated as the percentage of effort when an observer was present to total effort for the target fishery during that year, as reported in the *warehou* database. Effort measure was the number of tows. Dotted line indicates the average observer coverage rate, the percentage of total trawl effort directed towards the target species category is indicated in the top-left corner of each panel. The size of the circles scales with the overall trawl effort.

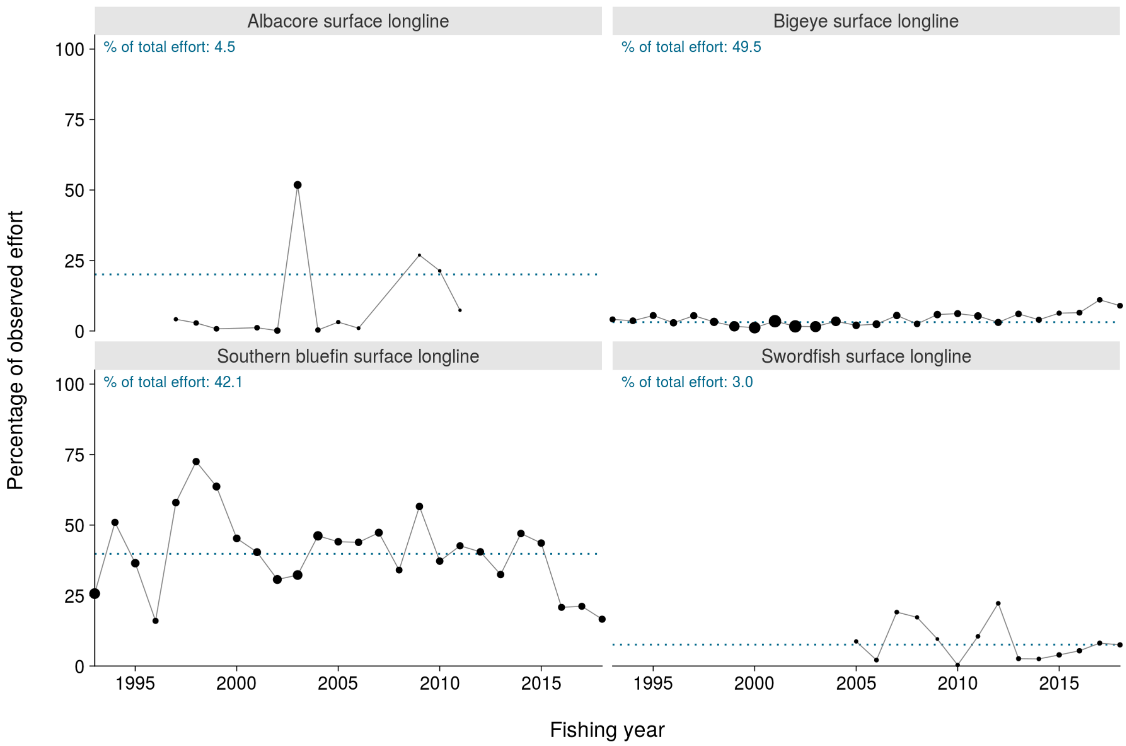

Figure B-2: Observer coverage for surface-longline fisheries by target species, for the period between 1992–93 and 2017–18. Observer coverage was calculated as the percentage of effort when an observer was present to total effort for the target fishery during that year, as reported in the *warehou* database. Effort measure was the number of hooks. Dotted line indicates the average observer coverage rate, the percentage of total surface-longline effort directed towards the target species category is indicated in the top-left corner of each panel. The size of the circles scales with the overall effort for surface longline.

