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DOLPHIN AND SEAL INTERACTIONS WITH MID-WATER TRAWLING IN THE COMMONWEALTH SMALL PELAGIC FISHERY, INCLUDING AN ASSESSMENT OF BYCATCH MITIGATION

Jeremy M. Lyle and Simon T. Willcox

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Dolphin and seal interactions with mid-water trawling in the Commonwealth Small Pelagic Fishery, including an assessment of bycatch mitigation strategies

Final Report Project R05/0996

Jeremy M. Lyle and Simon T. Willcox

February 2008

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Non-technical summary

The Small Pelagic Fishery (SPF) is at an early stage of development, with catches taken predominantly from Zone A, around Tasmania. Between the mid-1980s and late 1990s the vast majority of the catch was taken by purse seine, with jack mackerel the dominant species. Mid-water trawling was trialled during 2001 and commercial mid-water trawl operations commenced in late 2002, with redbait the primary target species.

A ‘soft’ rope-mesh Seal Excluder Device (SED) was included in the trawl net from the inception of mid-water trawling operations. In addition, a high level of observer coverage was applied to the fishery, with no marine mammal bycatch reported until late 2004, at which time 14 dolphin mortalities occurred in two separate incidents east of Flinders Island. Modifications were made to the exclusion device, a code of conduct implemented and full observer coverage imposed. The code of conduct specified, amongst other things, that the gear would not be set if dolphins were sighted around the vessel, and the vessel would steam at least 10 kilometres away from areas where dolphins were present before setting the gear. Also in response to the mortalities AFMA established the Cetacean Mitigation Working Group (CMWG) comprised of industry, government, research and conservation organisations. The primary role of the CMWG was to identify strategies to mitigate cetacean bycatch and to provide advice on research needs to develop mitigation measures.

By mid-2005 a further three incidents involving dolphin mortalities as well as three separate incidents involving seal bycatch had occurred. While interactions with cetaceans were of greatest concern, a pilot study conducted during the latter half of 2005 using an underwater video camera system established that fishery interactions with fur seals were far more common. The study also provided recommendations regarding the application of underwater video technology along with changes to the SED design, identifying the need for a rigid grid that was angled to direct megafauna towards the escape opening.

Many of the recommendations relating to improvements to the camera system have been implemented for the present investigation. Specific objectives include to determine the type and frequency of interactions between marine mammals and mid-water trawl gear, investigate potential factors contributing to bycatch, assess the performance of various exclusion devices, and identify operational factors that present an increased risk of bycatch occurring.

Through the full engagement of the industry, a high level of video coverage of trawl operations over the study period (January 2006 – February 2007) was achieved, with underwater video information for almost 100 trawls, representing over 700 hours of video footage. As such, this study represents the most comprehensive assessment of the nature of operational interactions between marine mammals and mid-trawls available, including information on net entry and exit, and potential rates of survival.

Fur seals, most probably Australian fur seals, entered the body of the trawl in over half of all monitored shots, though interaction rates peaked at over 70% during autumn and winter and were below 25% at other times of the year. This seasonality may, in part at least, be the result of habituation, since seals appeared to become increasingly adept at

entering the net to forage during periods of sustained fishing activity within localised areas.

During the study an estimated 151 seals were sighted inside the net in the vicinity of the SED. Up to 9 seals were present per shot, the vast majority (87%) having entered via the net mouth, only a small proportion (13%) entered through the escape opening. Conversely, the greatest majority (64%) exited the net via the escape opening, relatively few (22%) exited out of the net mouth. Interaction outcomes for the remainder (14%) were not observed, mainly due to the camera field of view being obscured by fish. Seals entered the net throughout the trawl operation, that is whilst the net was being set, during the fishing phase, during turns (which involved partially hauling the net and then resetting), hauling and while the catch was being pumped out. Although the highest rate of interactions occurred whilst the net was being set, numerically the majority of seals (62%) entered the net whilst it was fishing at depth, this particular operational phase accounting for the bulk (73%) of the trawl duration. Since trawling typically occurs in shelf waters (< 150 m), at depths that are within the dive capability of fur seals, the trawl effectively remains accessible to seals throughout the entire operation. Furthermore, most interactions occurred at night, reflecting the concentration of trawl effort during the hours of darkness. When standardised for effort, this diurnal pattern was no longer evident, suggesting that the probability of interactions occurring was unaffected by time of day.

The performance of bottom and top opening SED configurations were examined, though due to operational limitations we were unable to adequately trial the top opening design. Although SED configuration had no influence on interaction rates, we were able to demonstrate that by increasing the size of the escape opening, such that there was no floor in the net immediately in front of the excluder grid, a three-fold reduction in lethal interactions was achieved. By comparison with other Australian trawl fisheries the overall seal mortality rate is high in this fishery, around 0.19 seals per shot, though when the large escape opening was used this dropped to 0.12 per shot, which is comparable to the upper range for the winter blue grenadier fishery. During the 13 month study period, we estimated that there were 55 (95% CL 33-78) fishery induced seal mortalities, with the survival of a further 20 seals considered uncertain.

An important observation from the study was that all seal mortalities eventually fell out of the escape exit prior to the net being brought onboard the vessel, suggesting that many would not have been observed without the camera system and hence the scope of the bycatch issue would have been understated, even with a high level of observer coverage.

No interactions with dolphins were observed or reported over the entire study period, highlighting that such interactions are rare and unpredictable. Other bycatch observed included thresher and mako sharks, rays, sunfish, and broadbill swordfish, though captures were very rare and numbers low. There was evidence that some of this bycatch was ejected in a healthy condition.

This study has clearly demonstrated that seal bycatch in mid-water trawls is an issue that needs to be addressed in the SPF. The implementation of an exclusion device that optimises the probability that animals escape in a healthy condition represents the key to a successful mitigation strategy. In this respect there is considerable scope for further refinement in SED design, including a clear need to further examine the suitability of a top escape opening and to investigate options to reduce the ingress of marine mammals and loss of fish out of the escape opening. Such refinements as the inclusion of an escape hatch and/or a hood over the escape hole warrant consideration.

Significantly, this study also provides a model for other marine mammal bycatch studies, whereby through the full engagement of industry as a research partner it has been possible to achieve a high level of fishery coverage in a cost-effective manner as well as working collaboratively to mitigate the bycatch of marine mammals.

Acknowledgements

First and foremost, the success of this project is largely due to the support and commitment provided by Seafish Tasmania, in particular Gerry Geen. The skippers and crew of the FV *Ellidi*, in particular Al Roberts, Andre Schoeman and Chris Healey, deserve special mention for their significant dedication to deploying the camera system and downloading and archiving data, often in very trying conditions. Glenn Hill and Tim Boast also provided invaluable logistic and technical support.

Martin Cawthorn provided sound advice throughout the project, in particular in relation to seal behaviour and the performance of exclusion devices. We also acknowledge the TAFI staff that assisted with at sea monitoring, including Dirk Welsford and Graeme Ewing. The on-going interest and encouragement from Selina Stoute of AFMA is appreciated.

