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Tini a Tangaroa

# Desktop update of estimation of seabird cryptic mortality in trawls, via warp and net captures in the New Zealand domestic fleet using standard mitigation

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Stefan Meyer

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Fisheries New Zealand  
Ministry for Primary Industries  
PO Box 2526  
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Email: [Fisheries-Science.Editor@mpi.govt.nz](mailto:Fisheries-Science.Editor@mpi.govt.nz)  
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## **TABLE OF CONTENTS**

<b>EXECUTIVE SUMMARY</b>	<b>1</b>
<b>1. INTRODUCTION</b>	<b>2</b>
<b>2. METHODS</b>	<b>3</b>
2.1 Net captures	6
2.2 Warp strikes	10
2.3 Cryptic mortality multiplier	16
<b>3. RESULTS</b>	<b>16</b>
<b>4. DISCUSSION</b>	<b>17</b>
<b>5. ACKNOWLEDGEMENTS</b>	<b>19</b>
<b>6. REFERENCES</b>	<b>19</b>
<b>APPENDIX A: Source code for modelling cryptic mortality in net captures</b>	<b>21</b>
<b>APPENDIX B: Source code for modelling cryptic mortality in warp strikes</b>	<b>25</b>
<b>APPENDIX C: Contextualisation of estimated cryptic mortality multipliers in regard to fishery groups used in SEFRA</b>	<b>28</b>



## EXECUTIVE SUMMARY

**Meyer, S.<sup>1</sup> (2023). Desktop update of estimation of seabird cryptic mortality in trawls, via warp and net captures in the New Zealand domestic fleet using standard mitigation.**

*New Zealand Aquatic Environment and Biodiversity Report No. 322. 28 p.*

Estimated seabird captures are based on data collected through the fisheries observer services operated by the Ministry for Primary Industries. Each year, observers are placed on a sample of fishing trips to record fishing activity including the capture of protected species such as seabirds. First, seabirds can get caught or entangled in the mesh of the net and these captures can occur either inside or outside the net. Second, seabirds might experience a heavy contact with the warp cable during flight (potentially leading to sustained injuries) or while on the water (and then getting pulled under water). However, net captures and warp strikes are only recorded if affected birds are either returned to the vessel or were visible to the observer but then were knowingly lost prior to retrieval. Unknown seabird captures that cannot be retained until after hauling or until being at least visible to the observer are unobservable or cryptic. Cryptic mortality is one of the key parameters in the Spatially Explicit Fisheries Risk Assessment (SEFRA) framework, which is designed to estimate population-level risk to non-target species due to incidental mortality in commercial fisheries. In the SEFRA, risk is defined as a function of biological parameters (e.g., maximum population growth rate) and population-level impact, the latter including total fishery-related deaths. In the SEFRA framework, observable captures are modelled using data inputs for observed captures, spatial distribution of fishing intensity, and species distribution. However, not all observable captures result in mortalities and therefore need to be adjusted for cryptic mortality (and live release survival) to obtain an estimate of total fishery-related deaths. Cryptic mortality is usually estimated outside the SEFRA framework and then applied to estimated observable captures to obtain total fishery-related deaths. Including cryptic mortality in the SEFRA framework is crucial because it can have dramatic effects on estimated total fishery-related deaths, for example, in trawl fisheries where seabirds can get caught on warps and pulled under water but are not necessarily observed and/or recovered.

This study specifically assessed cryptic mortality of seabirds in trawl fisheries operating in New Zealand's Exclusive Economic Zone. Cryptic mortality multipliers (a correction factor for estimated seabird mortality based on observed captures) were estimated for net captures and warp strikes.

The estimated cryptic mortality multiplier for net captures was 2.538 (95% credible interval: 1.128–9.323) suggesting that net capture-related mortality was, on average, 2.5 times higher than when only based on observed captures. For warp strikes, 9 alternative models were tested that differed in the type of available input data. Estimated cryptic mortality multipliers were strongly dependent on the input data used to apportion warp strikes to those occurring in-flight and on the surface. When using data for New Zealand trawl fisheries (observations took place only during the towing phase) then average estimates ranged between 7.306 and 9.704. In contrast, when using surrogate data collected from South African demersal fisheries (observations took place during setting, towing, and hauling), then average estimates were 331.38 and 372.32. However, there was substantial uncertainty in these estimates and, further, seabird species composition and fishing practice (e.g., offal discharge management) might not be comparable with the New Zealand fishery.

The results of this study show that there is the need for the collection of data specifically aimed at assessing cryptic mortality in New Zealand trawl fisheries. The data used in this study were not fit for purpose and were partially characterised by sparseness.

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<sup>1</sup> Proteus, Otago, New Zealand.

## 1. INTRODUCTION

In New Zealand commercial fisheries, estimates of accidental seabird captures are based on data collected through the Fisheries New Zealand observer services operated by the Ministry for Primary Industries (MPI). Each year, observers are placed on a sample of fishing trips to record fishing activity including the capture of protected species such as seabirds. However, protected species captures can only be recorded if observable (e.g., when brought onto the vessel or when observers have identified a capture but it was knowingly unretrievable, e.g., due to safety concerns). Hence, the accuracy of estimated seabird captures relies heavily on the ability to retain or identify seabird captures (dead and alive) during fishing activity, specifically during hauling. Unknown seabird captures that are not retained until nets are hauled or are not at least visible to the observer are unobservable or cryptic (Pierre et al. 2014, Richard et al. 2020).

Cryptic mortality is one of the key parameters in the Spatially Explicit Fisheries Risk Assessment (SEFRA) framework, which is designed to estimate population-level risk to non-target species due to incidental mortality in commercial fisheries (Fisheries New Zealand 2022). Population-level risk is defined as a function of biological parameters (e.g., maximum population growth rate, total population size) and population-level impact, the latter including total fishery-related deaths. In the SEFRA framework, observable captures are modelled as the product of the probability of encounter per individual (based on the spatial overlap between fishing effort intensity and species probability density), probability of capture per encounter, and the population size at the time of the fishing event (Fisheries New Zealand 2022). To obtain fishery-related deaths, observable captures need to be adjusted for individuals that are released alive and survive subsequently and for individuals that die due to fishery interaction and are not recorded as captures (e.g., when not recovered on board). The estimation of observable captures is informed by data collected through the fisheries observer services. In contrast, data on cryptic mortality are often scarce and therefore additional input from experts or other sources is required. Thus, cryptic mortality is usually estimated outside the SEFRA framework and then applied to estimated observable captures to obtain total fishery-related deaths. Including cryptic mortality in the SEFRA framework is crucial because it can have dramatic effects on estimated total fishery-related deaths, for example, in trawl fisheries where seabirds can get caught on warps and pulled under water but are not necessarily observed and/or recovered (Fisheries New Zealand 2022).

Currently, two processes are described for New Zealand trawl fisheries where seabirds can interact with fishing gear and cryptic mortality might occur (Fisheries New Zealand 2022). First, seabirds can get caught or entangled in the mesh of the net (e.g., in cod-end) and these captures can occur either inside or outside the net. Second, seabirds might experience a heavy contact with the warp cable during flight (potentially leading to sustained injuries) or while on the water (and then getting pulled under water). These two interactions are generally referred to as net captures and warp strikes, respectively.

The total number of interactions (i.e., observed and unobserved fatal captures, and unobserved non-fatal captures) is likely to be higher, but statistical estimates of interaction rates with warps are considered unconstrained (according to Fisheries New Zealand), at least for fisheries with low levels of observer coverage. The reason for this is that not all bird fatalities are recorded by observers, such as when the bird is not retrieved after being captured during interaction with fishing gear.

For example, seabirds can collide and entangle their wings with trawl warps or similar structures (i.e., warp strike) and then be pulled underwater. However, seabirds drowning because of warp strikes are only evident when those birds are retrieved and are showing obvious signs of warp strikes (e.g., snagged wings).

The frequency of warp strikes is influenced by factors such as (but not limited to):

- the presence and absence of offal discharge during the fishing operation (Middleton & Abraham 2007)

- the species (e.g., birds that forage more aggressively with outstretched wings tend to have a high mortality when colliding with trawl warps) (Richard et al. 2017)
- sea conditions (with less warp strikes during calm conditions as opposed to more warp strikes during rough sea conditions when the warp cable is subject to strong water movements) (Middleton & Abraham 2007)
- fishery groups (Richard et al. 2017)
- the mitigation strategy (Middleton & Abraham 2007).

This study specifically assessed cryptic mortality of seabirds in trawl fisheries operating in New Zealand’s Exclusive Economic Zone (EEZ). The Bayesian modelling framework has been described by Meyer (2019) and model parameterisation for this project has been done with consultation with the Fisheries New Zealand Aquatic Environmental Working Group (AEWG). Available information on factors influencing the probability of warp strikes, the probability of those being fatal, and the probability of observing fatal warp strikes and general net captures was integrated in a Bayesian modelling framework that was originally developed for the assessment of cryptic mortality of New Zealand sea lions (Meyer 2019; project code: PMM2018-19). Cryptic mortality multipliers were estimated separately for net captures and warp strikes to align them with the model structure for trawl fishery-related seabird mortality in recent versions of the seabird risk assessment (Edwards et al. 2023). These multipliers are based on different input data and expert knowledge when explicit data were absent. The Bayesian framework allowed the use of input priors to reflect uncertainty in expert-based estimates (i.e., range and shape of specific model parameters were defined). The resulting posterior distributions of the cryptic mortality multiplier reflect uncertainty in actual estimates and expert knowledge and importantly highlight the effects of lack of knowledge regarding cryptic mortality to provide incentives for fishers to modify at-sea behaviours and to collect better data (Fisheries New Zealand 2022).

