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Tini a Tangaroa

Simulating sea lion dives to assess the probability of post-exit drowning for sea lions exiting SLEDs

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EXECUTIVE SUMMARY

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Data on sea lion dives and trawls in the SQU 6T fishery were used to simulate the outcomes of interactions when sea lions enter trawl nets equipped with a sea lion exclusion device (SLED). The simulation model allows estimation of overall sea lion survival as a result of interations with SLED-equipped trawls, including observable in-net mortality and cryptic mortality that occurs after sea lions exit the trawl via the SLED exit hole.

The simulation draws on summaries of sensor data from instrumented sea lions to estimate the time spent in various parts of a dive. If the total dive time exceeds the maximum survivable dive time then mortality of the sea lion is assumed to have occurred.

Sensitivity runs demonstrated that the model results were relatively insensitive to the assumed distribution of time within a dive at which a sea lion enters the trawl. The results are more sensitive to assumptions around the trawl exit process. If sea lions were to exit the net immediately upon reaching the SLED exit, then no mortality was estimated to occur. Parameterising additional in-trawl time such that sea lions exit the trawl at a constant rate after reaching the SLED exit hole, and tuning to independent estimates of sea lion retrieval from trawls, indicates that approximately 7 % of the exiting animals are estimated to drown before reaching the surface. The overall survival rate, taking into account animals that drown in the net or before reaching the surface, is 79.2 % and the ratio of total deaths to deaths that occur prior to exit is 1.4.

The ratio of total deaths to deaths that occur prior to exit is sensitive to the exit rate and, in the base case model with a constant rate of exit, is within the range 1.2–1.5 for exit rates of 70 % to 90 %.

An alternative parameterisation of sea lion exit times via the SLED used a Weibull distribution tuned to in-trawl interaction times for Australian fur seals observed using video. This model had sea lions exiting the net earlier than in the model with a constant exit rate, resulting in a reduction in the proportion of animals that died post-exit to 4.5 % and an estimated ratio of total deaths to deaths that occur prior to exit of 1.2.

In arriving at these estimates the key assumption made involves the distribution for maximum survivable dive times. Following consultation with the Aquatic Environment Working Group this was based on the addition of a fixed offset to the distribution of maximum natural dive times observed during foraging studies. While this adjustment is somewhat arbitrary, the resulting distribution for maximum survivable dive times nevertheless remains comparable with some estimates for maximum natural dive durations.

1. INTRODUCTION

Some New Zealand (Hooker's) sea lions enter trawl nets and drown. Incidental mortality of sea lions has been a particular concern in the Auckland Islands arrow squid (SQU 6T) fishery and a variety of measures to manage the interaction have been pursued. Annual limits (a Fisheries Related Mortality Limit, FRML) on the incidental mortality of sea lions in the fishery have been set since 1992 (Wilkinson et al. 2003), and in the mid-1990s a 'Marine Mammal Exclusion Device' (MMED) was developed (Gibson & Isakssen 1998); these were subsequently refined and renamed SLEDs (Sea Lion Exclusion Devices).

SLEDs comprise of an additional section of netting inserted between the lengthener and codend of a trawl (Figure 1). An angled, steel grid sewn into this netting aims to exclude sea lions from the trawl codend, and instead direct them to an exit hole in the top of the net. SLEDs are similar to Turtle Exclusion Devices (TEDs) and other fish bycatch mitigation devices. The success of such devices is typically measured by the absence of the intended species in future catches (e.g. Cox et al. 2007, Epperly 2003). However, before SLEDs were considered to be successful in the SQU 6T fishery, and the reduction of sea lions in the catch accepted as evidence that the FRML was not being exceeded, further assurance was sought that sea lions were actively exiting trawl nets and were subsequently likely to survive.
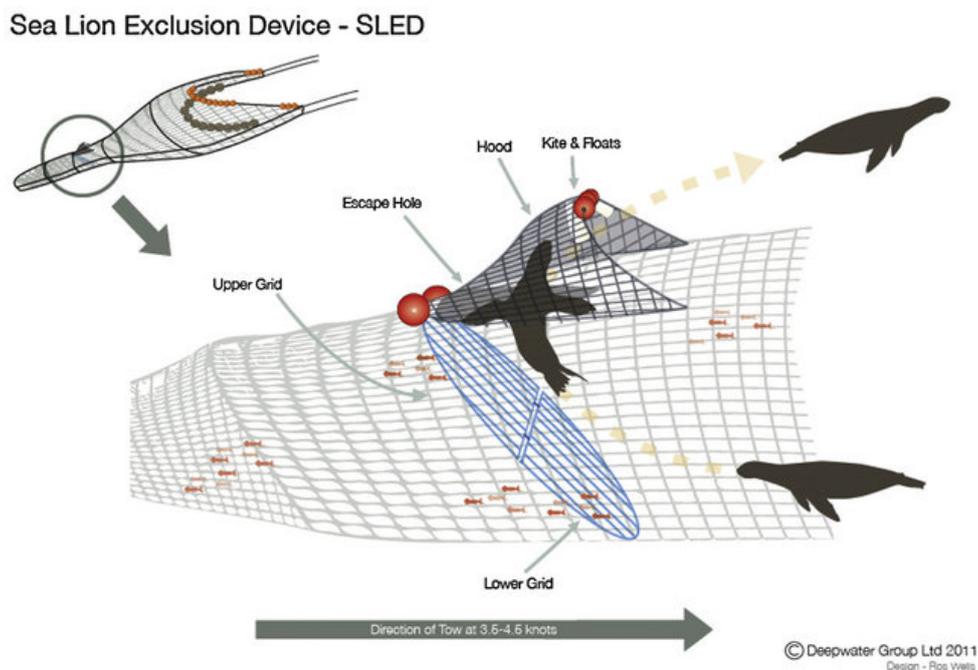
Figure 1: Illustration of a Sea Lion Exclusion Device installed in a trawl net. Graphic by Ros Wells provided by the Deepwater Group Ltd.

Initially, an experimental regime was established whereby sea lions exiting trawls via the SLED were captured in cover nets, with underwater video footage intended to assess sea lion viability when they exited the trawl (the animals subsequently drowned in the cover nets). Wilkinson et al. (2003) record:

> Vessels with SLEDs and government observers made 276 tows with closed cover nets in 2001. Thirty-three sea lions were caught by these vessels (a strike rate of 12 animals per 100 tows) and 30 were successfully ejected into the cover net by the SLED, giving an ejection rate of 91 %. Of the 30 ejected animals, only three were videotaped. The film documented the behaviour of the animals from the time of ejection until after their death by drowning. The tapes indicated that it was likely that the animals would have survived if the cover nets had not been present.

However, during these trials the results of necropsies of the drowned sea lions were interpreted as indicating that sea lions were suffering blunt-force trauma from interactions with the SLED grid. Wilkinson et al. (2003) further note:

> While visual assessment of vitality of sea lions ejected had indicated a positive outcome, subsequent analysis of autopsy results indicated otherwise (Gibbs et al. 2001). At least one and possibly two of the three animals seen on video exhibited severe internal trauma, which, in the view of the veterinary pathologist undertaking the examinations, would have led to the death of the animals. Examination of all autopsy results for 2001 suggested that at least 55% of the sea lions caught had suffered trauma sufficient to have compromised their survival, had they been ejected from the nets (Gibbs et al. 2001).

A subsequent review of sea lion necropsies concluded that the lesions previously interpreted as blunt-force trauma were, in fact, freezing artefacts (Roe & Meynier 2010). However, while Roe & Meynier (2010) concluded that the freeze-thaw process created artefactual lesions that mimic trauma, in the case of brain trauma they considered that this process could also obscure real lesions. The risk of sea lions suffering brain injury as a result of interactions with the SLED grid was therefore assessed by biomechanical testing and modelling. Abraham (2011) estimated the probability of mild traumatic brain injury for a New Zealand sea lion interacting with a trawl as 2.7%, with sensitivity runs leading to estimates of up to 8.2%.

Since 2012/13 high levels of observer coverage in the SQU 6T fishery have reduced uncertainty in estimates of sea lion captures (Ministry for Primary Industries 2017, chapter 4). However, some mortality of sea lions as a result of interations with trawl nets may not be detectable by fisheries observers and improving estimates of this 'cryptic mortality' is currently considered a key issue to be addressed (Ministry for Primary Industries 2017, Chapter 4). Observable mortalities arise when a sea lion enters a trawl net but is unable to exit, drowns, and is retrieved from the net when it is landed back on the vessel. Cryptic mortalities can arise either because (i) a dead sea lion is lost from the net before it is landed on the vessel or (ii) a sea lion exits the net but runs out of air and drowns before reaching the surface.