We are indebted to the team at Scielex for developing an underwater camera system that was robust enough to withstand the rigors of normal commercial fishing operations yet flexible enough to be operated by researchers and the crew of the *Ellidi*.

This research was conducted in accordance with University of Tasmania Animal Ethics Committee approval (A0008607).

The project was funded jointly by AFMA through the Natural Heritage Trust and the Research Fund, the Department of Environment and Water Resources and the Whale and Dolphin Conservation Society.

1 Background

1.1 General

Direct interactions between fishing gear and marine mammals (cetaceans and pinnipeds) occur in many fisheries worldwide and may result in incidental capture and mortality of some individuals (Read *et al*., 2006). For several species, fisheries bycatch is considered to pose a significant threat to population integrity.

Globally the bycatch of marine mammals is estimated to be in the hundreds of thousands of individuals, however, due to the absence of information from many fisheries, the reliability of estimates are uncertain and almost certainly conservative (Read *et al*., 2006). In order to adequately quantify marine mammal bycatch a high level of observer coverage is typically required (Northridge and Thomas, 2003). In practice, for many fisheries observer coverage is inadequate or non-existent, resulting in the majority of bycatch records being anecdotal (and potentially under-reported) rather than quantitative (Morizur *et al*., 1999; Lewison *et al*., 2004).

Although gillnet fisheries account for the bulk of the marine mammal bycatch, varying levels of cetacean and pinniped bycatch also occur in many trawl fisheries worldwide (Fertl and Leatherwood 1977, Morizur *et al*., 1999; Wilkinson *et al*., 2003; Northridge *et al*., 2005; Read *et al*., 2006). In this respect Australian trawl fisheries are no exception (Shaughnessy *et al*., 2003). For example, between 1993 and 2001 wet-boats operating in the South East Trawl Fishery captured an average of 720 seals per year, with approximately one third being released alive (Knuckey *et al*., 2002). Factory trawlers commenced fishing operations for blue grenadier (*Macruronus novaezelandiae*) off the west coast of Tasmania in 1997 and following the death of over 80 seals in 1999, seal bycatch was identified as an important issue for that fishery (Tilzey *et al*., 2006). Dolphins also interact with trawls in a number of Australian fisheries though mortalities tend to be rare (Shaughnessy *et al*., 2003). Dolphin mortalities have, however, been recorded in the Pilbara finfish trawl fishery (Stephenson and Chidlow, 2002).

1.2 Mitigation measures

Non-gear specific management strategies to minimise marine mammal bycatch include fishery closures in association with bycatch trigger limits, effort reduction and time/area closures (Wilkinson *et al*, 2003; Smith and Baird, 2005; Tilzey *et al*., 2006). In some fisheries, an industry code of practice has been adopted to reduce the level of interactions with marine mammals, including practices such as cessation of fishing operations when marine mammals are sighted, movement away from areas where marine mammals are present, and temporal (time of day, season) and spatial restrictions on fishing operations during periods of highest risk of interactions (Wilkinson *et al*, 2003; Tilzey *et al*., 2006).

Exclusion devices (selection grids) have also been used recently in attempts to mitigate megafauna bycatch in trawl nets. An exclusion device within the extension of a trawl net enables target species to pass through the grid or mesh barrier and on into the codend but prevents the passage of larger animals which are ejected out through an escape opening or swim back out of the mouth of the net.

Overall, modifications to gear and/or fishing practices have produced equivocal results for marine mammals (Northridge *et al*., 2005; Hamer and Goldsworthy, 2006; Tilzey *et al*., 2006). The same issue that makes quantifying mammal bycatch difficult hampers evaluation and refinement of any mitigation strategy, i.e. interactions are relatively rare and/or sporadic and it is difficult to actually observe interactions with fishing gear underwater. As a result, much of the previous research into marine mammal bycatch has been unable to produce definitive results as to the success of mitigation practices (Wilkinson *et al*., 2003; Hamer and Goldsworthy, 2006; Tilzey *et al*., 2006).

1.3 Marine mammal interactions in the Small Pelagic Fishery

The Small Pelagic Fishery (SPF) is at an early stage of development, with catches of the principal target species, redbait (*Emmelichthys nitidus*), jack mackerel (*Trachurus declivis*), and blue mackerel (*Scomber australasicus*), taken mainly from around Tasmania in Zone A. Between the mid-1980s and late 1990s the vast majority of the catch was taken by purse seine, with jack mackerel the dominant species. Mid-water trawling was trialled off the east coast of Tasmania during 2001 using the pair trawl method, the success of which lead to the introduction of a purpose built mid-water trawler into the fishery in late 2002. In contrast to purse seine catches, redbait rather than jack mackerel represents the primary target species for the mid-water trawl fishery.

Mid-water trawl fishing operations were initially subject to a high level of AFMA observer coverage which was complemented by onboard monitoring by Tasmanian Aquaculture and Fisheries Institute (TAFI) scientists as part of a biological assessment of the target species. From the commencement of operations, the mid-water trawl net included a ‘soft’ rope-mesh Seal Excluder Device (SED) (Browne *et al*., 2005). No marine mammal bycatch was reported until October 2004, at which time 14 dolphin mortalities occurred in two separate hauls east of Flinders Island. Modifications were made to the exclusion device, specifically by enlarging and moving the escape opening from the underside to the top of the net, in an attempt to make it easier for dolphins to exit the trawl. In addition, a code of conduct was adopted which included not setting the trawl if dolphins were visible around the vessel and moving at least ten kilometres from the area prior to setting the gear.

In response to the dolphin mortalities, AFMA implemented 100% observer coverage of fishing operations and established the Cetacean Mitigation Working Group (CMWG), comprised of representatives from industry (Seafish Tasmania), the Department of Environment and Water Resources (DEWR, formerly Department of Environment and Heritage), Department of Agriculture Fisheries and Forestry (DAFF), TAFI and conservation groups. The primary role of the CMWG was to identify strategies to mitigate cetacean bycatch for inclusion in the SPF Bycatch Action Plan and to provide advice on research needs to develop mitigation measures.

A month after the initial incidents in a location 150 nm further south, the vessel captured another three dolphins in a trawl shot. After withdrawing the vessel from the fishery for a short period and making further modifications to the exclusion device, fishing operations recommenced, again with continuous observer coverage. No further interactions occurred for 5 months until late April 2005 when a single dolphin was killed. A trawl-deck based closed circuit video system was then installed on the vessel by AFMA to continuously monitor for further dolphin interactions. In early May 2005, 7 dolphins were found dead in the trawl net. Three separate incidents involving the capture and mortalities of seals in the trawl net were also reported over the period of dolphin mortalities, seals being commonly sighted around the vessel whilst hauling the gear and during the pump-out of the catch.