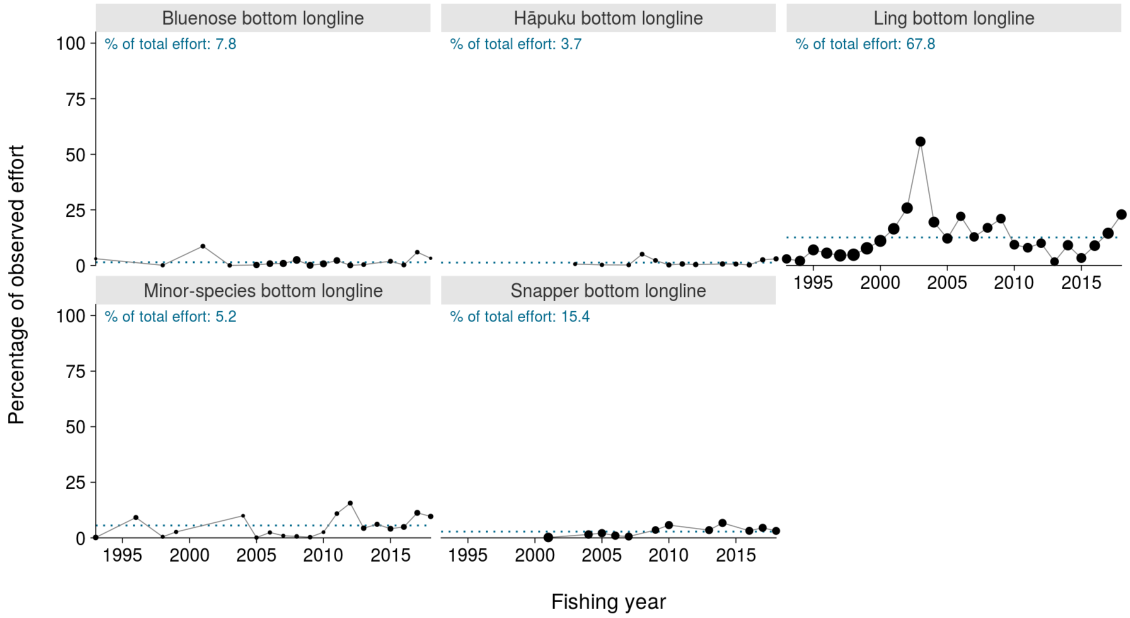

Figure B-3: Observer coverage for bottom-longline fisheries by target species, for the period between 1992–93 and 2017–18. Observer coverage was calculated as the percentage of effort when an observer was present to total effort for the target fishery during that year, as reported in the *warehou* database. Effort measure was the number of hooks. Dotted line indicates the average observer coverage rate, the percentage of total bottom-longline effort directed towards the target species category is indicated in the top-left corner of each panel. The size of the circles scales with the overall effort for bottom longline.

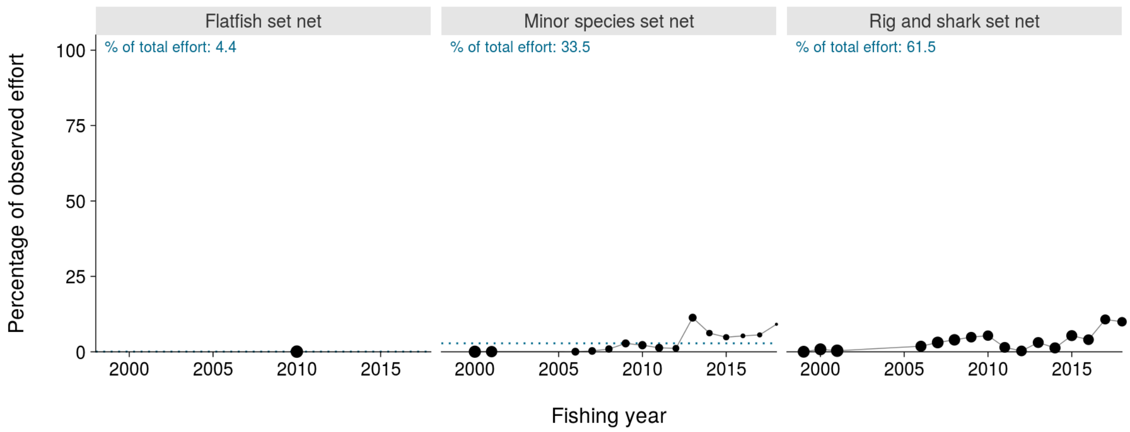

Figure B-4: Observer coverage for set-net fisheries by target species, for the period between 1998–99 and 2017–18. Observer coverage was calculated as the percentage of effort when an observer was present to total effort for the target fishery during that year, as reported in the *warehou* database. Effort measure was the length of net in metres. Dotted line indicates the average observer coverage rate, the percentage of total set-net effort directed towards the target species category is indicated in the top-left corner of each panel. The size of the circles scales with the overall effort for set net.

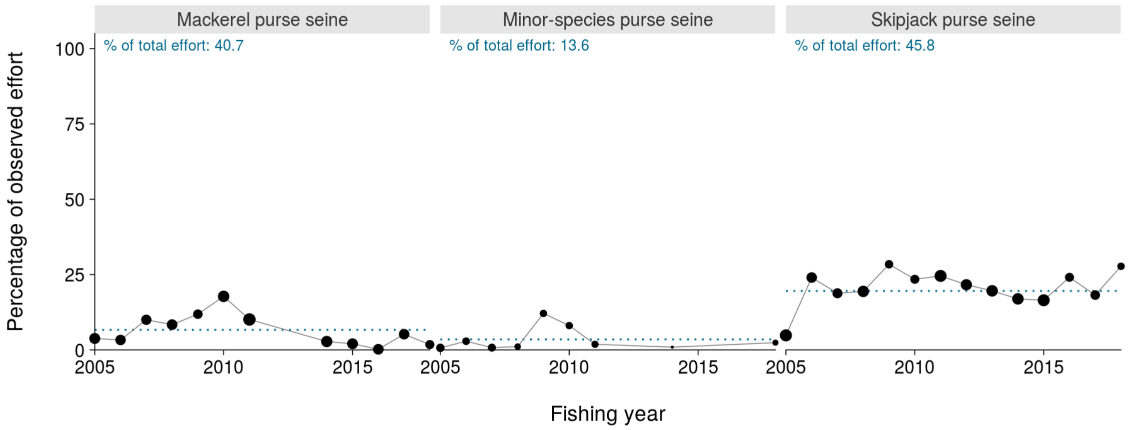

Figure B-5: Observer coverage for purse-seine fisheries by target species, for the period between 2004–05 and 2017–18. Observer coverage was calculated as the percentage of effort when an observer was present to total effort for the target fishery during that year, as reported in the *warehou* database. Effort measure was the number of sets. Dotted line indicates the average observer coverage rate and the percentage of total purse-seine effort directed towards that target species category is indicated in the top-left corner of each panel. The size of the circles scales with the overall effort for that gear.