A series of studies of sea lions at the Auckland Islands have deployed instrumentation to record sea lion diving behaviour. This report draws on this extensive dataset to develop simulations to investigate the probability of cryptic mortality arising due to sea lions drowning after exiting the trawl.

2. METHODS

2.1 Simulation framework

A simulation framework, drawing on data on squid target trawls in the SQU 6T fishery and published summaries of sea lion dive data, was developed. Interactions between sea lions and squid target tows were simulated by sampling from the available data, as follows:

1. a tow was selected by sampling with replacement from the set of SQU 6T tows between 1 October 2015 and 30 September 2018. Each tow has a recorded method (BT or MW), fishing depth, and tow speed;

2. a sea lion was selected by sampling with replacement from the animals studied by Crocker et al. (2001) (dataset described below);

3. the descent and ascent speed for the animal's dive was calculated from relationships with dive depth fitted by Crocker et al. (2001), and using the tow depth as the dive depth;

4. the dive was assigned a bottom swimming speed by sampling from a generalised beta distribution with the animal-specific mean and standard deviation. An overall minimum of $0.4 \, \text{m} \, \text{s}^{-1}$ and maximum of $3.5 \, \text{m} \, \text{s}^{-1}$ was specified based on Crocker et al. (2001, figure 1). Use of a beta distribution ensures the simulated speeds are positive while the generalisation transforms the beta distributed random variables (which are defined on the interval 0 to 1) to retain the observed mean and standard deviation;

5. the dive was assigned a natural duration by sampling from a generalised beta distribution with the animal-specific mean and standard deviation. This was considered the 'target duration' for the dive, interpreted as the duration of dive that would have occurred in the absence of an interaction with a trawl;

6. the bottom time for the dive was calculated as the residual duration after removing ascent and descent times;

7. dives without a positive bottom time were dropped from the set of simulated dives, as these dive profiles precluded interaction with the trawl.

For dives with a positive bottom time, the sea lion was assumed to enter the trawl net. The point in the dive that the animal entered the trawl was simulated under a variety of assumptions, described below. For each simulated interaction, the minimum time taken for the sea lion to transit between the mouth of the net and the SLED exit hole can be calculated. The distance from headline to grid was set at 55 m for a bottom trawl and 150 m for a mid-water trawl (Richard Wells, pers. comm.). The transit time was calculated taking account of both the sea lion bottom swimming speed and the tow speed. Sea lions were assumed to move directly towards the grid which is in turn approaching the sea lion, so the relative speed is the sum of sea lion swimming speed and tow speed. Additional time spent by the sea lion in the net prior to exit via the SLED was also simulated.

The *successful exit duration* was calculated for each interaction, defined as the total dive duration where a sea lion has entered the net, exited via the SLED and returned to the surface, i.e. the sum of the descent time, time before entering the net, the time taken to transit the distance between the mouth of the net and the SLED exit hole, any additional time spent in the net, and the ascent time. Where the successful exit duration exceeds the maximum survivable dive duration, the sea lion is assumed to have drowned. If the maximum survivable dive duration is exceeded before the sea lion exits via the SLED, the sea lion drowns in the net and is an observable capture. Alternatively, if the maximum survivable dive duration is exceeded after the sea lion exits via the SLED, a cryptic mortality is assumed to have occurred.

2.2 Parameterising the simulations

2.2.1 Trawl dataset

The set of trawls used in the simulations was based on the statutory trawl effort data reported to Fisheries New Zealand. Between 1 October 2015 and 30 September 2018 there were 3760 tows targeting squid in the SQU 6T quota management area and using either bottom (BT) or mid-water (MW) trawl gear, of which 76.6 % were bottom trawls. For both gear types, few tows are shallower than 150 m and modal tow depth is between 150 and 200 m. However, bottom trawl gear is used at a wider range of depths, to 350 m (Figure 2). Tow speeds are similar for the two gear types (Figure 3).
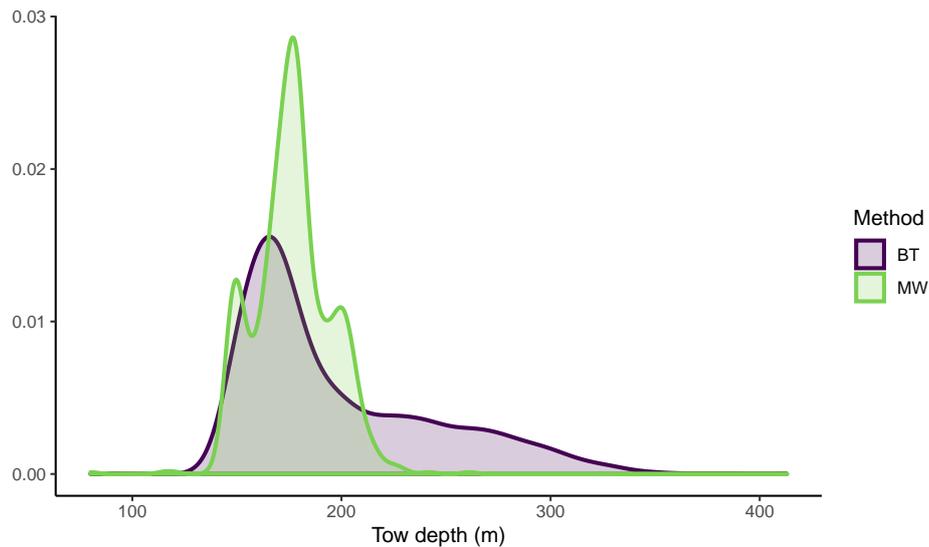
Figure 2: Tow depth distributions for bottom and mid-water trawls targetting squid in SQU 6T between 1 October 2015 and 30 September 2018.
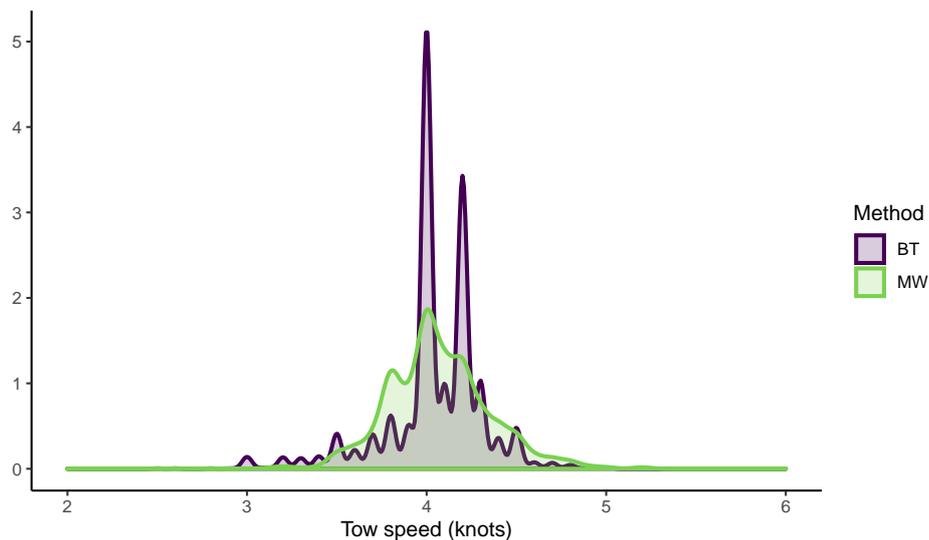
Figure 3: Tow speed distributions for bottom and mid-water trawls targetting squid in SQU 6T between 1 October 2015 and 30 September 2018.

2.2.2 Sea lion dive data

Crocker et al. (2001) deployed swimming speed and time-depth recorders on twelve female sea lions at Sandy Bay, Enderby Island in January and February 1996. Data were collected on 39 trips to sea and included 15 535 individual dives. A bimodal distribution of dive depths was found for all females with modes consisting of shallower dives (<20 m) and deeper dives (>100 m). Here, data relating to the deeper (>100 m) dives were considered because such dives may be to depths where squid-target trawling occurs. Per animal summaries of bottom swimming speed and dive duration are given in Table 1 (from Crocker et al. 2001, tables 3 and 4).