An underwater camera system was deployed on the trawl net in the vicinity of the SED between June and September 2005 in an attempt to better understand the behaviour of marine mammals in relation to the fishing gear. As a pilot study, the project was also tasked at making recommendations regarding the application of underwater video technology as a means to assess the performance of alternative mitigation strategies and operational factors that might pose increased risk to marine mammals. A total of 19 trawl shots were monitored using the underwater camera system and indicated a high incidence of seal interactions whilst the net was fishing. Seals were observed entering and exiting through the SED escape opening to feed in the net (Browne *et al*., 2005). Through this study several aspects of the SED design were identified for improvement, the most notable was the material and orientation of the mesh barrier. While the rope mesh used in the exclusion device did not appear to cause harm to the seals it was not effective in guiding them out of the net. The mesh was not sufficiently rigid and under the weight of a seal, deformed considerably, sometimes leading to partial entanglements. Furthermore, the vertical orientation of the barrier provided no passive assistance in directing the seals out through the escape opening. As a consequence the cargo mesh barrier was replaced with an inclined steel grid. While no dolphin interactions were observed, three seals were captured in two shots, two of which died in the net. Unfortunately due to limitations in recording time, these incidents were not captured on video.

The present study implements many of the recommendations from the pilot study and has been developed as a collaboration between industry, government and researchers to improve the understanding of the nature of marine mammal interactions and evaluate strategies to reduce the level of fatal interactions based on direct underwater observations during normal commercial fishing operations.

2 Need

Dolphin and seal mortalities that occur as a result of fishing operations generate substantial public concern and outcry. In response to several incidents involving dolphin bycatch in the Small Pelagic Fishery, DEWR has advised that it will not support any expansion of mid-water trawling activities in the fishery (that is in other zones or with more vessels) until significant progress has been made in mitigating these interactions. This advice has been translated into a condition of a Wildlife Trade Order for the fishery under the EPBC Act that will permit export of products only if this condition is complied with. Effectively, the further development of the SPF with regard to the use of mid-water trawling is limited until progress is made in resolving the incidental dolphin bycatch problem.

This research project is aimed at quantifying and characterising the nature and extent of the marine mammal bycatch in the SPF, and advancing the development of mitigation strategies for mid-water trawlers to reduce mortalities of marine mammals in the trawl gear.

3 Objectives

The primary objectives of this study are to:

1. determine the type and frequency of interactions between dolphins and seals and mid-water trawl gear based on underwater video observations.
2. determine the incidence of dolphin and seal capture in mid-water trawl nets and, where feasible, investigate potential contributing factors.
3. trial and assess the performance of various exclusion devices as options to mitigate dolphin and seal mortalities
4. identify factors such as changes in net geometry during trawl fishing operations that present potential risks to dolphins and seals.

4 Methods

4.1 General

Mid-water trawl operations undertaken by the 50 m FV *Ellidi* operating in Zone A of the Small Pelagic Fishery was monitored between January 2006 and February 2007. As this study was undertaken on a commercial vessel operating under normal fishing conditions it was not possible to prescribe a formal experimental design to trial alternative SED configurations and/or vary trawl operational characteristics to test for factors that influence marine mammal interactions. Rather, responsibility for operational decisions remained with the vessel master and fishing company, taking advice from the researchers, with the objective of achieving a high level of operational coverage using the underwater video camera system and trialling different SED configurations.

Deployment of the underwater camera system was primarily the responsibility of the crew, although researchers were onboard for several trips and assisted in the process. The camera was intended to be used as often as possible, with actual usage levels determined by factors such as the turn-around time between shots (time to download video data and replace the battery); sea conditions (crew safety); and system availability. In relation to the latter, there were occasions where components needed repair or replacement and as such the camera system was not always functional.

The mid-water trawl net used between January and August 2006 had a wing spread of approximately 48 m and head line height whilst fishing of between 30 – 35 m. This was replaced in late September 2006 with a larger net, with wing spread of about 60 m and 40 - 47 m headline height. For both nets the distance between the headrope to the extension piece (where the SED was located) was around 150 m, with the codend a further 55 m in length.

4.2 Camera system

The camera system used in this project was developed following a pilot study that involved the use of a black and white camcorder housed in a waterproof housing and coupled to a halogen light (Browne *et al*. 2005). Development of the system for this project had several key requirements highlighted by the pilot study. These included extended recording times to cover the entirety of the fishing operation, which can take up to 14-15 hours, and low intensity lighting to minimise the potential for behavioural modification. Since responsibility for data collection rested largely with the master and crew of the fishing vessel, other system requirements included ease of deployment and operation and the facility for on board data archiving of video footage. Furthermore, the system had to be robust to withstand the rigours of being deployed and retrieved under normal commercial fishing conditions.

A black and white 0.05 LUX digital camera with a 90 degree diagonal wide angle lens was coupled to a commercially available hard drive unit (Archos AV 500 mobile digital video recorder). Lighting was provided by a single Luxeon 3 watt LED light (equivalent to 20W dichroic) which penetrated around 3-5 metres through the water

(Fig. 1A). A light diffuser was used to reduce the 'hotspot' lighting effect. Power was supplied by a 14.8V 10 ah lithium ion battery which provided a run time for the light, camera and recorder of in excess of 15 hours. The hard drive and battery were housed in a stainless steel housing to which the camera and light were coupled (Fig. 1B). The camera unit was protected by an external frame that was designed to fit directly into a metal frame sewn into the trawl net.

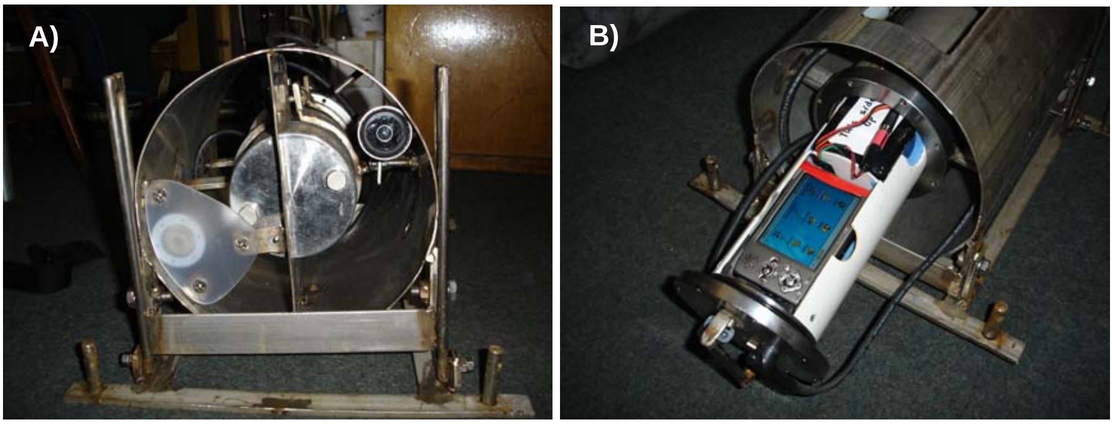

Fig. 1 Camera unit: A) Front view showing camera and light, covered by a diffuser; and B) hard drive unit and battery withdrawn from the stainless steel housing.