### **Overall objective for Fisheries New Zealand project PSB2020-08**

To summarise and integrate existing data to estimate cryptic mortality of seabirds in trawls using standard mitigation measures, where estimates should explicitly contain uncertainty, and be specific to the capture method and fishery groups identified under project PRO2019-10.

**Objective 1:** Summarise existing data to assign priors for various parameters within a simple transition matrix model to estimate cryptic mortality of seabirds in trawls using standard mitigation, including rates of: live release survival; death by drowning in the net; death by warp strike; as well as rates of body retention vs. body non-retention in the net.

**Objective 2:** Construct a simple Bayesian model combining the parameter estimates from Objective 1, and fit to available data (e.g., pre- vs. post-tori line warp strike rates; results of autopsies; injury reporting codes; capture method) to estimate cryptic mortality.

## **2. METHODS**

The results from this project were aimed to inform the parameterisation of cryptic mortality multipliers in a spatially explicit seabird risk assessment (Edwards et al. 2023; project code: PRO2019-10), which currently models net captures and warp strikes individually. Therefore, net captures and warp strikes are both treated separately in this project as well.

For each process a state-transition matrix has been developed to reflect the sequential states of seabirds interacting with trawl nets and trawl warps. Prior distributions for transition probabilities for each of these states were developed as part of this project and a cryptic mortality multiplier was estimated, for both net captures and warp strikes, based on the transition probabilities that result in unobservable or cryptic states (see Figures 1 & 2). The data sources used in this project are listed in Table 1 and more details on their use are described in the subsequent sections. These datasets and publications were discussed during an initial scoping meeting with Fisheries New Zealand. It is important to note that

these datasets and studies were not specifically designed for the use in this desktop study here, and rather reflect the best available information to date.

Each model was developed using the cryptic mortality app originally developed for New Zealand sea lion cryptic mortality in trawl fisheries (Meyer 2019). JAGS code is provided in Appendices A and B.

Fishery groups are one of several structural assumptions in the SEFRA framework. Richard et al. (2020) defined fishery groups based on vessel length, target species, and presence of a fish freezer, assuming that the risk profile for catching seabirds varies across these variables (see for fishery groups and how they align with this study). These fishery groups were carried forward into a recent SEFRA update after a review described by Edwards et al. (2023). In their assessment, Edwards et al. (2023) found that, within trawl fisheries, vessels with large freezers (which can fish for longer periods than vessels without freezers) and vessels targeting squid in the sub-Antarctic account for 30% and 57% of all seabird catch in New Zealand’s trawl fisheries, respectively. While this study here was initially aimed at estimating cryptic mortality multipliers separately for fishery groups as described by Edwards et al. (2023), the available data were insufficient to support such detailed analysis. Instead, this analysis was based on the best available data, and estimated cryptic mortality multipliers are contextualised (in regard to fishery groups used in the SEFRA) in the discussion of this report.

**Table 1: Data and literature sources used to parameterise state-transition processes for net captures and warp strikes for seabirds in trawl fisheries. (Continued next page)**

Data	Description
Protected species captures database (PSCDB) version 6	<p>Database containing groomed data on commercial fishing effort (observed and unobserved) and records of observed protected species captures between the 1992–93 and 2019–20 fishing years. Database grooming is described by Abraham &amp; Berkenbusch (2019).</p> <p>Relevant data for this project included whether caught birds were recorded as alive or dead (database field: <code>alive_code</code>) and whether birds were caught internally or externally of the net (database field: <code>capture_method</code>)*. More detailed information of the capture location commenced recently with the introduction of the Observer Protected Species Interaction Form and is reflected in the PSCDB from the 2018–19 fishing year onwards.</p>
Mitigation Assessment Warp-Strike Form	<p>Records from experimental study to record factors potentially influencing warp strikes on inshore trawl vessels. The protocol is described by Department of Conservation and Ministry for Primary Industries (2013).</p> <p>Relevant data for this project were tow observations during which observers were tasked to undertake 15-minute sampling periods during each tow (in daylight) which were repeated every 20 minutes. Observers had to record heavy contacts with the trawl warp and mitigation device, where heavy contacts were defined as the bird:</p> <ul style="list-style-type: none"> <li>• has its path of movement deviated when it comes into contact with the trawl warp, and the part of the body contacted is above the ‘wrist’ joint of the bird (i.e., on the upper part of the wing and or on the head or body).</li> </ul> <p>Observations were carried out during the fishing phase of the tow (i.e., when the net is in the water and cables are no longer being paid out). The information used here was as to whether warp strikes occurred on the surface (surface strikes) or in-flight (aerial strikes). Note, that warp strike-specific observations during setting or hauling were not collected.</p>
Richard et al. (2020)	<p>Risk assessment for seabirds in commercial New Zealand fisheries containing previously used information for the parameterisation of cryptic mortality multipliers. Here, a previously defined prior for body non-retention was used because data on seabird body retention in trawl nets are currently unavailable.</p>

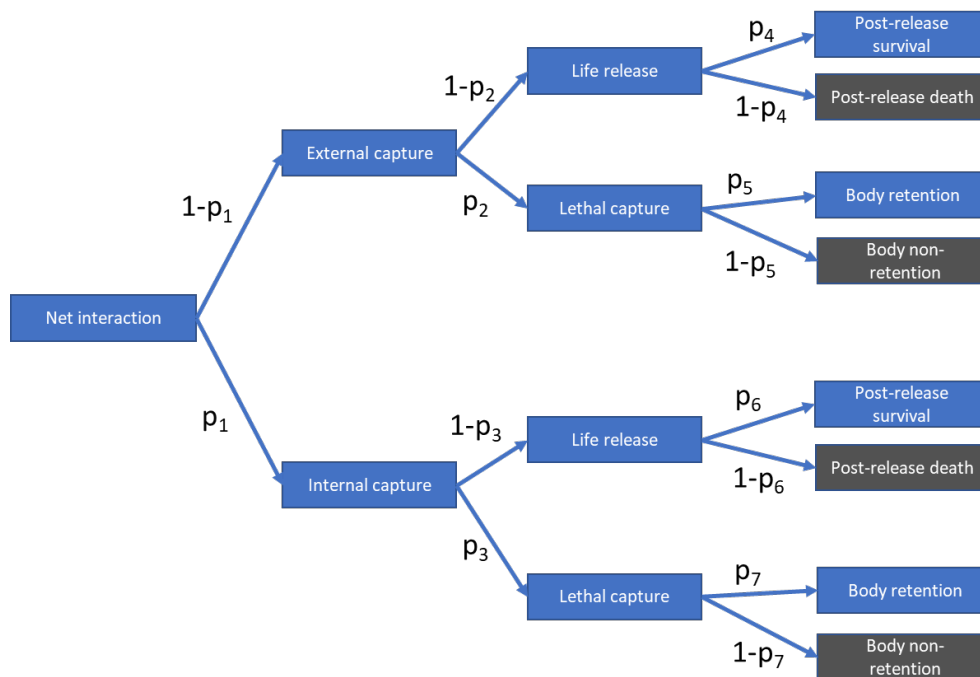


Data	Description
Parker et al. (2013)	<p>Study investigating cryptic mortality due to warp strikes in the Falkland Islands demersal trawl fishery. This study investigated whether the outcome of interactions between seabirds and warp cables could be confirmed by using a following vessel to observe the wake of the trawler, beyond the detection range of observer(s) positioned on the fishing vessel. Further, Parker et al. (2013) used corpse catcher devices to increase the chance of retaining birds killed by warp strikes.</p> <p>Relevant data for this project were taken from published data points on the number of observed warp strike-related mortalities recorded by observers on the fishing vessel and following vessel. Fishing trips where corpse catcher devices were used have been omitted from the analysis.</p> <p>Further, tori lines were used by trawlers in this study. This allowed the generation of input data for strikes separately for warps and tori lines as well as both combined.</p>
Watkins et al. (2008)	<p>Study assessing interactions (including warp strikes) between seabirds and deepwater hake trawl fisheries in South Africa. Observers were placed on commercial trawlers operating from mid-2004 to the end of 2005 (during daylight hours) to observe the number of birds attending vessels in relation to fishing activity. Observations re warp strikes were done in at least 5-min observation periods during trawling and provide information on species-specific numbers of surface strikes vs. aerial strikes. As per Watkins et al. (2008), seabirds were dragged under water during setting, trawling, and hauling operations. However, no specific description was provided to explain during which of these three phases most warp strikes were observed or whether the ratio of surface to warp strikes differed between setting, trawling, and hauling. Note, that no bird scaring lines were used during the study period (these were introduced to the South African deep-water trawl fishery from 1 August 2006).</p>
Edwards et al. (2023)	<p>Summary of data sources for a preliminary parameterisation of cryptic mortality for the seabird risk assessment under contract PRO2019-10. Edwards et al. (2023) aggregated data published by Watkins et al. (2008) into small- to medium-sized and large birds. The following birds were classified as small- to medium-sized birds:</p> <ul style="list-style-type: none"> <li>• Kelp gull</li> <li>• Cape gannet</li> <li>• Wilson’s storm petrel</li> <li>• Cape petrel</li> <li>• White-chinned petrel</li> <li>• Sooty shearwater</li> </ul> <p>Large birds included the following species:</p> <ul style="list-style-type: none"> <li>• Subantarctic skua</li> <li>• Shy albatross</li> <li>• Black-browed albatross</li> <li>• Yellow-nosed albatrosses</li> <li>• Giant petrels</li> <li>• Great shearwater</li> </ul> <p>Aggregated data from Watkins et al. (2008) as provided by Edwards et al. (2023) were used in this study here as an alternative data set to estimate the probability of surface strikes (as optional alternative to data based on Mitigation Assessment Warp-Strike Forms) and to estimate the probability of lethal surface strikes (as optional alternative to the data provided by Parker et al. (2013)).</p>

\* The PSCDB contains a general code for warp strikes only, but surface and aerial strikes are not further specified. Surface and aerial strikes were therefore modelled using data obtained from the Mitigation Assessment Warp-Strike Form.