Ascent rate and descent rate varied with dive depth and Crocker et al. (2001, figure 6) provide fitted regression equations for these rates as a function of dive depth (equations 1 and 2, giving rates in metres per second for depth in metres; it was assumed here that the fitted slope in the regression for descent rate given by Crocker et al. (2001, figure 6) has the digits transposed).

$$descent\ rate = -0.54 + 0.45 * ln(depth) \tag{1}$$

$$ascent\ rate = -0.82 + 0.50 * ln(depth) \tag{2}$$

Table 1: Per animal mean and standard deviation of bottom swimming speed (m/s) and dive duration (minutes) for dives greater than 100 m depth. From Crocker et al. (2001, tables 3 and 4).

Animal ID	Bottom swimming speed		Depth (100m+ dives)		Duration (100m+ dives)	
	Mean	SD	Mean	SD	Mean	SD
E40	1.63	0.26	188	44	5.0	1.0
E41	1.54	0.41	268	82	5.0	1.2
E43	1.06	0.38	132	11	4.4	0.6
E45	2.13	0.54	135	13	4.0	0.7
E46	1.29	0.38	128	12	4.3	0.6
E48	2.02	0.85	258	84	5.6	1.4
E52	1.53	0.41	159	22	4.5	0.9
E53	1.47	0.29	163	18	5.1	0.9
E56	1.73	0.36	247	75	5.2	1.2
E61	1.50	0.25	204	73	5.0	1.4
E62	1.96	0.39	223	87	4.5	1.5
E63	1.93	0.43	213	83	4.3	1.5

2.2.3 Simulating trawl entry and additional in-trawl time

The data from instrumented sea lions do not provide information that can be used to simulate two aspects of the interaction with trawls: the time of entry into the trawl, and the additional time an animal spends within a trawl over and above the time required to swim from the mouth of the next to the SLED exit hole.

For the base case simulations, the time that the animal entered the trawl is simulated by sampling from a uniform distribution, i.e. it is assumed that the animal can enter the trawl at any point in the dive bottom time. However, it is possible that animals may be less likely to enter a trawl towards the end of their intended dive time. As an alternative, trawl entry time was simulated using an exponential distribution with the possible entry time truncated such that trawl entry occurred within the available dive bottom time. In this case, and to provide contrast with the base case, the rate used in the exponential distribution was chosen such that 75% of the trawl entries occurred in the first half of the available bottom time. For

illustrative purposes, a further alternative used a uniform distribution but with all trawl entries in the final quarter of the available bottom time.

The minimum amount of time that animals must be in the trawl is the time taken to swim from the mouth of the net to the SLED exit hole. However, animals will not necessarily leave a trawl immediately upon reaching the SLED exit hole. Exit may be delayed due to difficulty in locating the exit hole, or by the animals choosing to remain in the net (for example, due to foraging within the net).

For the base case simulations, the additional time before exit was simulated from an exponential distribution, which makes the assumption that exit events occur continuously and independently at a constant average rate. The rate was tuned such that the proportion of animals remaining in the net matched independent estimates of this quantity. Two no-exit rates were considered. Using data from 1995/96 to 2014/15, Abraham & Berkenbusch (2017) estimated that the probability of not exiting the SLED was 0.148 (with 95% c.i. of 0.087 to 0.243). An alternative model fitted by Abraham & Berkenbusch (2017) allowed for a change in exit probability over time and resulted in a no-exit probability of 0.106 (95% c.i.: 0.008 to 0.492) for the period since 2005/06.

The rate of exit from a trawl may not be constant, for example if animals are more motivated to exit as they reach the end of their intended dive time. An alternative model for the additional time spent by sea lions within the net used a Weibull distribution, which allows the exit rate to vary over time. This was tuned both to the same no-exit rates used in the exponential exit time base case, and to the Lyle & Willcox (2008) data on in-trawl interaction times for Australian fur seals that is described below.

2.3 Maximum survivable dive duration

In the simulated interactions, mortality occurs if the total required dive duration (i.e. the total dive time from leaving the surface to returning to the surface) exceeds the maximum possible time the animal can spend underwater and survive. The maximum possible dive time required here is the time until death by drowning, which will clearly exceed the maximum natural dive times recorded from animals observed during foraging studies.

2.3.1 Maximum natural dive times

Crocker et al. (2001) does not present the maximum dive times observed in that study. However, Crocker et al. (2001, figure 3) (reproduced here as Figure 4) does show data on the relationship between dive bottom time and depth for two of the study animals. This indicates that bottom times of up to approximately 3.5 min and 5 min were observed for animals E56 and E48 respectively. Allowing for descent and ascent times implies a maximum observed dive time of around 7 min for animal E56 and 9.5 min for E48.

Gales & Mattlin (1997) report a maximum dive duration of 11.3 min over 19 720 dives recorded during 73 trips by fourteen female sea lions in January and February 1995. A more extensive dataset from the 1990s, including the animals in the studies by Gales & Mattlin (1997) and Crocker et al. (2001), reveals individual maximum dive durations ranging from 5.58 min to 12.08 min (data compiled by Jim Roberts, NIWA, pers. comm.).

Chilvers et al. (2006) reports the results of a further study using time-depth recorders attached to 'branded female NZ sea lions observed to be suckling a pup' at Sandy Bay during January and February 2003 and 2004. That study collected data from 18 sea lions over 137 foraging trips during which a total of 54 106 dives were logged. Summary statistics per sea lion Chilvers et al. (2006, table 1) show maximum dive durations between 7 and 14.5 min (Table 2).

However, Chilvers et al. (2006, figure 3) (reproduced here as Figure 5) also presents data on the relationship between dive duration and dive depth for one of the individuals studied. This suggests that dive durations of almost 20 min were recorded in the study. The reason for the disparity between this figure and the tabulated summaries is not clear. One possibility, suggested by the table headings, is that the
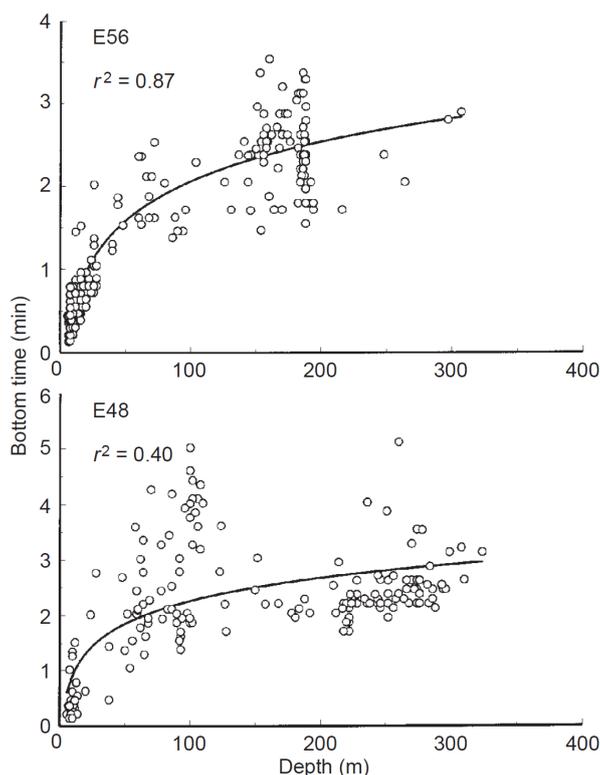
Figure 4: The relationship between bottom time and depth for the two sea lions that showed a significant relationship between these variables. Reproduced from Crocker et al. (2001, figure 3) ©2001 The Zoological Society of London.

maximum of 14.5 min is actually mean maximum duration, perhaps over the set of trips. While this interpretation appears inconsistent with the text which states 'our research documents the deepest dive recorded for a female NZ sea lion at 597m and one of the longest recorded dives at 14.5 min' it is also unclear why this text refers to '*one* of the longest dives ...' (i.e. raising the question of what set of longest dives is being referred to here).

2.3.2 Observations of animals interacting with trawls

In the period from 1999 to 2001, required research on the efficacy of SLEDs included the use of cover nets to trap and retain exiting animals with the intention that the video footage would allow the survival of exiting animals to be assessed (Wilkinson et al. 2003). Technical challenges with the video cameras meant that limited footage was obtained; Wilkinson et al. (2003) report that three animals were video-taped and it was considered 'likely that the animals would have survived if the cover nets had not been present'. These data were also used in calculations by Fletcher (2001), but neither report discusses how long the animals were observed alive in the cover nets in order to assess that they were likely to have survived.