The trawl net was deployed predominantly at night in depths of between 100 and 150 metres and as such ambient light levels were extremely low. Initial trials with the camera provided quite dark and information poor footage. This was addressed by adjusting the factory settings on the Archos unit and reviewing the footage obtained. The optimum settings were: bitrate 2000kb/s; brightness 32; and contrast 28. The time signal associated with the footage was matched to the time the camera entered the water at the start of a net shot, and any details noted while reviewing the footage were assigned a 24 hour time and elapsed trawl time (i.e. time since the net entered the water).

Date, times (trawl start and finish, camera in the water), shot location (latitude and longitude) and bottom depth were recorded for all trawl shots when the camera was deployed. This was matched against compulsory logbook records to provide additional operational information, including catch, and to inform on the level of video coverage achieved.

At the completion of the trawl shot the camera unit was removed from the trawl net, data downloaded to a computer and data files archived to DVD.

4.3 Camera deployment and trawl operations

We had planned to use SCANMAR net monitoring equipment to examine the effect of changes in net geometry as a potential risk factor for marine mammals in the net. Unfortunately for logistic and availability reasons we were not able to undertake these trials. However, by dividing the trawl operation into operational phases, based on a combination of elapsed trawl time and observed changes in net geometry, water flow and fish behaviour we were able distinguish the following phases - setting, fishing, tow manoeuvres (turning), hauling, and pump-out/streaming.

In setting the trawl net, the cod-end was fed over the stern as the vessel moved forward at around 2-3 knots. When the SED reached the stern of the vessel the net was halted and camera unit inserted into a frame located on the top of the net and forward of the SED, with the camera directed backwards to face the SED (Fig. 2). As the SED and camera entered the water 'video start time' was noted on the camera log sheet. Trawl doors were attached to the trawl warps and the net deployed to fishing depth, with the net obviously spreading and filling out and causing the SED to straighten. It usually took 20-30 minutes for the net to reach fishing depth from the time the camera entered the water.

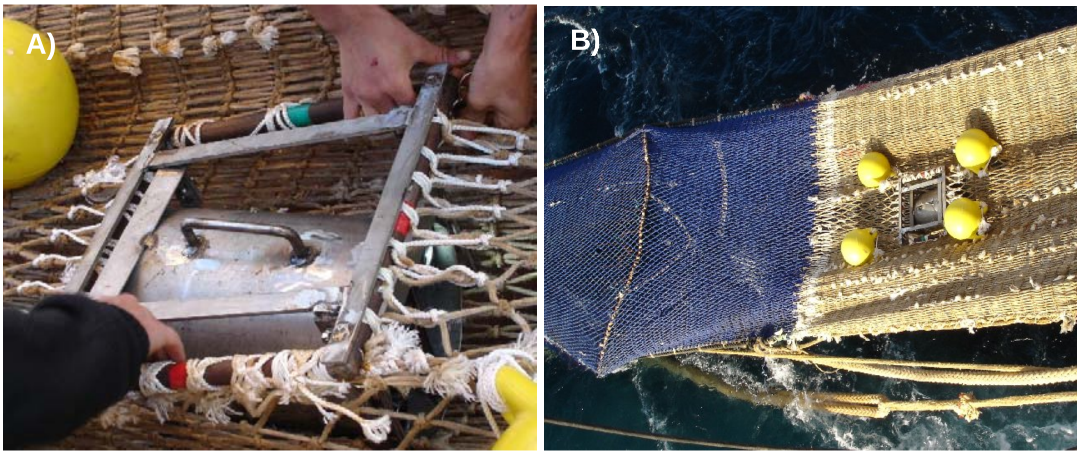

Fig. 2 A) Camera unit being fitted into the net frame; and B) camera unit in position in the net as it is being shot away.

Whilst fishing, the net appeared tight and stable on the video, with tow speeds ranging between 3-5 knots (mean 3.9 knots). Trawls often involved manoeuvres ranging from small changes in course to U-turns. Small changes in direction or long gradual turns were not usually detectible by video. However, sharp turns which involved winching the trawl boards to the surface and turning sharply to run back over fish marks were distinguishable, with an obvious reduction of trawl speed, and partial collapse of the net. Reduced flow rates often resulted in fish surging back up the net from the codend. In effect the net was partially hauled and then reset during a turn.

Similarly, hauling was associated with a marked drop in flow rate in the net, a softening and increased instability of the net structure and often a surge of fish up the net from the codend. After the net reached the surface, the codend was typically drawn along side the vessel and the catch pumped directly into the fish holds. This process involved attaching a fish pump to the end of the codend, and then allowing the codend to hang vertically while the catch was pumped on board. During this process the remainder of the net, including the extension containing the SED, was streamed behind the vessel as it moved ahead slowly. Depending on the size of the catch this phase took 0.5-2.5 hours to complete. The net was then retrieved onto the net drum and camera unit removed, data files downloaded and battery replaced. In situations were catches were very small the net was retrieved directly up the stern ramp and wound onto the net drum.

4.4 Analysis of video data

For analysis, video data were divided into 30 minute blocks commencing from the video start time, the start time for each block was then based on time signature generated by the Archos recorder. The following information was recorded for each video block: catch rate (categorical descriptor of the density of fish passing into the codend, defined as low, medium or high), catch composition (categorical descriptor of catch composition, defined as clean redbait, redbait and jack mackerel, barracouta, or other key species) and trawl operational phase if evident (setting, turning, hauling, pumpout/streaming). By default, if the net appeared tight and stable and there was no evidence of variability in water flow or other indicators of trawl phase (including elapsed time in relation to trawl duration) it was assumed to be fishing.

A variety of descriptive and behavioural information was recorded for each observed interaction event involving marine mammals or other megafauna. Information included interaction start time (based on video time signature), species, its relative size (small, medium or large), its condition (active/alert, weak/disorientated or unresponsive), mode of entry into the field of view (FOV) (from up the net or via the SED escape opening), where the individual made contact on the SED (top, mid or bottom third), its orientation on contact (horizontal, ‘tail stand’ or vertical), nature of contact (classified as ‘crash’, ‘bump’, ‘brush’), duration of the interaction event (time observed in FOV), and mode of exit from the FOV (up the net, out the escape opening or retained against the SED). Where individuals were observed to have exited via the escape opening, the mode of exit was categorised as active or passive, the former referring to individuals which swam actively out through the opening.