## 2.1 Net captures

Fishing activity attracts seabirds, and these can get entangled during shooting or hauling of the net. Most birds are caught during hauling and these captures can occur internally (i.e., when trapped inside the net) and externally (often when the mesh tightens and closes). There are two main processes leading to cryptic (i.e., unobservable) mortality of seabirds due to net entanglement. First, some birds (mainly those caught externally) can get released by the crew. However, some released birds might die subsequently due to sustained injuries. Because the fate of released birds is unknown, any post-release mortality caused by net entanglement is considered as cryptic. Second, entangled birds are only observable if retained during hauling or at least being sighted by an observer, but the animal was not recoverable. Nevertheless, widening and tightening of the mesh during hauling can lead to some caught birds getting lost (and previous sighting of these birds is not guaranteed), in which case they are unobservable and cannot be counted against captures by the observer. The sequential states of seabirds during trawl net interactions are shown in the state-transition matrix in Figure 1 and are further described in Table 2.



**Figure 1:** State-transition matrix for seabird-trawl net interactions; boxes for cryptic (i.e., unobservable) death-related states are coloured in grey; letter across rows denote transition probabilities.

**Table 2: Description of states to model seabird-trawl net interactions (Figure 1); available data sources to estimate transition probabilities are also listed. The same states for internal and external captures are only described once but note that these could have different transition probabilities; PSCDB: Protected Species Captures database.**

State	Description	Data/literature sources
Net interaction	Bird gets in vicinity of trawl net, e.g., to prey on species targeted by crew.	–
External capture	The bird is caught/tangled in the mesh of the cod-end, lengthener/taper, or net wings/body.	PSCDB
Internal capture	The bird is caught inside the trawl net/cod-end/pounds.	PSCDB
Live release	The bird is released alive by the crew.	PSCDB
Lethal capture	The captured bird dies.	PSCDB
Post-release survival	The alive bird that was released by the crew has not sustained any serious injuries and thus survives.	–
Post-release death	The alive bird that was released by the crew has sustained serious injuries resulting in its subsequent death.	–
Body retention	The death of the captured bird is observable because the body has been retained.	Richard et al. (2020)
Body non-retention	The death of the captured bird is unobservable because the body was not retained in or outside the net.	Richard et al. (2020)

Where possible, transition probabilities were estimated. If data were unavailable, then published values from the literature were used or best estimates applied. Estimated parameters or literature values for transition probabilities to model net captures are provided in Table 3 and are further described here.

**Table 3: Summary of prior distributions derived from data or literature for transition probabilities of net captures (see Figure 1); PSCDB: Protected Species Capture database; shown are the type of distribution and relevant summary statistics (note for normal distribution with logit-link also estimates on probability scale are shown in parentheses; for calculation of  $p_5$  and  $p_7$ , odds ratios are given).**

Parameter	Distribution	Mean/Range	SD	95% CI	$\mu$ ; $\sigma$	Source
$p_1$ (internal capture)	Normal (logit-link)	-0.047 (0.488)	0.085 (0.021)	-0.212–0.117 (0.447–0.530)	–	Estimated from PSCDB
$p_2$ (lethal capture – external)	Normal (logit-link)	0.162 (0.540)	0.119 (0.029)	-0.067–0.397 (0.482–0.597)	–	Estimated from PSCDB
$p_3$ (lethal capture – internal)	Normal (logit-link)	1.983 (0.877)	0.179 (0.019)	1.644–2.343 (0.838–0.912)	–	Estimated from PSCDB
$p_4$ (post-release survival – external)	Uniform	0.5–1	–	–	–	–
Odds ratio of body non-retention (external) to calculate $p_5$	Log-normal	0.3	–	0.1–0.7	-1.330; 0.486	Richard et al. (2020)
$p_6$ (post-release survival – internal)	Uniform	0.5–1	–	–	–	–
Odds ratio of body non-retention (external) to calculate $p_7$	Log-normal	0.3	–	0.1–0.7	-1.330; 0.486	Richard et al. (2020)

**Probability of internal net captures ( $p_1$ ).** The PSCDB contains information regarding the number of observed captured seabirds per fishing event (stored in the `all_captures_t` table) including additional information on the capture location (column: `capture_method`). The `all_captures_t` table of the PSCDB version 6 was queried for internal net captures (`capture_method` was NI, i.e., caught inside the trawl net/cod-end/pounds, as per Protected Species Interaction (PSI) form) and external net captures (`capture_method` was NC, NL, or NW; i.e., caught/tangled in the mesh of the cod-end, lengthener/taper, or net wings/body, respectively) during the 2019–20 fishing year. Prior to that fishing year, some captures were still coded as net captures only and thus were not useful for distinguishing between internal and external captures. For each row in the queried data, internal net captures were coded as 1 and 0 otherwise. The probability of internal net captures ( $p_1$ ) was estimated in JAGS by fitting a Bernoulli distribution to the Boolean coded data for internal vs. external net captures. The prior distribution for  $p_1$  was defined as a beta distribution with both shape parameters being set to 1. Estimates for  $p_1$  are shown in Table 3. The prior distribution derived from this model was supplied as a normal distribution on logit-scale to ensure that the modelled distribution lies within the range of 0 to 1.

**Probability of an external net capture being lethal ( $p_2$ ).** The `all_captures_t` table of the PSCDB version 6 was queried for external net captures (`capture_method` was NC, NL, or NW; i.e., caught/tangled in the mesh of the cod-end, lengthener/taper, or net wings/body, respectively) as well as dead and alive birds (alive code was 1 and 2, respectively) during the 2018–19 and 2019–20 fishing years. For the 2018–19 data, net capture records were omitted when internal and external net captures were not specifically recorded. For each row in the queried data, dead captures were coded as 1 and 0 (i.e., released alive) otherwise. The probability of a lethal external net capture ( $p_2$ ) was estimated in JAGS by fitting a Bernoulli distribution to the Boolean coded data for dead captures vs. alive release. The prior distribution for  $p_2$  was defined as a beta distribution with both shape parameters being set to 1. Estimates for  $p_2$  are shown in Table 3. The prior distribution derived from this model was a normal distribution on logit-scale to ensure that the modelled distributions is within the range of 0 to 1.

**Probability of an internal net capture being lethal ( $p_3$ ).** The `all_captures_t` table of the PSCDB version 6 was queried for internal net captures (`capture_method` was NI, i.e., caught inside the trawl net/cod-end/pounds, as per Protected Species Interaction (PSI) form) as well as dead and alive birds (alive code was 1 and 2, respectively) during the 2018–19 and 2019–20 fishing years. For the 2018–19 data, net capture records were omitted when internal and external net captures were not specifically recorded. For each row in the queried data, dead captures were coded as 1 and 0 (i.e., released alive) otherwise. The probability of a lethal internal net capture ( $p_3$ ) was estimated in JAGS by fitting a Bernoulli distribution to the Boolean coded data for dead captures vs. alive release. The prior distribution for  $p_2$  was defined as a beta distribution with both shape parameters being set to 1. Estimates for  $p_2$  are shown in Table 3. The prior distribution derived from this model was a normal distribution on logit-scale to ensure that the modelled distribution is within the range of 0 to 1.

**Probability of post-release survival for external captures ( $p_4$ ).** Data for post-release survival (i.e., for seabirds that were released from the net by a crew member) are not available and there exists, to our knowledge, currently no published study on post-release survival of seabirds that were entangled in trawl nets. Therefore, a uniform distribution in the range of 0.5 to 1 was used to model post-release survival for seabirds caught inside the net. This assumes that between 50% and 100% of released birds would survive but also acknowledges that the actual survival is unknown.