Lyle & Willcox (2008) report on the analysis of footage from the inside of mid-water trawls in the Australian Commonwealth Small Pelagic Fishery in 2006–2007. Footage totalling 735 h was obtained from 98 trawls, during which an estimated 151 fur seals (thought to be Australian fur seals, *Arctocephalus pusillus doriferus*) were sighted in the net. A seal exclusion device (SED) was deployed in the study, in most cases with an exit hole in the bottom of the trawl (rather than in the top of the trawl which is the case for SLEDs used in the squid fishery). This study allowed the duration of the interaction (i.e. the time for which the animal was observed in the net) to be measured, and linked to outcome. Most interactions were short: a third were less than a minute, half were under three minutes and 70% were less than six minutes (Figure 6).
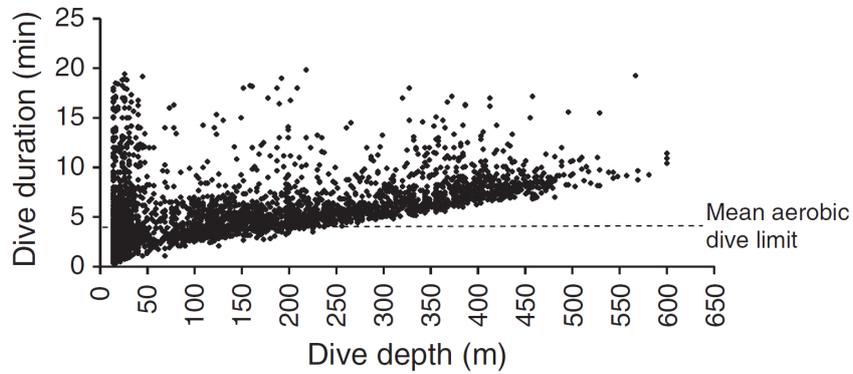
Figure 5: The relationship between dive duration and depth for female ID 1456. Reproduced from Chilvers et al. (2006, figure 3) ©2006 The Authors. Journal compilation ©2006 The Zoological Society of London.
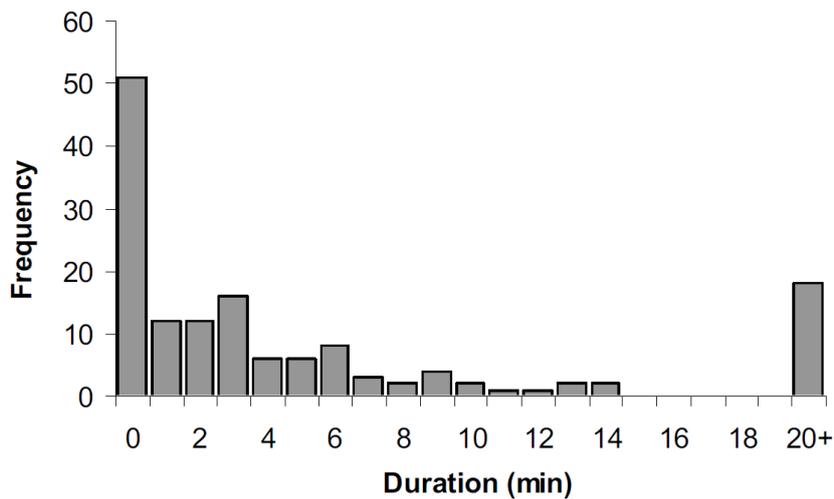
Figure 6: Interaction duration for Australian fur seals observed inside mid-water trawls. Reproduced from Lyle & Willcox (2008, figure 14).

Table 2: Per animal summaries of dive depths and durations from Chilvers et al. (2006, table 1).

Animal ID	Trips	Dives	Mean dive depth (m)			Mean dive duration		
			Mean	SE	Max	Mean	SE	Max
1433	6	3349	142.4	0.84	315	4.42	1.2	8.4
1492	10	3271	178.9	1.58	424	4.97	1.7	11.3
1399	13	3203	147.3	1.88	500	3.64	1.9	10.8
1397	6	3869	114.1	0.53	194	4.29	0.9	7.0
1391	10	3378	134.3	1.24	597	4.48	1.6	10.6
1409	9	3246	169.8	2.05	535	3.89	1.9	9.8
1458	6	3795	119.5	0.82	203	4.01	1.2	8.8
1484	10	4641	109.7	0.45	175	4.39	0.8	13.5
1470	3	1144	128.4	3.74	471	3.56	4.0	9.7
1462	7	3022	119.2	1.08	199	4.18	1.7	9.2
1456	14	3851	135.4	2.28	592	3.51	2.1	14.5
1371	2	496	133.9	5.36	450	4.11	5.0	13.2
1439	9	2888	130.9	1.99	512	3.59	2.2	9.6
1438	5	1457	129.5	2.69	443	3.45	2.6	10.1
1406	5	2729	143.0	2.09	462	4.14	2.7	12.9
1400	3	1846	94.6	1.09	172	3.92	1.7	7.7
1385	9	3804	97.6	0.85	170	3.37	1.2	8.1
1443	10	4117	101.4	0.70	422	3.96	1.1	9.7

Animals were observed actively exiting the net for interaction durations up to nine minutes, and seals exiting via the SED opening 'whilst exhibiting some level of responsiveness' did so up to about 14 minutes from first sighting within the net. Lyle & Willcox (2008) divided interations into three categories:

low risk interactions less than 6 min in duration;

medium risk interactions between 6 and 10 min in duration; and

high risk interactions which were greater than 10 min in duration.

All interactions where mortality of the seal was the assumed outcome fell in the high risk category. For the 151 seal interactions, 19 mortalities were identified and a further 8 interactions were classified as high-risk interactions (Lyle & Willcox 2008, table 6).

Lyle & Willcox (2008) noted that 'under natural conditions, maximum dive durations of 6.8 and 8.9 min have been recorded for male and female Australian fur seals, respectively' whereas durations of up to 14.8 min had been recorded for New Zealand fur seals. A more recent study reports a maximum observed dive duration of 9.8 min for a male Australian fur seal (Knox et al. 2017). In summary, Lyle & Willcox (2008) conclude that probability of survival of seals interacting with trawls is reduced when the time spent in the net exceeds the maximum observed natural dive times.

2.3.3 Assumed maximum breath hold

The Aquatic Environment Working Group discussed the available data on maximum dive times on 19 March 2019. The group proposed that the distribution of maximum *observed* dive times can be assumed to be a proxy for the maximum *possible* dive times (i.e. time to drowning) if the curve for time to drowning is right-shifted by a constant number of minutes from the curve for observed maximum observed dive times.

Specifically, it was agreed that:

- available data on maximum observed dive times should be combined for animals, and filtered – where possible – to include animals diving deeper than 150 m;

- the resulting distribution of maximum observed dive times would be right shifted by adding a constant such that 16 % of the distribution was less than 11 min.

Two sets of data on maximum observed dive times are available. NIWA (Jim Roberts, pers. comm.) have compiled data from early research at the Auckland Islands representing 51 individuals with dives deeper than 150 m. Based on the reported animal identifiers, this includes the animals studied by Crocker et al. (2001) and other studies during the 1990s. The data reported by Chilvers et al. (2006) appear to represent a different group of 18 animals with data collected in the early 2000s.