For each interaction event a judgement was made as to whether the sighting represented the repeat sighting of an individual or a new individual entering the FOV. Factors such as the time interval between sightings, size and condition of the animal and outcome of the most recent sighting were taken into account. Where an individual was sighted within about 5-7 minutes of a previous sighting and was of similar size it was flagged as the same animal returning. Exceptions occurred where the individual in previous sightings was observed to have exited through the escape opening, individuals were physically identifiable as different (size, markings, colour, etc), and/or if the behaviour of the latter individual suggested otherwise. For instance, seals that were strong and alert even after an apparent 5-7 minute gap between sightings (or combined interaction time that exceeded about 8 minutes) were assumed to have been different individuals. In this way it was possible to infer the mode of entry into the net, duration within the net and final outcome of the interaction for individual animals. Individuals last sighted swimming out of the FOV and up the net were assumed to have exited the net via the net mouth. In practice, factors such as sub-optimal camera orientation, obscuring effects when large quantities of target species passed down the net, and occasional problems with lighting quality meant it was not always possible to clearly observe the outcome of each interaction event and in such instances interaction outcomes were noted as being uncertain.

In instances where more than one seal was present in the net simultaneously it was not always possible to distinguish individual behaviour. It was, however, usually possible to identify outcomes on the basis of condition and mode of exit seals from the net.

4.5 SED configuration

Three SED configurations were trialled during the study period, (i) bottom opening, small escape hole, (ii) bottom opening, large escape hole, and (iii) top opening. The bottom opening SED was comprised of two panels, producing a 2.3 x 2.3 m steel grid, with 10 vertical steel bars spaced at 21 cm (Fig. 3A). The SED was angled forwards at about 15-25°, with the escape opening located at the base of the SED. The 'small escape hole' configuration, with an approximate 1 x 1 m escape opening, was trialled initially (Fig 4A). The hole was subsequently enlarged to 1.9 m wide, producing the 'large escape hole' configuration (Fig 4B). Escape holes were either left open, or had a flap of netting or short lengths of rope attached to the leading edge in an attempt to discourage the loss of target species while not hindering the exit of large bycatch species[1]. The top opening SED was constructed of four panels, to produce a grid that was 5 m high by 2.1 m wide with steel bars spaced at 23 cm, which was angled backwards at 45° (Fig. 3B). A 1.8 m wide by 0.55 m deep escape opening was positioned on top of the net, immediately in front of the SED. A cover flap of trawl netting was attached to the leading edge of the escape opening.

The bottom opening, small escape hole configuration was used continuously until early June 2006 when the escape opening was enlarged (large escape hole configuration) following several seal mortalities. The large escape hole configuration was used to the end of January 2007. The top opening configuration was then trialled for about a month but owing to operational problems, specifically difficulties in retrieving the SED onto the net drum, it was deemed operationally unsuitable for the vessel and replaced with the bottom opening configuration at the end of the study period[2].

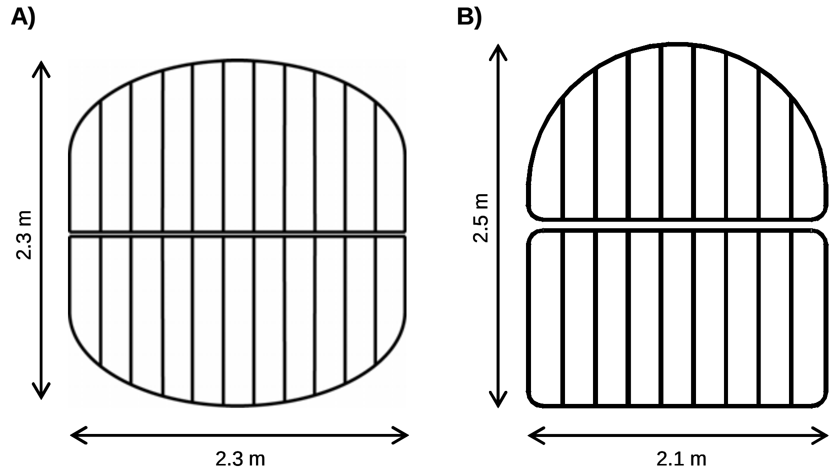

Fig. 3 SED designs used in this study. A) Two panel SED, and B) four panel SED (only two panels are shown).

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[1] These modifications were made at the discretion of the master and crew and were not examined as potential factors in influencing interactions.

[2] Retrieving the backwards orientated top opening SED exerted extreme forwards pressure onto the top of the net and SED, resulting in damage to the SED and on one occasion injury to a crew member.

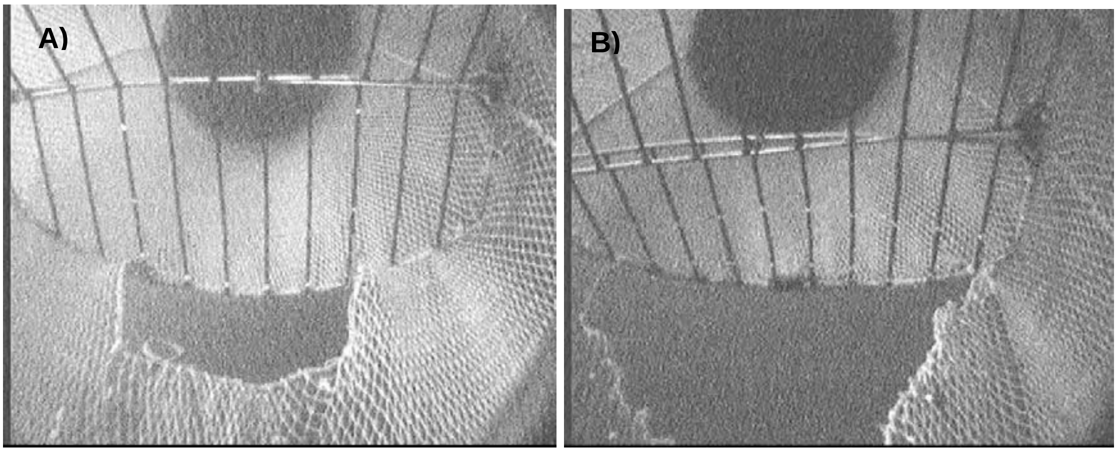

Fig. 4 Underwater views of the bottom opening SED showing, A) the small escape hole; and B) the large escape hole configurations.

4.6 Data analysis

Since the bulk of the interaction data was in the form of frequencies, contingency table analysis was the primary statistical test used to examine hypotheses. Estimates of bycatch were determined by bootstrapping sample data 10,000 times, with 95% confidence intervals (95% CI) determined using the percentile method. Other statistical tests are described in the text as appropriate.

5 Results

5.1 Video coverage

During the study period mid-water trawl operations targeted shelf waters off the east and south-west coasts of Tasmania, with most of the effort concentrated in two areas off the east coast and one in the south-west (Fig. 5). Trawls were typically fished close to the substrate in bottom depths averaging 112 m (range 90 – 240 m) off the east coast and 131 m (range 65 – 180 m) off the south-west coast[3]. Trawl durations averaged 6.25 h shot $^{-1}$ (range 0.4 – 13.25 h)[4]. In terms of catch, redbait accounted for almost 90% and jack mackerel a further 8% of the total landed weight. The relative contribution of these two species was similar in catches taken from each of the main fishing regions.