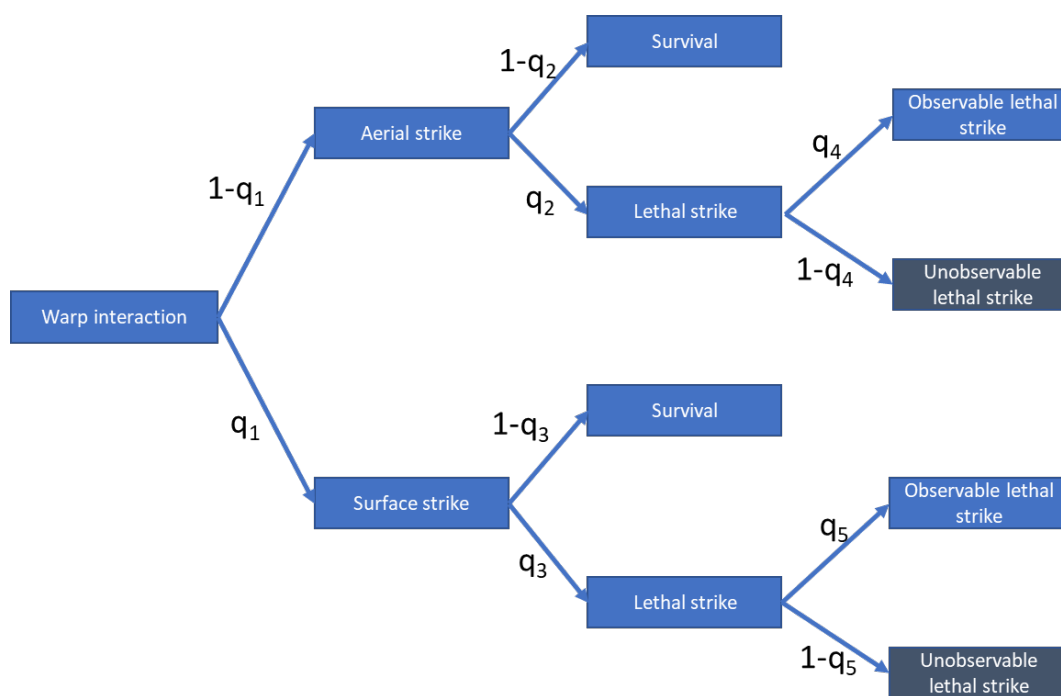
**Probability of post-release survival for internal captures ( $p_6$ ).** The same as  $p_4$  because there exists no sufficient information to distinguish between post-release survival of birds that were entangled the inside or outside the net.

**Probability of body retention for external captures ( $p_5$ ).** Data for body retention of external captured seabirds do not exist. Richard et al. (2020) assumed an odds ratio for body retention (for internal and external captures combined) using a log-normal prior with a mean of 0.3 and 95% confidence interval of 0.1–0.7. Since there is no other available information, the same prior distribution was used in this study.  $p_5$  was then calculated as odds of body non-retention/(1+ odds of body non-retention).

**Probability of body retention for internal captures ( $p_7$ ).** Data for body retention of external captured seabirds do not exist. Richard et al. (2020) assumed a body retention (for internal and external captures combined) using a log-normal prior with a mean of 0.3 and 95% confidence interval of 0.1–0.7. Since there exists is no other available information, the same prior distribution was used in this study.  $p_7$  was then calculated as body: odds of body non-retention/(1+ odds of body non-retention).

## 2.2 Warp strikes

Seabirds can come into contact with warp cables that are used to tow trawl nets. These warp strikes can occur for birds in-flight (aerial strikes) or while being on the water (surface strikes). Most mortality is assumed to be caused by surface strikes when wings get entangled around the warp cable and then the bird is dragged under water while water flows over the warp. Observers, however, are only able to count surface warp strikes if the body is somehow retained (predominantly when snagged on warp splices) and returned to the vessel. Note that the assumption of surface warp strikes only being observable if retained is based on the interpretation done in consultation with the AEWG. The instructions for the Protected Species Interaction (PSI) form, used by fishery observers, asks the observers to record whether captures occurred “on warp or door”. This implies that the seabird experiencing a warp strike was retained, i.e., caught on the warp cable. Seabirds that are entangled around the warp cable but fall off and are not landed on the vessel are therefore unobservable. Birds caught by aerial strikes (i.e., a heavy collision during flight leading to sustained injuries) are not retained and are therefore considered entirely cryptic to the observer. The different states that can occur during warp strikes are described in Figure 2 and Table 4.



**Figure 2:** State-transition matrix for seabird-trawl warp interactions. Boxes for cryptic (i.e., unobservable) death-related states are coloured in grey. Note, strikes with tori lines are not shown for simplicity but would be characterised by the same states as shown for aerial and surface strikes.

**Table 4: Description of states to model seabird-trawl warp interactions (Figure 2); available data sources to estimate transition probabilities are also listed. The same states for aerial and surface strikes are only described once but note that these could have different transition probabilities.**

State	Description	Data/literature sources
Warp interaction		–
Aerial strike	Heavy contact* between bird and warp cable in the air.	Mitigation Assessment Warp-Strike Form
Surface strike	Heavy contact* between bird and warp cable on the water.	Mitigation Assessment Warp-Strike Form
Survival	Bird survives heavy contact with warp cable.	Parker et al. (2013)
Lethal strike	Bird dies due to heavy contact with warp cable.	Parker et al. (2013)
Observable lethal strike	The lethal strike between bird and warp cable is observable from the fishing vessel.	Parker et al. (2013)
Unobservable lethal strike	The lethal strike between bird and warp cable is unobservable from the fishing vessel.	Parker et al. (2013)

\* as per Seabird Warp-Strike Measurement Protocol, a heavy contact is one in which a bird:

- has its path of movement deviated when it comes into contact with the trawl warp, and
- the part of the body contacted is above the ‘wrist’ joint of the bird (i.e., on the upper part of the wing and or on the head or body).

This can occur on the water or in the air. Birds on the water may be dragged under the water by a heavy contact. Heavy contacts occur either when the bird, through active movement, comes into contact with the warp/mitigation device, or when the warp/mitigation device moves to contact the bird (e.g., whilst the bird is sitting on the water).

Where possible, transition probabilities were estimated. If data were unavailable, then published values from the literature were used or best estimates applied. Estimated parameters or literature values for transition probabilities to model net captures are provided in Table 5 and are further described here. Note, that for warp strikes alternative datasets were available. Further, data provided by Parker et al. (2013) can be aggregated into groups with alternative definitions regarding the identification of bird mortalities, as well as split into strikes with warp cables and tori lines. Therefore, nine alternative sensitivity scenarios were considered (labelled from Sens1 to Sens9; see Table 5)).

**Table 5: Summary of prior distributions derived from data or literature for transition probabilities of warp and tori line strikes (see Figure 2); estimates on probability scale are shown; priors are supplied as normal distribution on logit-scale and summary statistics; first column shows how parameters were combined for 9 different sensitivity trials. (Continued next page)**

Sensitivities	Parameter	Mean	SD	95% CI (prob scale)	$\mu; \sigma$	Source
Sens1– Sens7	$q_1$ (surface strike)	1.362 (0.787)	0.477 (0.076)	0.492–2.352 (0.623–0.915)	–	Mitigation Assessment Warp-Strike Form
Sens8	$q_1$ (surface strike) – large seabirds	-0.533 (0.370)	0.106 (0.025)	0.322–0.419		Edwards et al. (2023) using data from Watkins et al. (2008)
Sens9	$q_1$ (surface strike) – “small-sized” and “medium-sized” seabirds	-1.373 (0.203)	0.101 (0.016)	0.172–0.236		Edwards et al. (2023) using data from Watkins et al. (2008)
Sens1– Sens9	$q_2$ (lethal strike – aerial)	0.007 (log- normal)		0.005–0.01	-4.952; 0.173	Personal communication with Graham Parker
Sens1	$q_3$ (lethal strike – surface) – dead only (warp + tori)	-3.147 (0.042)	0.290 (0.011)	-3.744–2.619 (0.023–0.067)	–	Parker et al. (2013)
Sens2	$q_3$ (lethal strike – surface) – dead + broken wings (warp + tori)	-3.067 (0.046)	0.279 (0.012)	-3.658–2.559 (0.026–0.072)	–	Parker et al. (2013)
Sens3	$q_3$ (lethal strike – surface) – dead birds + broken wings + suspected and possible deaths (warp + tori)	-2.855 (0.056)	0.250 (0.013)	-3.363–2.390 (0.033–0.084)	–	Parker et al. (2013)
Sens4	$q_3$ (lethal strike – surface) – dead only (warp only)	-3.029 (0.048)	0.297 (0.013)	-3.642–2.488 (0.025–0.077)	–	Parker et al. (2013)
Sens5	$q_3$ (lethal strike – surface) – dead + broken wings (warp only)	-2.944 (0.052)	0.287 (0.014)	-3.537–2.415 (0.028–0.081)	–	Parker et al. (2013)
Sens6	$q_3$ (lethal strike – surface) – dead birds + broken wings + suspected and possible deaths (warp only)	-2.717 (0.064)	0.262 (0.016)	-3.269–2.235 (0.037–0.098)	–	Parker et al. (2013)
Sens7	$q_3$ (lethal strike – surface) – dead only (tori only)	-3.563 (0.036)	0.818 (0.021)	-5.420–2.247 (0.004– 0.096)	–	Parker et al. (2013)



**Table 5: continued.**

Sensitivities	Parameter	Mean	SD	95% CI (prob scale)	$\mu; \sigma$	Source
Sens8	q <sub>3</sub> (lethal strike – surface) – large seabirds	-1.386 (0.20)	0.3 (0.050)	0.13–0.27		Edwards et al. (2023) using data from Watkins et al. (2008)
Sens9	q <sub>3</sub> (lethal strike – surface) – “small-sized” and “medium-sized” seabirds	-2.734 (0.061)	1.445 (0.143)	0.024–0.11		Edwards et al. (2023) using data from Watkins et al. (2008)
Sens1-Sens9	q <sub>4</sub> (observable strike – aerial)	0 (as always unobservable)			-	
Sens1-Sens9	q <sub>5</sub> (observable strike – surface) – dead birds + broken wings (warp + tori) – trawl with corpse catcher-based observations removed	-0.630 (0.358)	0.573 (0.123)	-1.811–0.461 (0.141–0.613)		Parker et al. (2013)