The distribution of natural dive times is right-shifted by adding a constant 3.9 min to produce an assumed distribution of maximum survivable dive times (Figure 7, Figure 8).
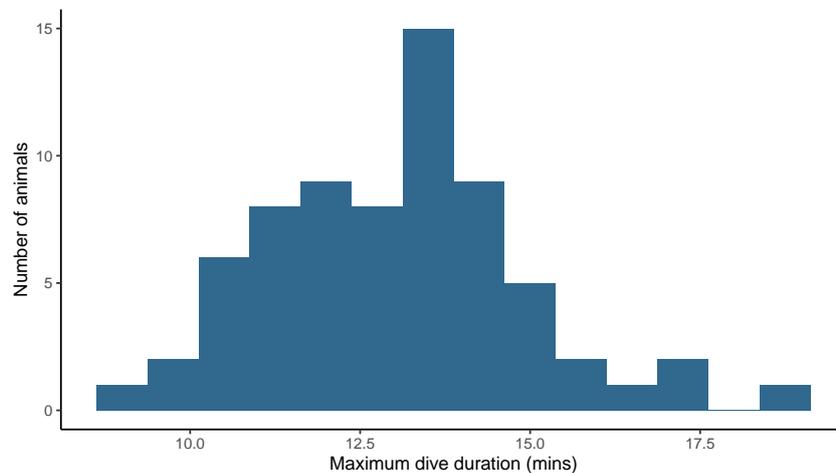
Figure 7: Distribution of assumed maximum survivable dive duration, created by right shifting the distribution of maximum natural dive times.
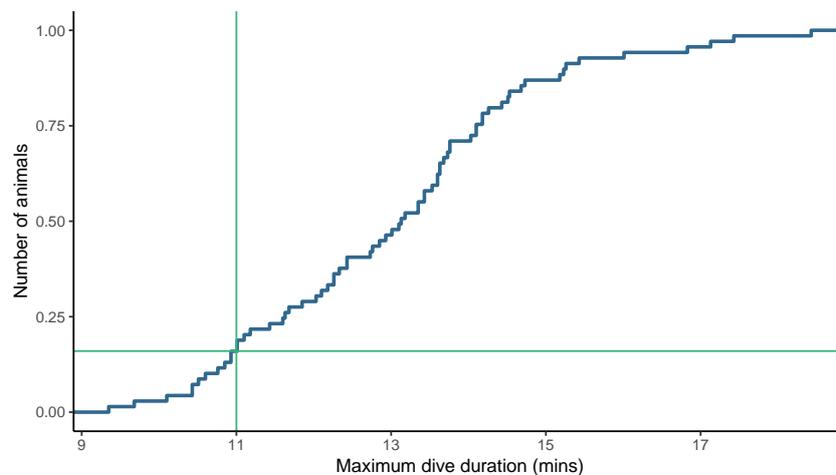
Figure 8: Cumulative distribution of assumed maximum survivable dive duration, created by right shifting the distribution of maximum natural dive times.

3. RESULTS

A set of 10 000 interactions was simulated by resampling the recorded SQU 6T tows from 1 October 2015 to 30 September 2018, and the sea lion dive data provided by Crocker et al. (2001). After eliminating tows where the calculated descent and ascent times provided no available bottom time, a set of 8367 simulated interactions was available.

3.1 Simulated tows

As expected, given the nature of the simulation, the set of simulated tows has similar characteristics to the recorded tows. In the simulated tows, 76.6 % are bottom trawls. The distributions of simulated tow depths and speeds (Figure 9) are similar to the set of observed tows (Figure 2 and Figure 3, respectively).
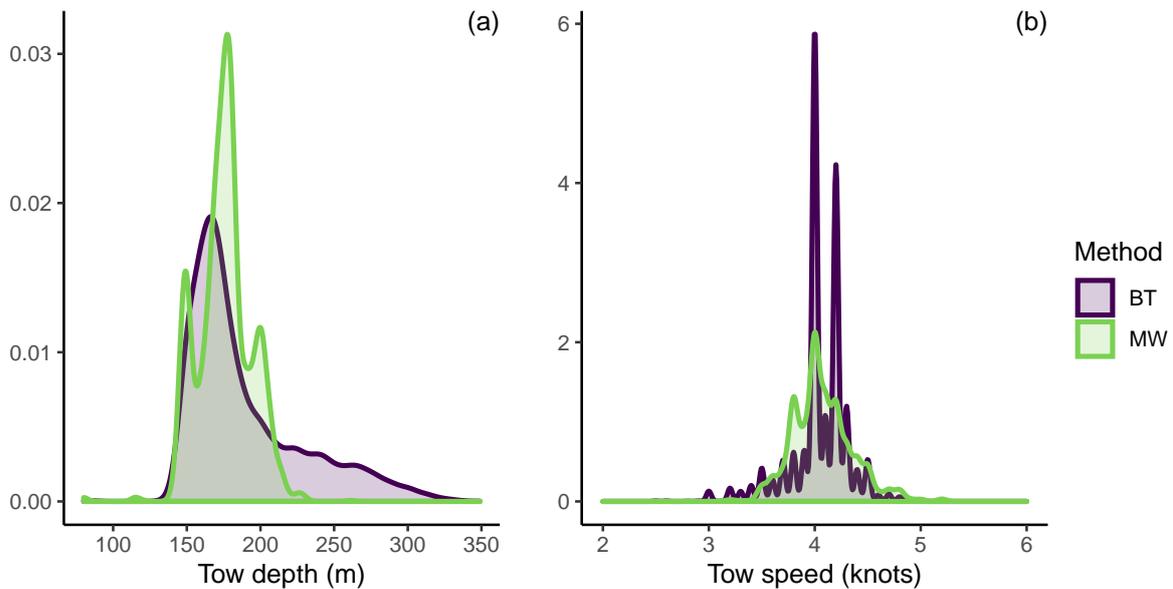
Figure 9: Simulated tow depth (a) and speed (b) distributions for bottom and mid-water trawls.

3.2 Simulated dives

Statistics relating to the simulated dives are summarised per animal in Table 3. Simulated dive depths are based on the tow depths and therefore do not show the between-animal variation seen in natural dives (Table 1). However, the simulated bottom swimming speeds and dive durations (where this is the dive duration in the absence of an interaction) show the expected between-animal variation.

As intended, the simulated base case distribution of trawl entry times is uniform over the available bottom time (which represents the bottom time that would have occurred in the absence of a trawl interaction; Figure 10). The two alternative distributions of trawl entry times are illustrated in Figure 11.

Table 3: Simulated dive parameters for the twelve sea lions included in the simulation data set. Values given are means over simulated dives.

| Animal ID | Dives | Depth (m) | Bottom speed (m/s) | Dive times (mins) if no interaction | |
				Duration	Bottom time
E40	751	187.58	1.67	5.09	1.64
E41	740	186.93	1.55	5.18	1.73
E43	658	183.25	1.06	4.58	1.18
E45	591	180.26	2.12	4.33	0.97
E46	658	185.11	1.31	4.53	1.11
E48	783	189.37	2.04	5.70	2.22
E52	698	185.63	1.52	4.82	1.39
E53	799	187.61	1.46	5.13	1.68
E56	738	190.65	1.75	5.33	1.83
E61	730	188.83	1.45	5.19	1.72
E62	650	183.59	1.98	4.81	1.41
E63	571	182.63	1.88	4.85	1.46
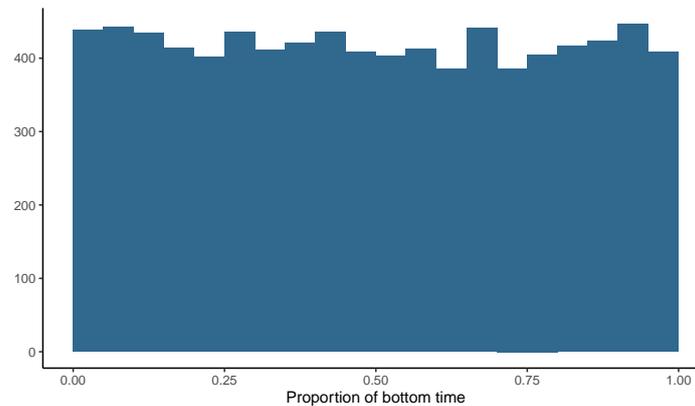
Figure 10: Simulated time of net entry, as a proportion of expected bottom time, for the base case where simulations assume trawl entry is uniform over the intended bottom time.
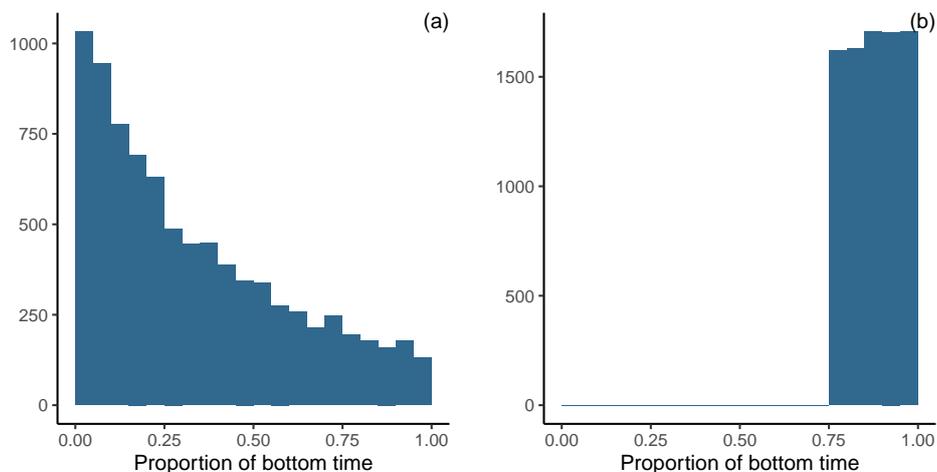
Figure 11: Simulated time of net entry, as a proportion of expected bottom time, for the two alternate models; (a) truncated exponential tuned such that 75% of entries occur in the first half of the intended bottom time and (b) all trawl entries occuring in the final quarter of the intended bottom time.