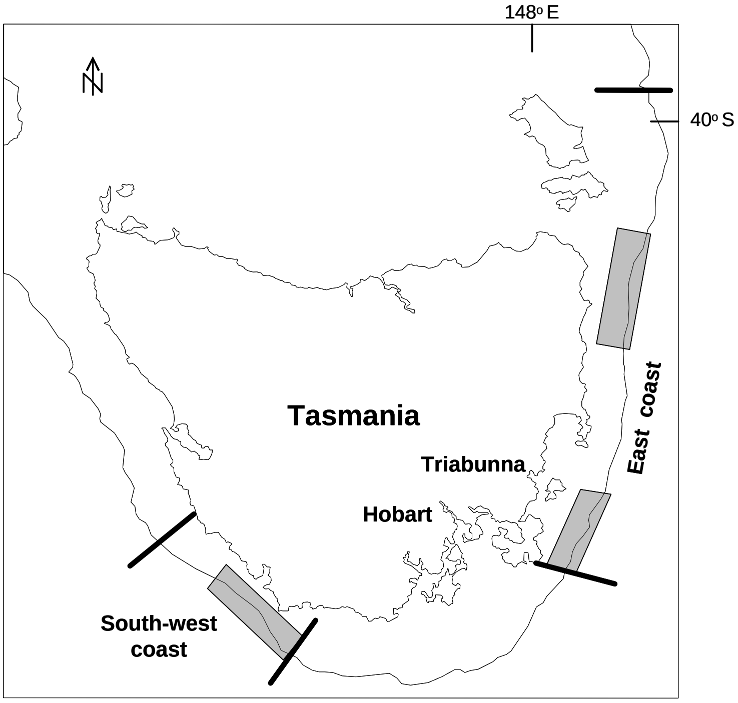

Fig. 5 Map showing the East and South-west coast fishing areas off Tasmania, the main fishing grounds are indicated by the shaded boxes and the bold lines indicate the boundaries of where trawling occurred. The 200 m depth contour is shown.

The underwater camera system was deployed on 138 occasions (60% of trawl shots) and successfully produced useable images for 98 trawls (71% of deployments), representing 735 hours of video footage (Table 1). Factors such as operator error, component malfunction, and fouling of the camera in net, influenced whether data was recorded and/or its quality. There was, however, no obvious difference in the proportion of successful deployments between fishing regions.

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[3] In practice, the footrope often made contact with the substrate during trawl operations.

[4] Trawl duration is defined as the time from setting the gear to the start of hauling, it does not include pump-out.

Interactions with megafauna were observed in 60 (61%) of monitored trawls, with fur seals (*Arctocephalus* spp) observed in 55 shots (56%) (Table 1). While species could not be distinguished readily, the distribution and observed behaviour suggests that most were likely to be Australian fur seals (*A. pusillus doriferus*) rather than the closely related New Zealand fur seal (*A. forsteri*) (M. Hindell, pers. comm.). Although the seal interaction rate was higher for the south-west coast (67%) compared with the east coast (48%), this regional difference was not significant ($\chi^2 = 3.55$; d.f. = 1; $P = 0.06$).

Other megafauna bycatch observed on video included sunfish (*Mola mola*), thresher shark (*Alopias vulpinus*), broadbill swordfish (*Xiphias gladius*) and unidentified rays. No dolphins were observed in the video footage and there were no reports of dolphin captures during the study period.

In practice, video coverage of entire fishing operations was not achieved in 34 of the 98 monitored trawl shots; data was either lost due to corrupted files, files failed to download from the Arcos unit, or human error resulted in the accidental deletion of files. Battery or equipment failure part way through trawl operations also resulted in some incomplete video records. Despite these problems, seal interaction rates did not differ significantly between partial and complete video records ($\chi^2 = 0.23$; d.f. = 1; $P = 0.63$), neither did the number of seals sighted per shot (Students *t*-test = 0.98, $P = 0.50$).

Table 1: Trawl video coverage and interaction rates for midwater trawl operations off Tasmania.
* refers to trawls undertaken while the camera system was on board the vessel

	Region		
	East coast	**South-west coast**	**Total**
Total no. of trawl shots*	122	105	227
Trawl shots where camera was deployed	82	56	138
(% shots)	(67.2)	(53.3)	(60.8)
Trawl shots with usable footage	58	40	98
(% camera deployments)	(70.7)	(71.4)	(71.0)
Usable video footage reviewed (hours)	430	305	735
Trawl shots with megafauna interactions	32	28	60
(% of usable video shots)	(55.2)	(70.0)	(61.2)
Trawl shots with seal interactions	28	27	55
(% of usable video shots)	(48.3)	(67.5)	(56.1)

5.2 Seal interactions

5.2.1 General

Overall, it was estimated that 170 individual seals were observed by underwater video (based on 457 interaction events), 151 of which were observed wholly within the trawl net, the remainder were observed to partially enter the net via the escape opening, usually to feed on fish in the net (Table 2). It is, however, likely that these represent minimum estimates, since it is possible that some of the assumed repeat sightings may have been different individuals with similar physical characteristics.

Of the shots with seal interactions, 53 involved seals observed fully within the net and, unless otherwise noted, subsequent analyses relate only to seals that had fully entered the net. Interaction rates ranged between 30 – 60% depending on SED configuration (Table 2), these differences were not, however, significant ($\chi^2 = 0.29$; d.f. = 2; $P = 0.23$).

Table 2: Interaction rates and numbers of seals by SED configuration for midwater trawl operations off Tasmania.

	SED configuration			
	Bottom opening, small escape hole	**Bottom opening, large escape hole**	**Top opening**	**Total**
Trawl shots with usable footage	40	48	10	98
Trawl shots with seal interactions	25	27	3	55
(% of shots)	(62.5)	(56.2)	(30.0)	(56.1)
Seals observed (no.)	69	98	3	170
Trawl shots with seals wholly inside the net	24	26	3	53
(% of shots)	(60.0)	(54.2)	(30.0)	(54.1)
Seals observed wholly within net (no.)	65	83	3	151

The mean number of seals observed in the net was 2.8 shot^{-1} (range of 1 – 9), with 58% of shots involving two or fewer seal interactions (Fig. 6). Observed seal numbers in the net were not correlated with video (shot) duration (no. shots = 53, $r^2 = 0.079$) (Fig. 7).

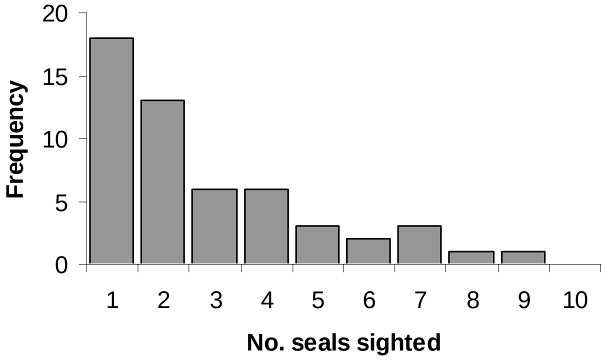

Fig 6. Frequency distribution of seal numbers observed per trawl shot.