**Probability of surface strikes ( $q_1$ ).** Data for seabird warp strikes in New Zealand inshore trawl vessels (supplied by MPI) were assessed for suitability to estimate the probability of surface strikes. The data summary in Table 6 shows that the data are too sparse for fitting a model specific to each species group in the supplied data. Combining all bird groups in Table 6, leads to 5 aerial strikes vs. 21 surface strikes (all remaining strike categories combined), or 19% aerial vs. 81% surface strikes. This is similar to observations made by Parker et al. (2013), which assessed cryptic mortality of seabirds due to warp and tori line strikes by using a following vessel to observe the wake of the fishing vessel in the Falkland Islands trawl fisheries. In that study, the majority of all warp strikes appeared on the water (82%) and the remaining in-flight (18%). All strikes or heavy contacts with tori lines were on the water. The probability of a surface strike ( $q_1$ ) was estimated in JAGS by fitting a binomial distribution to the total number of trials (i.e., 26 strikes) and number of successes (i.e., 21 surface strikes) based on the supplied warp strike data. Alternative estimates for  $q_1$  are provided by Watkins et al. (2008) and are currently utilised by Edwards et al. (2023) for the seabird risk assessment. These estimates are provided separately for large and small- to medium-sized seabirds and were 0.370 (95% CI: 0.32–0.42) and 0.20 (95% CI: 0.17–0.24), respectively. Raw numbers for surface strikes (139 surface warp strikes from 376 warp strikes for large seabirds, and 124 surface strikes out of 615 total warp strikes for small- to medium-sized seabirds) were used to re-estimate  $q_1$  (see Sens8 and Sens9 in Table 5) and supplied as alternative prior distributions. The prior distribution for  $q_1$  was defined as a uniform distribution with a range from 0 to 1. Estimates for  $q_1$  are shown in Table 5. The prior distribution derived from this model was a normal distribution on logit-scale to ensure that the modelled distributions is within the range of 0 to 1.

**Table 6: Total counts of seabird strikes during towing between 10/11/2012 and 17/03/2018 reported on warp strike forms; air: aerial strike; warp\_drag: dragged under the water by a heavy contact (i.e., surface strike); warp\_defl: contact with warp deflector; mit\_drag: bird comes into contact with the mitigation device, or mitigation device (tori line) moves to contact the bird and dragged under water; mit\_delf: contact with tori line deflector.**

	Large albatrosses	Small albatrosses	Shearwaters and other petrels	Cape pigeons	Shags
air	0	3	1	1	0
warp_drag	0	2	1	0	0
warp_defl	0	6	2	3	1
mit_drag	0	0	0	0	0
mit_delf	0	2	0	4	0

**Probability of a lethal aerial strike ( $q_2$ ).** All deadly heavy contacts in Parker et al. (2013) were caused by surface strikes, and as per personal communication with Graham Parker lethal aerial strikes seemed very rare. To allow for some proportion of aerial strike to be lethal, an arbitrary but low probability was defined for lethal aerial strike by supplying a log-normal prior with a mean of 0.007 and 95% confidence interval of 0.005 to 0.01.

**Probability of a lethal surface strike ( $q_3$ ).** Data on the fate of birds after striking the warp cable were not directly available. Parker et al. (2013) investigated whether the outcome of interactions between seabirds and warp cables in Falkland Islands trawl fisheries could be confirmed by observing the wake of the trawler, beyond the detection range of observer(s) positioned on the fishing vessel. In their study, all the birds recorded as mortalities (and heavy strikes during observations) were on the water (personal communication with Graham Parker). Further, as per personal communication with Graham Parker, aerial strikes with trawl warps are rare (for the problem species in that fishery, black browed albatross *Thalassarche melanophrys*), and when aerial strikes do occur, it would be highly unusual for the bird to be severely injured. Therefore, for this study the information from Parker et al. (2013) was used to develop a prior distribution for the probability of lethal surface strikes only.

Data were directly taken from table 2 of Parker et al. (2013) (see Table 7 in this report), which provides the total mortalities due to heavy contacts with the warp cable on the surface, observed from both the actual fishing vessel and the following vessel. The number of heavy contacts were provided in the main text and were 303. These contacts were for black-browed albatrosses and giant petrels, and also included 54 contacts with bird scaring lines (BSL) of which one resulted in a dead bird. Seven alternate datasets were created. The first set of data was for strikes against warp cables and tori lines combined (303 total strikes), and either included (1) dead birds only, (2) dead birds and those with broken wings, or (3) dead birds, those with broken wings, and suspected and possible deaths. The second set of data comprised only warp strikes (240 strikes) and either included (1) dead birds only, (2) dead birds and those with broken wings, and (3) dead birds (11; i.e., one tori line strike has been removed), those with broken wings, and suspected and possible deaths. Further, one dataset for tori lines only was created with 54 strikes and 1 death. The probability of a lethal surface strike ( $q_2$ ) was estimated in JAGS by fitting a binomial distribution to the total number of surface strikes and number lethal surface strikes for each of the seven alternate datasets. The prior distribution for  $q_2$  was defined as a uniform distribution with a range from 0 to 1. Estimates for  $q_3$  are shown in Table 5. The prior distribution derived from this model is a normal distribution on logit-scale to ensure that the modelled distribution is within the range of 0 to 1. The sensitivity of the final cryptic mortality estimate is assessed against the different datasets that are available for lethal surface strikes (i.e., based on different criteria to define birds as being dead). Further, the transition matrix in Figure 2 can be parameterised by supplying a prior distribution for warp and tori line strikes combined or by modelling each strike type separately.

**Table 7: Number of seabird mortalities and serious injuries recorded from the seven-day research trip. The unknown outcomes were only recorded from the Fishing Vessel; taken from Parker et al. (2013).**

	Day (n=7)	Station (n=13)	Dead	Broken wing	Suspected Death	Possible Death	Unknown outcome
Patrol vessel	2	2	1	–	2	1	–
	5	9	1	–	–	–	–
	7	13	–	1	–	–	–
Trawl vessel	2	2	6 (in corpse catcher)	–	–	–	8
	5	9	1	–	–	–	4
	7	13	3	–	–	–	19
Total			12	1	2	1	31

**Probability of observable lethal aerial strike ( $q_4$ ).** Aerial strikes (i.e., a heavy collision during flight leading to sustained injuries) are not retained and are therefore considered entirely cryptic to the observer.

**Probability of observable lethal surface strike ( $q_5$ ).** Table 7 provides three separate samples of warp and tori line strikes observation on both the patrol vessel and fishing vessel. The study by Parker et al. (2013) included seabirds that were retained by a corpse catcher device to increase the chance of retaining birds killed by surface warp strikes. Parker et al. (2013) state, “the corpse catcher was deployed on alternate days in the second trawl of the day for a total of three deployments” and “[o]f the ten mortalities recorded, three were caught on the warp slices and six were caught by the corpse catcher, the latter in a single trawl”. Thus, the trawl event with the six seabirds retained in corpse catchers (day 2, station 2; Table 6) were removed from the analysis to avoid an upwards bias in the estimates cryptic mortality (since corpse catcher devices are not used in New Zealand trawl fisheries). The new dataset included seabirds identified as dead or having broken wings on the two remaining trawl events. That means, a dataset was prepared including each individual sample and comprised the total number of dead birds combined on both vessels (i.e., 2, 3 dead birds) and the number of deaths observed from the fishing vessels (i.e., 1, 3 observed dead birds). Strikes with warp cables and tori lines were combined, assuming

that the chance to observe strikes are the same for both types of strikes. The probability of an observable lethal surface strike ( $q_5$ ) was estimated in JAGS by fitting a binomial distribution to the total number of dead birds and dead birds observed from the fishing vessel. The prior distribution for  $q_5$  was defined as a uniform distribution with a range from 0 to 1. The prior distribution derived from this model will be a normal distribution on logit-scale to ensure that the modelled distribution is within the range of 0 to 1.

### 2.3 Cryptic mortality multiplier

The cryptic mortality multiplier was defined as:

$$M = (\text{cryptic\_mortality\_rate} + \text{observable\_mortality\_rate}) / \text{observable\_mortality\_rate} \quad (1)$$

where the *cryptic\_mortality\_rate* for net captures and warp strikes were calculated as:

$$(1-p_1)*(1-p_2)*(1-p_4) + (1-p_1)*p_2*(1-p_5) + p_1*(1-p_3)*(1-p_6)+p_1*p_3*(1-p_7) \quad (2)$$

and

$$(1-q_1)*q_2*(1-q_4) + q_1*q_3*(1-q_5), \quad (3)$$

respectively.

The *observable\_mortality\_rate* for net captures and warp strikes were defined as

$$(1-p_1)*p_2*p_5+p_1*p_3*p_7 \quad (4)$$

and

$$(1-q_1)*q_2*q_4 + q_1*q_3*q_5, \quad (5)$$

respectively.

## 3. RESULTS

Estimated cryptic mortality multipliers for net captures and warp strikes are shown in Table 8. For warp strikes-related cryptic mortality multipliers, nine alternative models were compiled. The average cryptic mortality multiplier estimate for net captures was 2.538 with a 95% credible interval (CrI) of 1.128–9.323. The large uncertainty for this estimate is caused by lack of knowledge regarding both the probability of post-release survival (here an arbitrary value between 0.5 and 1 was chosen as the actual post-release survival is unknown) and probability of body non-retention with 95% CI of 0.1–0.7 (see Table 3).