3.3 Simulated interaction outcomes

3.3.1 No additional in-trawl time

Before considering the full simulation results, it is helpful to consider the case where sea lions exit the net immediately after transiting from the net mouth to the SLED. In this case, the simulations indicate that most sea lions have a residual dive time (i.e. the difference between the maximum survivable dive time and the simulated dive time) of between five and ten minutes (Figure 12).

For the set of 8367 simulated interactions and the base case uniform entry time model, zero sea lions fail to exit the trawl and zero drown before reaching the surface. The alternate model where all trawl entries occur in the final quarter of the available dive time results in slightly shorter residual dive times (Figure 12), but in this model it is also the case that zero sea lions fail to exit the trawl and zero drown before reaching the surface.
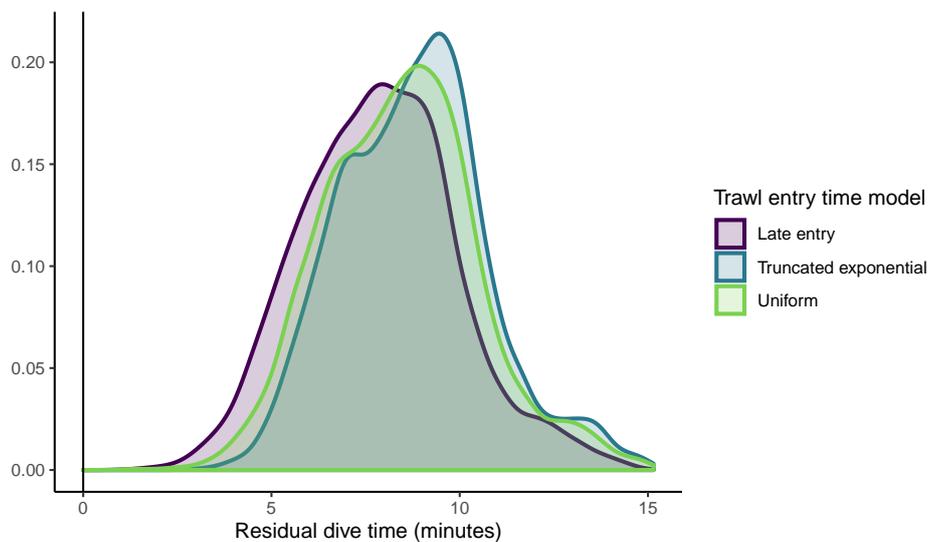
Figure 12: Residual dive time: the difference between the assumed maximum survivable dive time, and the simulated dive times with no additional in net time.

3.3.2 Survival and cryptic mortality – base case

In the full simulations, the required dive time for a successful exit includes additional simulated time spent inside the trawl. In the base case model, the exit time after reaching the SLED follows an exponential distribution with a rate tuned to reproduce the overall no-exit rate of 0.148 estimated by Abraham & Berkenbusch (2017). For a rate parameter of 0.196, 85.2 % of animals are estimated to exit. As the additional time spent in the net increases, the proportion of animals surviving decreases (Figure 13).

The base case simulations suggest that 7 % of the exiting animals drown before reaching the surface, i.e. these animals have a negative residual dive time (Figure 14). For bottom trawl this represents 6.7 % of exiting animals and 7.9 % for mid-water trawl. Although mid-water nets are larger, and the time taken for a sea lion to swim from the mouth of the net to the SLED exit hole is therefore longer (Figure 15a), bottom trawl effort can be deeper (Figure 2) and descent and ascent times for interactions with bottom trawls can therefore be longer than for mid-water trawls (Figure 15b, c).

For the base case model, the overall survival rate, taking into account animals that drown in the net or before reaching the surface, is 79.2 %. The ratio of total deaths to deaths that occur prior to exit is 1.4. With the constant exit rate assumed in the base case model, 17.9 % of animals exit within a minute, 44.8 % within three minutes and 69 % within six minutes.
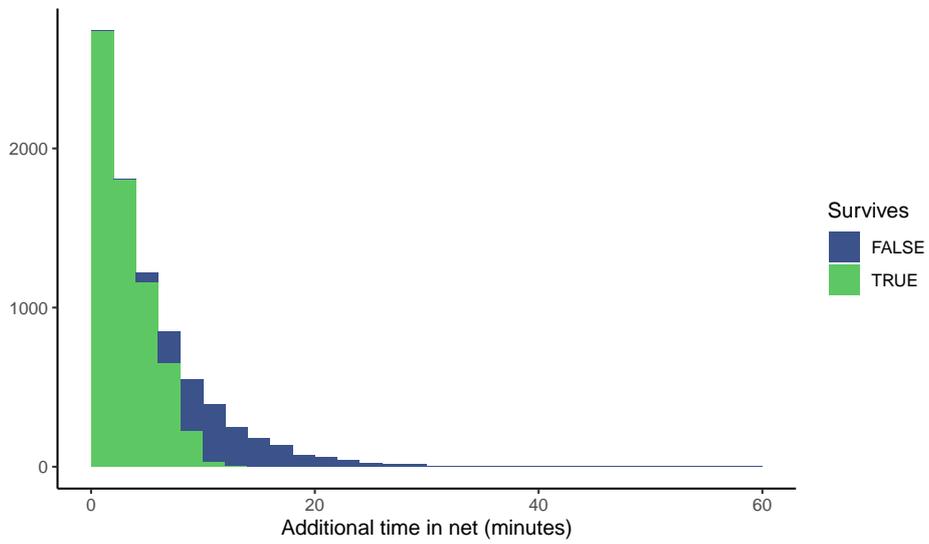
Figure 13: Additional time spent in net for constant exit rate tuned to a no-exit probability of 0.148.
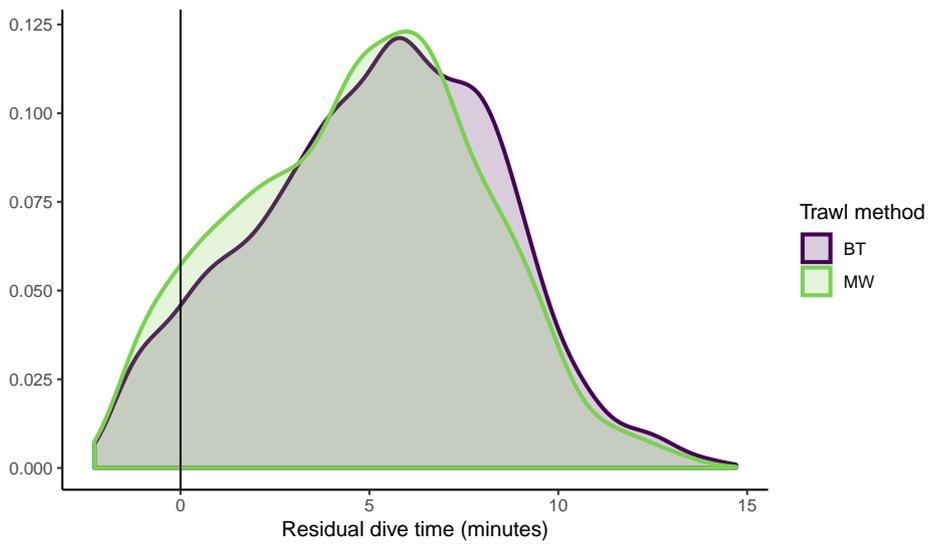
Figure 14: Residual dive time for the base case model for sea lions that exited the net in interactions with bottom and mid-water trawls.
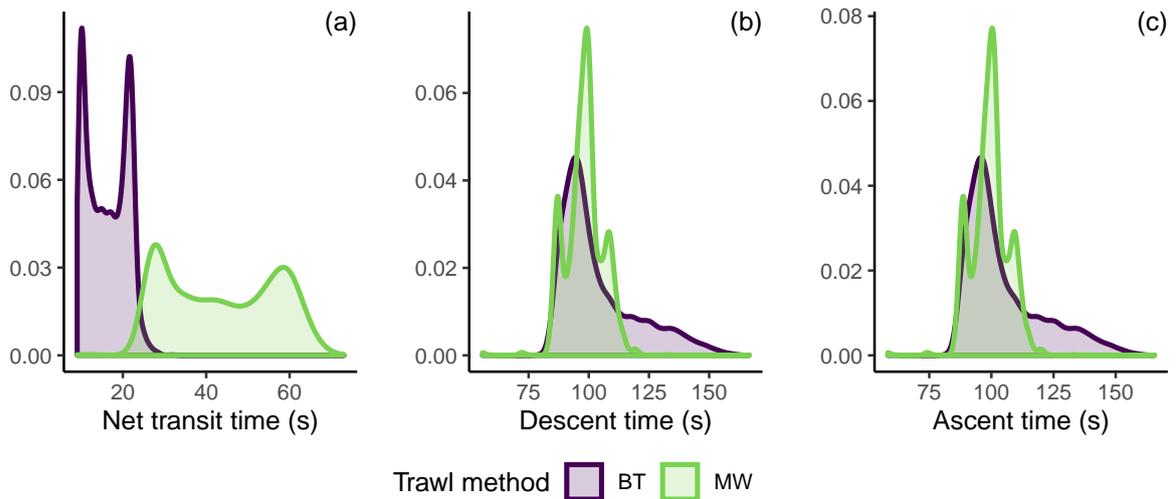
Figure 15: Time spent transiting the net (a), and on descent (b) and ascent (c), for simulated interactions with bottom and mid-water trawls.