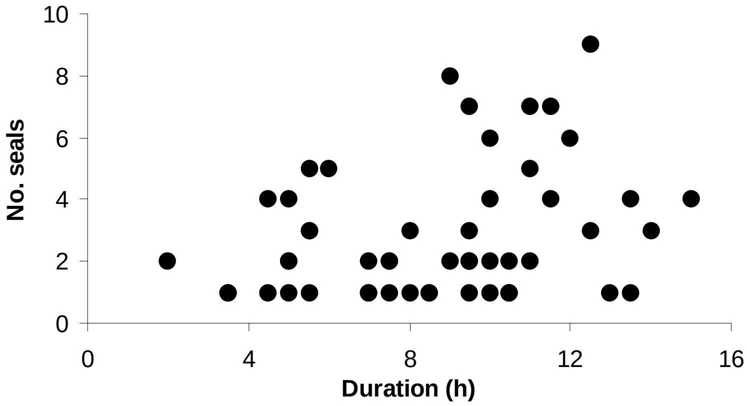

Fig. 7. Plot of number of seals observed in the net and video duration for trawl shots involving interactions.

5.2.2 Seasonality and habituation

There was marked seasonality in the rate of interactions, which exceeded 70% for trawls conducted between March and August, falling to around 25% in September/October and January/February 2007 (Fig. 8). No interactions were recorded in January/February 2006, though relatively few trawls were monitored during this period.

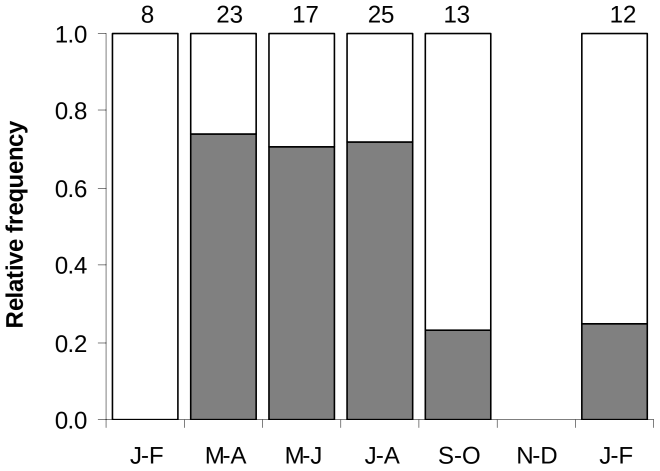

Fig. 8 Relative frequency of seal interactions with midwater trawls by bi-monthly period between January 2006 and February 2007. Values refer to the number of monitored shots.

In order to examine the potential impact of learning and habituation on the frequency of interactions, data were tracked over about three months of sustained fishing activity in a limited area off the south-west coast (Fig. 5). The period in question commenced on 26 January and ceased on the 29 April 2006, after which the vessel switched operations to the east coast. Prior to this time the vessel had only spent five fishing days (between 30 December 2005 and 9 January 2006) in the area since ceasing fishing operations for vessel maintenance in mid-October 2005. The vessel fished on a total of 41 days during the period, undertaking 63 shots, 25 of which were monitored using the underwater camera system. The overall interaction rate was 60%, however, no interactions were observed for the first 7 monitored shots (between 4 February and 10 March), despite seals being commonly present around the vessel during fishing operations (Fig. 9). Between 11 March and 29 April, 83% (15) of the 18 monitored shots included interactions, implying that seals may have learnt how to enter the trawl net whilst it was fishing and as a consequence the frequency with which interactions occurred was very high. This observation gives rise to the possibility that the observed seasonality in interactions may be confounded to some extent by habituation.

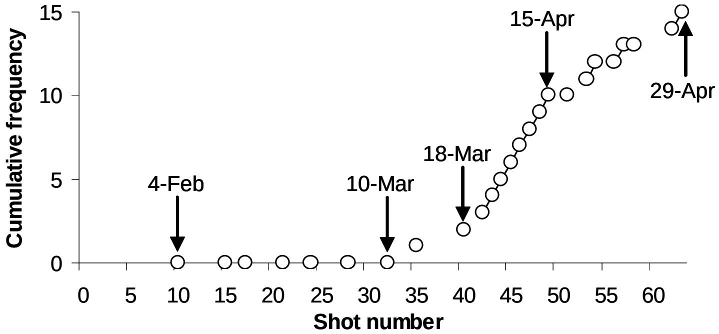

Fig. 9 Cumulative frequency of seal interactions (0 for no interaction; 1 for interaction) by trawl shot for the period 26 Jan – 29 Apr 2006 off south-west Tasmania. Circles are indicated for 25 video monitored shots, with the cumulated frequency updated for these shots only. Some reference dates are indicated on the figure.

5.2.3 Nature of interactions

Interaction events involved a range of behaviours and outcomes, with individual seals often observed several times moving into and out of the FOV within an event. Similarly some seals were represented in a number of interaction events, with an average of 2.6 interaction events per seal (SE 0.15, range 1-10).

Seals were often observed to enter the FOV from behind the camera (i.e. from further up the net), actively swimming or apparently gliding with the current created by the forward motion of the trawl net (Fig. 10A). Seals either made contact with the SED, often more than once in an interaction event, and/or moved freely about, sometimes feeding on fish before swimming back up the net and out of view (e.g. Fig. 10B). SED contacts were classified as ‘brush’, where the seal appeared to make light contact whilst turning and moving away (occasionally swimming out of the escape opening), ‘bump’ where the seal made relatively light contact with the SED, and ‘crash’ where the seal made heavy, full-body contact with the SED. Based on 348 interaction events for which contact details were recorded, the majority (70%) were classified as crash, followed by bump (27%), with brush contacts relatively rare (3%). Most contacts occurred in the mid-third region of the SED (54%), with upper third next in importance (33%) and lowest occurrence being contacts with the lower third of the SED (13%). In about one in four contacts (24%) seals were observed tail-standing on the SED, that is with the body more or less perpendicular to the SED and facing into the current. In the remaining contacts, seals either lay against the SED in predominantly horizontal (38%) or vertical (38%) orientation. Having made contact with the SED some individuals made immediate attempts to swim away whereas others appeared to rest for a period before making any further responses. Some SED contacts resulted in the seals rolling passively towards the SED escape opening and being expelled from the net or actively swimming through the opening.

Seals were also observed to swim into the net through the escape opening and then exhibit the range of behaviours reported above. As noted previously, some interactions involved partial entry of the upper body area into the net via the escape opening, usually to take fish passing down the net or possibly to investigate whether fish were present.