Cryptic mortality multipliers for warp strikes were very similar across most of the different model scenarios (Sensitivity 1–7; Table 8) suggesting that mortality of seabirds due to warp strikes might be between seven to ten times higher when accounting for unobservable mortalities. However, the estimates had a large level of uncertainty most likely reflecting the wide uncertainty in the probability of observing lethal strikes (see Table 5). However, when applying estimates specifically for large and small- to medium-sized birds reported for South African trawl fisheries by Watkins et al. (2008) (and used by Edwards et al. (2023)), then estimates for the cryptic mortality multiplier increased by two orders of magnitude (but note the substantial uncertainty, e.g., the 95% CrI was 1.247–760.469 for the cryptic mortality multiplier for large seabirds).

**Table 8: Estimated cryptic mortality multipliers (CMM) for net captures and warp strikes.**

CMM for	Sensitivity	Mean	SD	95% Credible interval
Net captures	–	2.538	13.469	1.128–9.323
Warp strikes	1	8.839	41.331	1.209–44.440
Warp strikes	2	9.704	117.151	1.212–42.110
Warp strikes	3	8.872	31.406	1.208–43.937
Warp strikes	4	8.853	43.207	1.208–41.508
Warp strikes	5	8.441	47.501	1.202–40.607
Warp strikes	6	9.456	71.841	1.195–41.097
Warp strikes	7	7.306	16.537	1.222–37.045
Warp strikes	8	331.38	6 853.40	1.247–760.469
Warp strikes	9	372.32	8 648.02	1.312–1 204.178

#### 4. DISCUSSION

For the current update of the seabird risk assessment, warp strike and net-related mortalities are estimated separately (Edwards et al. 2023). Therefore, in this project, two separate estimates of the cryptic mortality multiplier were compiled for each interaction type.

Previously, cryptic mortality caused by net captures was modelled as the (assumed) ratio of unobserved net captures to observed net captures (Richard et al. 2020). Here, the net-related cryptic mortality was updated by apportioning captures as internal and external captures and acknowledging that some birds were released alive (with some of those birds dying subsequently). Estimates for the probability of internal net captures and both internal and external net captures being lethal were based on observer notes (made since 2018–19 via the PSI form) that were preserved in the PSCDB. Data on post-release survival and body non-retention (for unreleased birds) were not available. Previously, all net captures were assumed to be fatal but here we acknowledged that some released birds would potentially survive by allowing post-release survival probability to be between 0.5 and 1. The cryptic mortality multiplier estimated here (2.538 on average) was about twice as high as reported for the current seabird risk assessment of Edwards et al. (2023), who used the approach by Richard et al. (2020). The difference is likely caused by additionally accounting for internal and external net captures (derived from a small proportion of the available data in the PSCDB) also leading to higher uncertainty in the estimates produced in this study.

For the cryptic mortality multiplier for seabird mortality due to warp strikes, nine alternative models were tested. The first seven models were based on data obtained from Mitigation Assessment Warp-Strike Forms designed to assess seabird-warp interactions during towing in New Zealand inshore trawl fisheries and data derived from a study in Falkland Islands trawl fisheries published by Parker et al. (2013). Based on these scenarios, average estimates of the cryptic mortality multiplier suggest that warp strike-related mortalities could be about seven to ten times higher than those based purely on observations. However, actual estimates were uncertain. For example, the 95% credible interval for the cryptic mortality multiplier in the first sensitivity scenario was 1.209–44.440 and was similar for all other sensitivity scenarios based on data from Mitigation Assessment Warp-Strike Forms and the Falkland Islands trawl fisheries study. Both average estimates and credible intervals were in the same order of magnitude as for cryptic multipliers for trawl fisheries reported by Richard et al. (2020).

Based on the Protected Species Captures database, between 19 to 31% of observed tows had tori lines deployed between the 2015–16 and 2019–20 fishing years. Trawlers studied by Parker et al. (2013) also used tori lines to deter birds from warp cables, and experimental trials in Falkland Islands trawl fisheries showed that tori lines can significantly reduce heavy contacts between seabirds and warps (Sullivan et

al. 2006a). Strikes with tori lines were recorded, although rarely, in the warp strike assessment data in New Zealand inshore trawl fisheries (see Table 6). The chance of birds flying into tori lines can be influenced by the design of the tori line (e.g., the length of the tori line, the device attached to the seaward end of the tori line to create drag (tow device), etc.) (Snell et al. 2012). Using data reported by Parker et al. (2013), the sensitivity of the cryptic mortality multiplier to bird mortalities due to warp strikes plus tori line contacts was assessed and showed that tori line contact-related mortality had only small effects on cryptic mortality. In fact, tori line contacts only added a small amount of additional mortality when compared with warp strikes (see Table 5).

When using data published for warp strikes in South African demersal trawl fisheries by Watkins et al. (2008) (sensitivities Sens8 and Sens9; see Table 5), which are currently used for the seabird risk assessment (Edwards et al. 2023), then the average multiplier suggests that warp strike-related mortalities could be more than 300 times higher, although the credible interval, for example for large birds, ranged from 1.247–760.469. Data by Watkins et al. (2008) suggest that, for example for large birds, only 37% (95% CI: 32.2–41.9%) of all warp strikes are surface strikes. In contrast, data from New Zealand inshore trawl fisheries (Mitigation Assessment Warp-Strike Forms) showed that 78.7% (95% CI: 62.3–91.5%) of warp strikes are surface strikes. That means, model parameterisations using estimates for the surface strike probability based on Watkins et al. (2008) allocate most warp strikes to aerial strikes which are, by definition, all cryptic, hence leading to a substantially higher estimate for the cryptic mortality multiplier. A similar order of magnitude for warp-strike related cryptic mortality was reported by Edwards et al. (2023).

The results of this study show that there is the need for collection of data specifically aimed at assessing cryptic mortality in New Zealand trawl fisheries. The data used in this study were not fit for purpose and were partially characterised by sparseness. For example, data from Mitigation Assessment Warp-Strike Forms supplied valuable information regarding the ratio of surface to aerial warp strikes in New Zealand inshore trawl fisheries but only during the actual tow duration, whereas most interactions might occur during setting and hauling. In contrast, data collected in South African trawl fisheries (Watkins et al. 2008) were collected throughout setting, towing, and hauling but fishing operations might not be fully comparable with those in New Zealand waters (e.g., due to differences in fishing practice).

The SEFRA framework considers that cryptic mortality can be different between different species groups (e.g., based on body mass) and different fishery groups (e.g., fisheries targeting different species and using differently sized vessels) (Fisheries New Zealand 2022). While the data published by Watkins et al. (2008) allows modelling probabilities of surface strikes and those being lethal separately for large and small- to medium-sized birds (as done by Edwards et al. 2023), Mitigation Assessment Warp-Strike data, in contrast, only contained 26 strikes out of 3161 observations limiting the ability to create prior distributions specifically for different species groups. Using data from New Zealand trawl fisheries comes therefore with the drawback of not being able to disaggregate these probabilities according to bird groups. Moreover, for other parameters, there is currently no information (e.g., for probability of observing a surface strike) or limited information (e.g., information on internal vs. external net captures has been collected only since the 2019–20 fishing year) to inform the estimation of cryptic multipliers for different species groups. With additional years of data collection through the PSI form, data to disaggregate the probability of net captures by species groups should become attainable.

Cryptic mortality multipliers for different fishery groups have not been explicitly modelled in this study due to the lack of sufficient data. However, depending on the data sets that were used in this study, the resulting cryptic mortality multipliers for net captures can be applied to the predominant trawl fishery groups: large trawler with a fish freezer and those targeting squid in the sub-Antarctic (as described by Edwards et al. 2023) (Table C-1). For cryptic mortality in net captures, the only data source used was the PSCDB. For the data from the PSCDB used here (i.e., 2019–20 fishing year), most fishing events (411 out of 434 tows) were from large vessels (> 28 metres) with a fish freezer that predominantly targeted arrow squid (*Nototodarus sloanii* & *N. gouldi*) (280 out of 434 fishing events) and hoki (*Macruronus novaezelandiae*) (98 out of 438 fishing events). For warp strikes, estimated cryptic mortality multipliers are representative for inshore and offshore fisheries depending on the data source

(Table C-1). On Mitigation Assessment Warp-Strike Forms, data were collected specifically from inshore trawl vessels (Department of Conservation and Ministry for Primary Industries 2013). Parker et al. (2013) collected data from Falkland Island fisheries and most of the fishing occurred 40 miles off the coast to the east and south, though some fishing can extend further offshore (Sullivan et al. 2006b). Hence, estimated cryptic multipliers for warp strikes that were based on Mitigation Assessment Warp-Strike Forms and data collected by Parker et al. (2013) should be used to model cryptic mortality in small-vessel inshore trawl fisheries. In contrast, data from Watkins et al. (2008) (as used by Edwards et al. 2023) are derived from demersal offshore fisheries and, hence, the associated cryptic mortality multiplier estimates are rather typical for offshore trawling (Sensitivities 8 and 9 in Table 8).