3.3.3 Survival and cryptic mortality – recent rates of non-exit

When the base model is tuned to the lower, recent no-exit rate estimate of 0.106 (Abraham & Berkenbusch 2017), the rate parameter for the exponential exit rate distribution is set to 0.233 and 89.4 % of animals are estimated to exit.

For this case, simulations suggest that 5.9 % of the exiting animals drown before reaching the surface. For bottom trawl this represents 5.8 % of exiting animals and 6.1 % for mid-water trawl. The overall survival rate, taking into account animals that drown in the net or before reaching the surface, is 84.2 %. The ratio of total deaths to deaths that occur prior to exit is 1.5.

The impact on the cryptic multiplier (the ratio of total deaths to deaths that occur prior to exit) when the simulation model is tuned to different exit rates is illustrated in Figure 16. The multiplier is below two until the percentage of animals exiting exceeds 97%.
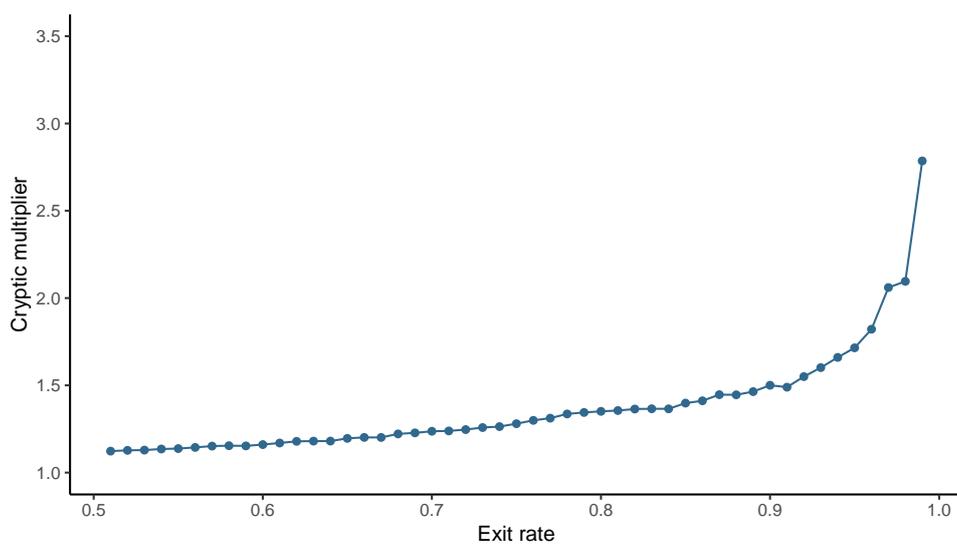
Figure 16: Cryptic multiplier as a function of the tuned exit rate.

3.3.4 Survival and cryptic mortality – Weibull exit times

In the base case model, with a constant rate of exit once sea lions have arrived at the SLED exit hole, sea lions remain in the net for longer than the Lyle & Willcox (2008) data on in-trawl interaction times would suggest (Figure 17a). A Weibull model for exit times allows the exit rate to vary with time and allows for a better fit to the distribution of interaction times observed by Lyle & Willcox (2008) for Australian fur seals (Figure 17b).
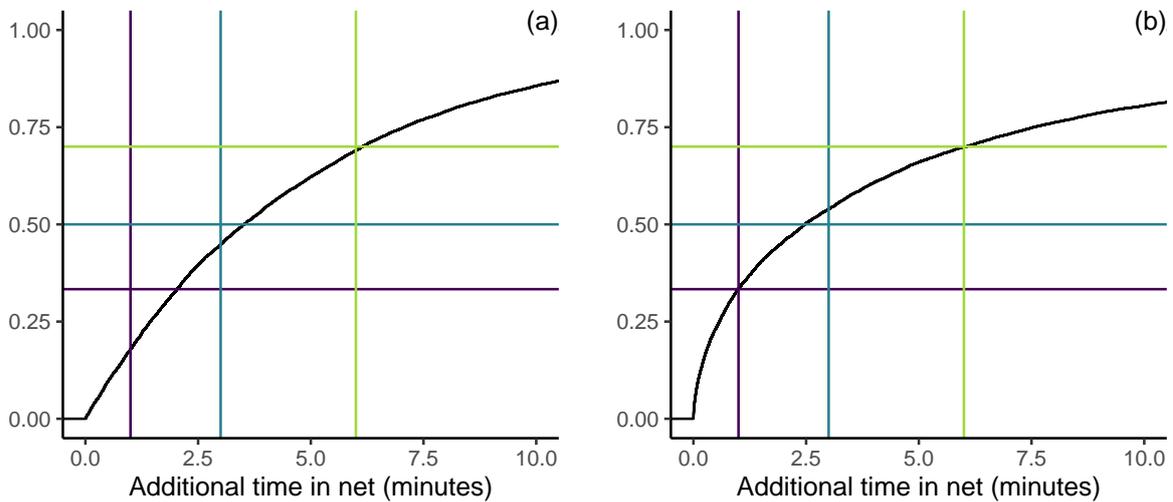
Figure 17: Cumulative distribution of the additional time spent in the net with (a) a constant exit rate tuned to a no-exit probability of 0.148, and (b) a Weibull exit time distribution tuned to the Lyle & Willcox (2008) interation time distribution and a no-exit probability of 0.148. The summary statistics (proportion of interactions lasting less than 1, 3 and 6 minutes) reported by Lyle & Willcox (2008) for in-trawl interactions of Australian fur seals are indicated by the horizontal and vertical lines.

With a Weibull model for the additional time in the trawl, tuned to both the base non-exit rate of 0.148 and the Lyle & Willcox (2008) interaction time distribution, 33.4 % of animals exit within a minute, 53.9 % within three minutes and 69.9 % within six minutes (Figure 18).
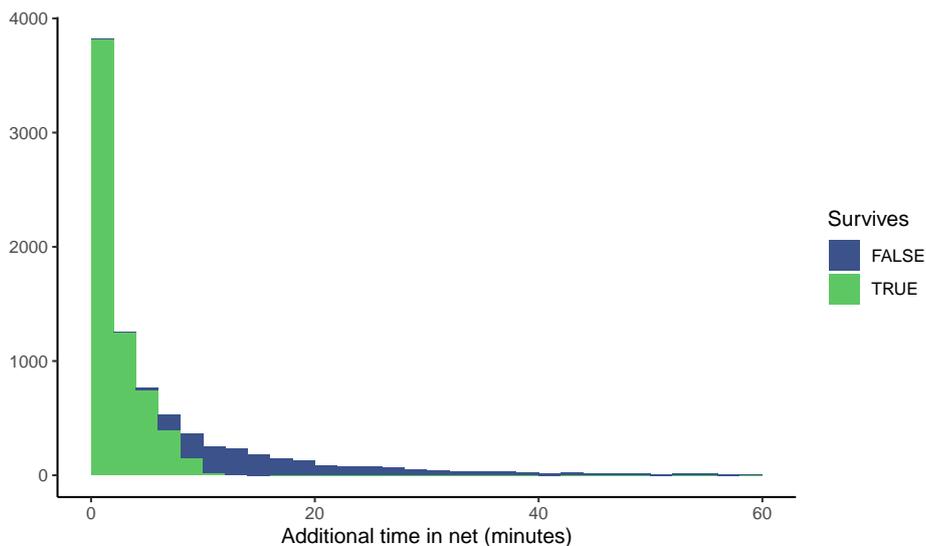
Figure 18: Additional time spent in net for a Weibull exit time distribution tuned to a no-exit probability of 0.148.