Further mentioned in Fisheries New Zealand (2022) is the potential need to model temporal-specific cryptic mortality multipliers (to avoid a decline in fishery-related deaths being masked by falsely modelling temporarily invariant cryptic mortality), especially for warp captures due to uptake and improvements in bycatch mitigation measures (e.g., tori lines). For example, there was a continuous decline in warp captures between the 2003–04 and 2006–07 fishing years (Fisheries New Zealand 2022). The results in this study, however, should not be affected by changes in seabird warp strikes because data used here from the Mitigation Assessment Warp-Strike Form were collected between the years 2012 and 2018, hence reflecting recent fishing practices used in New Zealand commercial trawl fisheries.

## 5. ACKNOWLEDGEMENTS

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## APPENDIX A: SOURCE CODE FOR MODELLING CRYPTIC MORTALITY IN NET CAPTURES

See main text (Table 3) for description of model priors.

```
txtstring <- '  
  model{  
  
  ## Priors  
  # p1 (internal capture)  
  lpINT ~ dnorm(-0.047,0.085);  
  pINT <- 1 / (1 + exp(-lpINT));  
  
  # p2 (lethal capture – external)  
  lpLETHAL1 ~ dnorm(0.162, 0.119);  
  pLETHAL1 <- 1 / (1 + exp(-lpLETHAL1));  
  
  # p3 (lethal capture – internal)  
  lpLETHAL2 ~ dnorm(1.983, 0.179);  
  pLETHAL2 <- 1 / (1 + exp(-lpLETHAL2));  
  
  # p4 (post-release survival – external)  
  pSURV1 ~ dunif(0.5,1);  
  
  # Odds ratio of body non-retention (external) to calculate p5  
  oddsNRET1 ~ dlnorm(-1.330, 1/pow(0.486,2));  
  pNRET1 <- oddsNRET1 / (1+oddsNRET1);  
  
  # p6 (post-release survival – internal)  
  pSURV2 ~ dunif(0.5,1);  
  
  # Odds ratio of body non-retention (external) to calculate p7  
  oddsNRET2 ~ dlnorm(-1.330, 1/pow(0.486,2));  
  pNRET2 <- oddsNRET1 / (1+oddsNRET2);  
  
  ## Transition matrix (only needed when modelling individuals transitioning through states)  
  ps[1,1] <- 0;  
  ps[2,1] <- 0;  
  ps[3,1] <- 0;  
  ps[4,1] <- 0;  
  ps[5,1] <- 0;  
  ps[6,1] <- 0;  
  ps[7,1] <- 0;  
  ps[8,1] <- 0;  
  ps[9,1] <- 0;  
  ps[10,1] <- 0;  
  ps[11,1] <- 0;  
  ps[12,1] <- 0;  
  ps[13,1] <- 0;  
  ps[14,1] <- 0;  
  ps[15,1] <- 0;  
  ps[1,2] <- pEXT;  
  ps[2,2] <- 0;  
  ps[3,2] <- 0;  
  ps[4,2] <- 0;  
  ps[5,2] <- 0;  
  ps[6,2] <- 0;  
  ps[7,2] <- 0;  
  ps[8,2] <- 0;  
  ps[9,2] <- 0;  
  ps[10,2] <- 0;  
  ps[11,2] <- 0;  
  ps[12,2] <- 0;  
  ps[13,2] <- 0;  
  ps[14,2] <- 0;  
  ps[15,2] <- 0;  
  ps[1,3] <- pINT;  
  ps[2,3] <- 0;  
  ps[3,3] <- 0;  
  ps[4,3] <- 0;  
  ps[5,3] <- 0;  
  ps[6,3] <- 0;  
  ps[7,3] <- 0;  
  ps[8,3] <- 0;  
  ps[9,3] <- 0;
```

```
ps[10,3] <- 0;
ps[11,3] <- 0;
ps[12,3] <- 0;
ps[13,3] <- 0;
ps[14,3] <- 0;
ps[15,3] <- 0;
ps[1,4] <- 0;
ps[2,4] <- pLIFE1;
ps[3,4] <- 0;
ps[4,4] <- 0;
ps[5,4] <- 0;
ps[6,4] <- 0;
ps[7,4] <- 0;
ps[8,4] <- 0;
ps[9,4] <- 0;
ps[10,4] <- 0;
ps[11,4] <- 0;
ps[12,4] <- 0;
ps[13,4] <- 0;
ps[14,4] <- 0;
ps[15,4] <- 0;
ps[1,5] <- 0;
ps[2,5] <- pLETHAL1;
ps[3,5] <- 0;
ps[4,5] <- 0;
ps[5,5] <- 0;
ps[6,5] <- 0;
ps[7,5] <- 0;
ps[8,5] <- 0;
ps[9,5] <- 0;
ps[10,5] <- 0;
ps[11,5] <- 0;
ps[12,5] <- 0;
ps[13,5] <- 0;
ps[14,5] <- 0;
ps[15,5] <- 0;
ps[1,6] <- 0;
ps[2,6] <- 0;
ps[3,6] <- 0;
ps[4,6] <- pSURV1;
ps[5,6] <- 0;
ps[6,6] <- 1;
ps[7,6] <- 0;
ps[8,6] <- 0;
ps[9,6] <- 0;
ps[10,6] <- 0;
ps[11,6] <- 0;
ps[12,6] <- 0;
ps[13,6] <- 0;
ps[14,6] <- 0;
ps[15,6] <- 0;
ps[1,7] <- 0;
ps[2,7] <- 0;
ps[3,7] <- 0;
ps[4,7] <- pDEATH1;
ps[5,7] <- 0;
ps[6,7] <- 0;
ps[7,7] <- 1;
ps[8,7] <- 0;
ps[9,7] <- 0;
ps[10,7] <- 0;
ps[11,7] <- 0;
ps[12,7] <- 0;
ps[13,7] <- 0;
ps[14,7] <- 0;
ps[15,7] <- 0;
ps[1,8] <- 0;
ps[2,8] <- 0;
ps[3,8] <- 0;
ps[4,8] <- 0;
ps[5,8] <- pOBS1;
ps[6,8] <- 0;
ps[7,8] <- 0;
ps[8,8] <- 1;
ps[9,8] <- 0;
```

```

ps[10,8] <- 0;
ps[11,8] <- 0;
ps[12,8] <- 0;
ps[13,8] <- 0;
ps[14,8] <- 0;
ps[15,8] <- 0;
ps[1,9] <- 0;
ps[2,9] <- 0;
ps[3,9] <- 0;
ps[4,9] <- 0;
ps[5,9] <- pNRET1;
ps[6,9] <- 0;
ps[7,9] <- 0;
ps[8,9] <- 0;
ps[9,9] <- 1;
ps[10,9] <- 0;
ps[11,9] <- 0;
ps[12,9] <- 0;
ps[13,9] <- 0;
ps[14,9] <- 0;
ps[15,9] <- 0;
ps[1,10] <- 0;
ps[2,10] <- 0;
ps[3,10] <- pLIFE2;
ps[4,10] <- 0;
ps[5,10] <- 0;
ps[6,10] <- 0;
ps[7,10] <- 0;
ps[8,10] <- 0;
ps[9,10] <- 0;
ps[10,10] <- 0;
ps[11,10] <- 0;
ps[12,10] <- 0;
ps[13,10] <- 0;
ps[14,10] <- 0;
ps[15,10] <- 0;
ps[1,11] <- 0;
ps[2,11] <- 0;
ps[3,11] <- pLETHAL2;
ps[4,11] <- 0;
ps[5,11] <- 0;
ps[6,11] <- 0;
ps[7,11] <- 0;
ps[8,11] <- 0;
ps[9,11] <- 0;
ps[10,11] <- 0;
ps[11,11] <- 0;
ps[12,11] <- 0;
ps[13,11] <- 0;
ps[14,11] <- 0;
ps[15,11] <- 0;
ps[1,12] <- 0;
ps[2,12] <- 0;
ps[3,12] <- 0;
ps[4,12] <- 0;
ps[5,12] <- 0;
ps[6,12] <- 0;
ps[7,12] <- 0;
ps[8,12] <- 0;
ps[9,12] <- 0;
ps[10,12] <- pSURV2;
ps[11,12] <- 0;
ps[12,12] <- 1;
ps[13,12] <- 0;
ps[14,12] <- 0;
ps[15,12] <- 0;
ps[1,13] <- 0;
ps[2,13] <- 0;
ps[3,13] <- 0;
ps[4,13] <- 0;
ps[5,13] <- 0;
ps[6,13] <- 0;
ps[7,13] <- 0;
ps[8,13] <- 0;
ps[9,13] <- 0;

```

```

ps[10,13] <- pDEATH2;
ps[11,13] <- 0;
ps[12,13] <- 0;
ps[13,13] <- 1;
ps[14,13] <- 0;
ps[15,13] <- 0;
ps[1,14] <- 0;
ps[2,14] <- 0;
ps[3,14] <- 0;
ps[4,14] <- 0;
ps[5,14] <- 0;
ps[6,14] <- 0;
ps[7,14] <- 0;
ps[8,14] <- 0;
ps[9,14] <- 0;
ps[10,14] <- 0;
ps[11,14] <- pOBS2;
ps[12,14] <- 0;
ps[13,14] <- 0;
ps[14,14] <- 1;
ps[15,14] <- 0;
ps[1,15] <- 0;
ps[2,15] <- 0;
ps[3,15] <- 0;
ps[4,15] <- 0;
ps[5,15] <- 0;
ps[6,15] <- 0;
ps[7,15] <- 0;
ps[8,15] <- 0;
ps[9,15] <- 0;
ps[10,15] <- 0;
ps[11,15] <- pNRET2;
ps[12,15] <- 0;
ps[13,15] <- 0;
ps[14,15] <- 0;
ps[15,15] <- 1;

## Obtain posterior distributions for cryptic mortality rate (i.e. lost bycatch and other lethal interactions) and cryptic mortality multiplier
cryptic_mortality_rate <-
pEXT*pLIFE1*pDEATH1+pEXT*pLETHAL1*pNRET1+pINT*pLIFE2*pDEATH2+pINT*pLETHAL2*pNRET2;

observable_mortality_rate <- pEXT*pLETHAL1*pOBS1+pINT*pLETHAL2*pOBS2;

cryptic_multiplier <- (cryptic_mortality_rate + observable_mortality_rate) / observable_mortality_rate;

## Derive remaining parameters
pEXT = 1 - pINT;
pLIFE1 = 1 - pLETHAL1;
pLIFE2 = 1 - pLETHAL2;
pDEATH1 = 1 - pSURV1;
pOBS1 = 1 - pNRET1;
pDEATH2 = 1 - pSURV2;
pOBS2 = 1 - pNRET2;

## Derive number of individuals experiencing each fate across all interactions; via matrix multiplication
fate_abundances[1,1] ~ dnorm(interactions_mean_priormodel, 1/interactions_sd_priormodel^2)
for(i in 2:15){fate_abundances[i,1] <- 0}

for(i in 2:height){ fate_abundances[1:15,i] <- fate_abundances[1:15,i-1]*%*%ps }
}

```

## APPENDIX B: SOURCE CODE FOR MODELLING CRYPTIC MORTALITY IN WARP STRIKES

See main text (Table 5) for description of model priors. Note, that values have to be adjusted for each sensitivity scenario.

```
txtstring <- '  
  model{  
  
  ## Priors  
  # q1 (surface strike)  
  lpSURFACE ~ dnorm(1.362,0.477);  
  pSURFACE <- 1 / (1 + exp(-lpSURFACE));  
  
  # q2 (lethal strike – aerial)  
  pLETHAL1 ~ dlnorm(-4.952, 1/pow(0.173,2));  
  
  # q3 (lethal strike – surface) – dead only (warp + tori)  
  lpLETHAL2 ~ dnorm(-3.147 ,0.290);  
  pLETHAL2 <- 1 / (1 + exp(-lpLETHAL2));  
  
  # q4 (observable strike – aerial)  
  pOBS1 <- 0  
  
  # q5 (observable strike – surface) – dead birds + broken wings (warp + tori) – trawl with corpse catcher-based observations removed  
  lpOBS2 ~ dnorm(-0.630 ,0.573 );  
  pOBS2 <- 1 / (1 + exp(-lpOBS2));  
  
  ## Transition matrix  
  ps[1,1] <- 0;  
  ps[2,1] <- 0;  
  ps[3,1] <- 0;  
  ps[4,1] <- 0;  
  ps[5,1] <- 0;  
  ps[6,1] <- 0;  
  ps[7,1] <- 0;  
  ps[8,1] <- 0;  
  ps[9,1] <- 0;  
  ps[10,1] <- 0;  
  ps[11,1] <- 0;  
  ps[1,2] <- pAERIAL;  
  ps[2,2] <- 0;  
  ps[3,2] <- 0;  
  ps[4,2] <- 0;  
  ps[5,2] <- 0;  
  ps[6,2] <- 0;  
  ps[7,2] <- 0;  
  ps[8,2] <- 0;  
  ps[9,2] <- 0;  
  ps[10,2] <- 0;  
  ps[11,2] <- 0;  
  ps[1,3] <- pSURFACE;  
  ps[2,3] <- 0;  
  ps[3,3] <- 0;  
  ps[4,3] <- 0;  
  ps[5,3] <- 0;  
  ps[6,3] <- 0;  
  ps[7,3] <- 0;  
  ps[8,3] <- 0;  
  ps[9,3] <- 0;  
  ps[10,3] <- 0;  
  ps[11,3] <- 0;  
  ps[1,4] <- 0;  
  ps[2,4] <- pSURV1;  
  ps[3,4] <- 0;  
  ps[4,4] <- 1;  
  ps[5,4] <- 0;  
  ps[6,4] <- 0;  
  ps[7,4] <- 0;  
  ps[8,4] <- 0;  
  ps[9,4] <- 0;  
  ps[10,4] <- 0;  
  ps[11,4] <- 0;  
  ps[1,5] <- 0;
```

```

ps[2,5] <- pLETHAL1;
ps[3,5] <- 0;
ps[4,5] <- 0;
ps[5,5] <- 0;
ps[6,5] <- 0;
ps[7,5] <- 0;
ps[8,5] <- 0;
ps[9,5] <- 0;
ps[10,5] <- 0;
ps[11,5] <- 0;
ps[1,6] <- 0;
ps[2,6] <- 0;
ps[3,6] <- 0;
ps[4,6] <- 0;
ps[5,6] <- pOBS1;
ps[6,6] <- 1;
ps[7,6] <- 0;
ps[8,6] <- 0;
ps[9,6] <- 0;
ps[10,6] <- 0;
ps[11,6] <- 0;
ps[1,7] <- 0;
ps[2,7] <- 0;
ps[3,7] <- 0;
ps[4,7] <- 0;
ps[5,7] <- pUNOBS1;
ps[6,7] <- 0;
ps[7,7] <- 1;
ps[8,7] <- 0;
ps[9,7] <- 0;
ps[10,7] <- 0;
ps[11,7] <- 0;
ps[1,8] <- 0;
ps[2,8] <- 0;
ps[3,8] <- pSURV2;
ps[4,8] <- 0;
ps[5,8] <- 0;
ps[6,8] <- 0;
ps[7,8] <- 0;
ps[8,8] <- 1;
ps[9,8] <- 0;
ps[10,8] <- 0;
ps[11,8] <- 0;
ps[1,9] <- 0;
ps[2,9] <- 0;
ps[3,9] <- pLETHAL2;
ps[4,9] <- 0;
ps[5,9] <- 0;
ps[6,9] <- 0;
ps[7,9] <- 0;
ps[8,9] <- 0;
ps[9,9] <- 0;
ps[10,9] <- 0;
ps[11,9] <- 0;
ps[1,10] <- 0;
ps[2,10] <- 0;
ps[3,10] <- 0;
ps[4,10] <- 0;
ps[5,10] <- 0;
ps[6,10] <- 0;
ps[7,10] <- 0;
ps[8,10] <- 0;
ps[9,10] <- pOBS2;
ps[10,10] <- 1;
ps[11,10] <- 0;
ps[1,11] <- 0;
ps[2,11] <- 0;
ps[3,11] <- 0;
ps[4,11] <- 0;
ps[5,11] <- 0;
ps[6,11] <- 0;
ps[7,11] <- 0;
ps[8,11] <- 0;
ps[9,11] <- pUNOBS2;
ps[10,11] <- 0;

```

```

ps[11,11] <- 1;

## Obtain posterior distributions for cryptic mortality rate (i.e. lost bycatch and other lethal interactions) and cryptic mortality multiplier
cryptic_mortality_rate <- pAERIAL*pLETHAL1*pUNOBS1+pSURFACE*pLETHAL2*pUNOBS2;
observable_mortality_rate <- pAERIAL*pLETHAL1*pOBS1+pSURFACE*pLETHAL2*pOBS2;
cryptic_multiplier <- (cryptic_mortality_rate + observable_mortality_rate) / observable_mortality_rate;

## Derive remaining parameters
pAERIAL = 1 - pSURFACE;
pSURV1 = 1 - pLETHAL1;
pSURV2 = 1 - pLETHAL2;
pUNOBS1 = 1 - pOBS1;
pUNOBS2 = 1 - pOBS2;

## Derive number of individuals experiencing each fate across all interactions; via matrix multiplication
fate_abundances[1,1] ~ dnorm(interactions_mean_priormodel, 1/interactions_sd_priormodel^2)
for(i in 2:11){fate_abundances[i,1] <- 0}

for(i in 2:height){ fate_abundances[1:11,i] <- fate_abundances[1:11,i-1]*%*%ps }
}

```

**APPENDIX C: CONTEXTUALISATION OF ESTIMATED CRYPTIC MORTALITY MULTIPLIERS IN REGARD TO FISHERY GROUPS USED IN SEFRA**

**Table C-1: Fishery group structure used in seabird risk assessments (Richard et al. 2020, Edwards et al. 2023) and their alignment with cryptic mortality multipliers (CMMs) modelled in this study.**

Trawl fishery groups used by Richard et al. (2020) and Edwards et al. (2023)	CMM for net captures	CMM for warp strikes
Small inshore < 17 m	Not applicable	Based on Mitigation Assessment Warp-Strike Forms and Parker et al. (2013) assessing cryptic mortality in small-vessel inshore trawl fisheries.
Small inshore 17 to 28 m		
Southern blue whiting		
Scampi		
Mackerel		
Squid	Based on PSCDB with events predominantly from large vessels with freezers targeting arrow squid and hoki	Derived from Watkins et al. (2008) for demersal offshore fisheries.
Large processor (with freezer)		
Larger fresher (no freezer)	Not applicable	
Deepwater		