For this model, the simulations suggest 4.5 % of the exiting animals drown before reaching the surface. For bottom trawl this represents 4.5 % of exiting animals and 4.6 % for mid-water trawl. The overall

survival rate, taking into account animals that drown in the net or before reaching the surface, is 76.4 %. The ratio of total deaths to deaths that occur prior to exit is 1.2.

3.3.5 Sensitivity to trawl entry time parameterisation

Summary statistics for the three different parameterisations of the trawl entry time process are given in Table 4. In all cases the constant exit rate model was used to specify the additional in trawl time, and the exit rate was tuned to the base no-exit probability of 0.148. It is apparent that the different entry time parameterisations have little impact on the key results of overall survival and ratio of total to in-trawl mortality.

Table 4: Summary statistics for simulations with different parameterisations for the trawl entry distribution.

Model	Exit success (%)	Exit rate	Post-exit mortality (%)	Overall survival (%)	Cryptic multiplier
Uniform	85.19	0.20	6.99	79.24	1.40
Truncated exponential	85.18	0.19	6.96	79.25	1.40
Late entry	85.25	0.21	7.58	78.79	1.44

4. DISCUSSION

This report illustrates that it is possible to simulate the outcome of interactions between sea lions and trawls using information from studies of natural sea lion dive activity combined with data on trawl activity. The simulations considered:

1. the time spent by sea lions descending to a trawl;

2. time spent at depth prior to entering the trawl;

3. the time required to transit the length of the trawl from net mouth to SLED exit hole;

4. additional time spent within the trawl; and

5. the time spent on ascent.

If the sum of the time spent on these various components of a dive exceeded the maximum survivable time underwater, then mortality of the sea lion is assumed to have occurred. Completion of the simulation framework required modelling assumptions to be made around three processes:

• the entry of sea lions into trawls;

• the exit of sea lions from trawls via the SLED; and

• the maximum survivable dive time of sea lions.

In the base case, it was assumed that a sea lion could enter a trawl at any point in their intended dive time. Sensitivity runs explored the case where sea lions were less likely to enter a trawl as their dive progressed, and the contrasting case where all trawl entries occurred towards the end of the intended dive. While late entries into the trawl slightly increased the simulated probability of post-exit drowning, the impact of the different parameterisations was small. This is likely to be due to the fact that the model was tuned to match independent estimates of sea lion retrieval from trawls; that is the model is tuned to a process later in the dive and this can therefore accomodate differences in the preceeding processes.

The available sensor data from instrumented sea lions provide no information on sea lion behaviour when they are in a trawl. However, there are two sources of information that allowed the additional time that sea lions spend within a trawl (over and above the time required to transit the distance from net mouth to SLED exit) to be simulated. The key information used is the no-exit rate of sea lions within trawls (also expressed as the inverse, exit success). In early trials of SLEDs, exit success was estimated at 91 % (Wilkinson et al. 2003). Breen et al. (2005) developed the approach for estimating a constant exit rate from datasets containing closed (no SLED) or open (SLED) nets, and estimated exit success at 69.5 %, while Smith & Baird (2007) estimated a mean no-exit probability of 0.284 with data up to the 2004/05 fishing year. In 2006/07 there was a detailed audit of SLEDs (Clement & Associates 2007) and the development of a process for ongoing certification of the devices. The most recent estimate of no-exit probability of 0.148 (Abraham & Berkenbusch 2017, using data to 2014/15) tends to suggest that exit rates have increased, but estimates of a recent no-exit rate were uncertain. Overall, it appears that exit rates are in the region of 70 % to 90 %.

The simulation tuning process assumes that non-exiting sea lions are those which exceed their maximum survivable dive time before SLED exit occurs. Where a sea lion exceeds their maximum survivable dive time after SLED exit, this is considered a cryptic mortality. The ratio of total deaths to deaths occuring in the net varies depending on the assumed non-exit rate but, in the base case model with a constant rate of exit, is within the range 1.2–1.5 for exit rates of 70 % to 90 %. The design of the SLED (Figure 1) is expected to minimise the passive loss of items from the net. If sea lions that drown in the net are sometimes not retained, then the the ratio of total mortalities to in-net mortalities would be overestimated

but this would also result in an underestimate of observable to cryptic mortalities. A retention process could be explicitly added to the simulations if required.

The base case model parameterised the additional time spent in the net using an exponential distribution which implies a constant rate of exit. A sensitivity run used a Weibull distribution for this process, which implies that the rate can change. Use of the Weibull distribution allowed a better fit to the distribution of in-trawl interaction times observed on video for Australian fur seals by Lyle & Willcox (2008). In this sensitivity run, sea lions tend to exit the trawl sooner; as a result, when tuning to the base no-exit rate of 0.148 there are fewer post-exit mortalities and the cryptic multiplier is reduced to 1.2.

It is assumed that the available sea lion dive data represent dives in the absence of a trawl interaction. The data from Crocker et al. (2001) were collected in 1996, prior to the introduction of SLEDs in the fishery. However, the data used in parameterising maximum dive durations included data collected in 2003 and 2004 (Chilvers et al. 2006) when SLEDs were in use in the fishery. Thus it is possible that some trawl interactions could be present in the data and these dive durations already include additional time (if any) arising from the interaction.

The simulation framework developed here is simple, but draws on an extensive dataset of trawl and sea lion dive data. Fishery data are comprehensive, and fishery patterns (in terms of depths fished, in particular) have been stable for some time. The key change has been an increasing use of bottom trawls, but the simulation results suggest that the different net lengths have only a minor impact on the proportion of exiting animals that fail to survive.

The data from instrumented sea lions is from adult females, the demographic group of particular interest in terms of fishery interactions. Although dive speed data are available for only a subset of the instrumented animals, data from other animals in other years suggest that the data reported by Crocker et al. (2001) are not atypical. A potential improvement to the simulation framework would be resampling from actual sea lion dive data rather than generating the relevant swimming speeds and durations from summary statistics and, if available, using swim speed data from more animals rather than the subset of instrumented sea lions reported by Crocker et al. (2001). One limit of the approach of simulating from summary data is that covariance between dive parameters present in the original data is not maintained. For example, intended dive duration may vary with target dive depth and potentially affect the maximum survivable dive duration as a result of variation in how animals prepare for different dive depths. Crocker et al. (2001, figure 3) found evidence of a relationship between dive duration and depth for only two of the twelve animals they studied. However, in these two animals, dives of very short duration were restricted to shallow depths (less than 50 m). In the simulations reported here, the simulated duration was based on statistics for dives greater than 100 m when variation in duration with depth is less evident (Figure 4).

All interactions were simulated as if they occurred at the fishing depth of the tow. Some interactions may occur as the trawl is descending through the water column or being hauled at the end of the tow. In these cases dive durations will be shortened due to the reduced ascent and descent time requirements, thus increasing the time available to sea lions underwater. While this would indicate that the probability of post-exit drowning is overestimated in the simulations reported here, some of this 'conservatism' will be lost if near surface interactions are by animals that are less prepared for an extended time underwater.

Information on maximum survivable dive times is clearly the key information required for the results of the simulations to usefully inform the likelihood that animals exiting via the SLED survive the ascent to the surface. Sensor information only provides observations on the longest dives undertaken during natural foraging activity. The agreed approach to producing the distribution of maximum survivable dive times used in these simulations is somewhat arbitrary. However, the resulting distribution is centered around 13 min (Figure 7) which is less than the longest natural dive of 14.5 min reported by Chilvers et al. (2006). Likewise the entire distribution assumed for maximum survivable dive times is less than the greatest natural dive durations plotted in Chilvers et al. (2006, figure 3). It therefore seems quite possible that the approach used has underestimated the maximum times that sea lions can survive underwater in extreme situations. However, unless review of historic video footage from the 2001 'cover net trials' yields significant new information, it seems unlikely that new data on time-to-drowning in sea lions

will become available and comparison with natural dive times will continue to provide the key basis for judging the reasonableness of the assumptions made here.

5. ACKNOWLEDGEMENTS

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