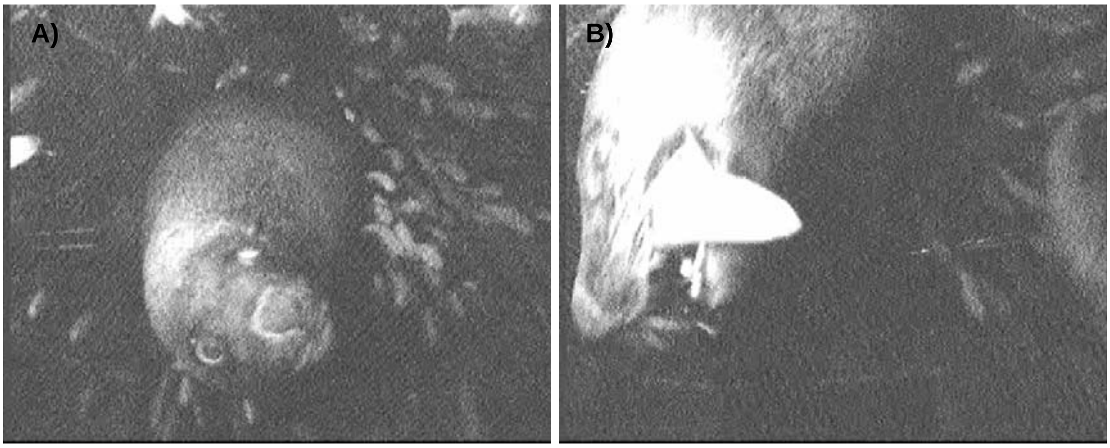

Fig. 10 Images of seals inside the net: A) swimming forward and away from the SED; and B) eating a fish.

5.2.4 Operational factors and interactions

Trawl phase

As noted in Section 4.3, trawl operations can be divided into a number of phases, namely setting, fishing, tow manoeuvres (turning), hauling, and pump-out/streaming. Generally, the trawl phases could be distinguished based on a combination of elapsed trawl time and changes in net geometry, water flow and fish behaviour. Each 30 minute video block was characterised using these criteria and assigned a trawl phase (noting that minor changes of tow direction or long sweeping turns were not distinguishable from ‘fishing’). In practice, some video blocks encompassed more than one trawl phase and in such cases if more than about 20% of the block time involved either setting, turning or hauling, the whole block was assigned to one of these phases, as appropriate. This approach recognised that these phases may pose greater risk to marine mammals as they involved changes in overall net geometry.

Seals were observed to enter the net during each of the operational phases. By relating the presence and number of seals (based on the time of initial sighting) with the trawl phase it was evident that the majority of interactions occurred whilst the net was fishing (Table 3). Interaction rates and mean seal numbers by video block were, however, about three times higher during setting compared with other operational phases. Overall there was a significant trawl phase effect on interaction rates (χ^2 = 15.25; d.f. = 4, *P* = 0.004) but if the setting phase was excluded from the analysis this effect was no longer significant (χ^2 = 0.86; d.f. = 3, *P* = 0.836).

Table 3 Video blocks and seal interactions (presence and numbers) based on trawl phase for mid-water trawls (n = 53) in which seal interactions were observed.

	No. video blocks			Estimated no. of seals	
Trawl phase	**Total**	**Incl. seal interaction**	**Interaction rate**	**Total**	**Mean per video block**
Setting	51	15	0.29	24	0.47
Fishing	666	74	0.11	94	0.14
Turning	86	12	0.14	17	0.20
Hauling	57	7	0.12	7	0.12
Pump-out	53	5	0.09	9	0.17
Total	913	113	0.13	151	0.17

Interaction rates were also compared based on observed video block catch rates (categorised as low, medium or high). This comparison revealed no significant relationship between catch rate and the probability of seal interactions (χ^2 = 3.22; d.f. = 2, *P* = 0.20).

Timing of interactions

Since interactions were time-referenced it was possible to investigate when seals entered the net based on elapsed trawl time and time of day. In relation to the former, interactions in absolute (numbers of seals) and relative (seals per video-hour) terms were highest within the first hour of the trawl operation, coinciding with setting of the net (Fig. 11). The interaction rate fell sharply in the third hour but then generally increased with time, implying that interactions became more frequent in the latter stages of the fishing operation, noting that most trawl shots were less than 10 hours in duration.

Most interactions occurred between 18:00 and 07:00, a pattern that was heavily influenced by the concentration of fishing effort during the night (Fig. 12A). Trawl operations typically commenced in the late afternoon or early evening period when fish schools started to form up in the water column, with trawl duration influenced by catch rates determined by net sensors. In some cases multiple night shots were attempted, the final shot usually being hauled shortly after day break. Very few day-time shots were attempted, mainly because fish tended to be dispersed during daylight hours. There was no evidence for a diurnal trend in the rate of interactions when standardised for effort (seals per video-hour) (Fig. 12B), noting that the absence of interactions during the afternoon (13:00 – 17:00) was influenced by limited trawl effort and is thus unlikely to be indicative of a period of nil or very low seal activity.

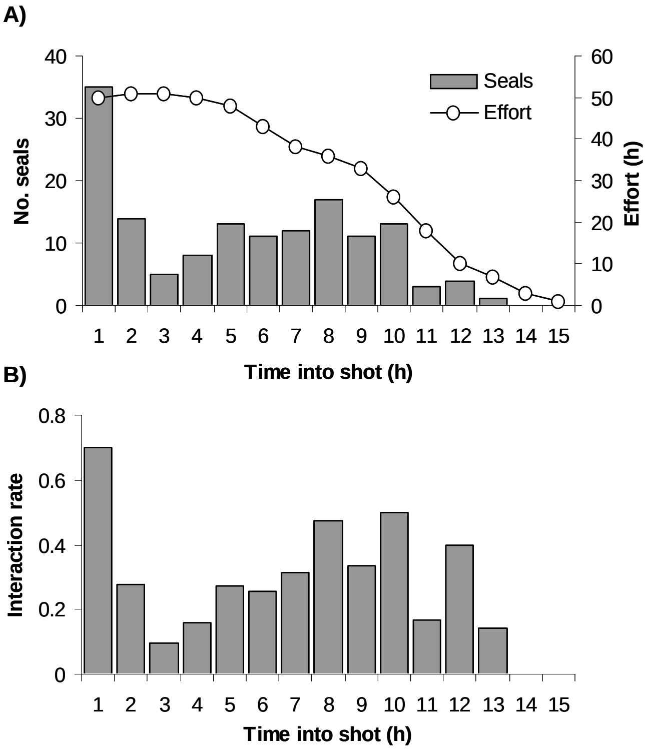

Fig. 11 Seal interactions based on time elapsed since the net entered the water ('video start time'), based on one-hour categories (effectively two video blocks). A) Number of seals and effort, based on video-hours for trawls in which interactions were observed, by elapsed trawl time; and B) interaction rate (seals per trawl-video hour) by elapsed trawl time.

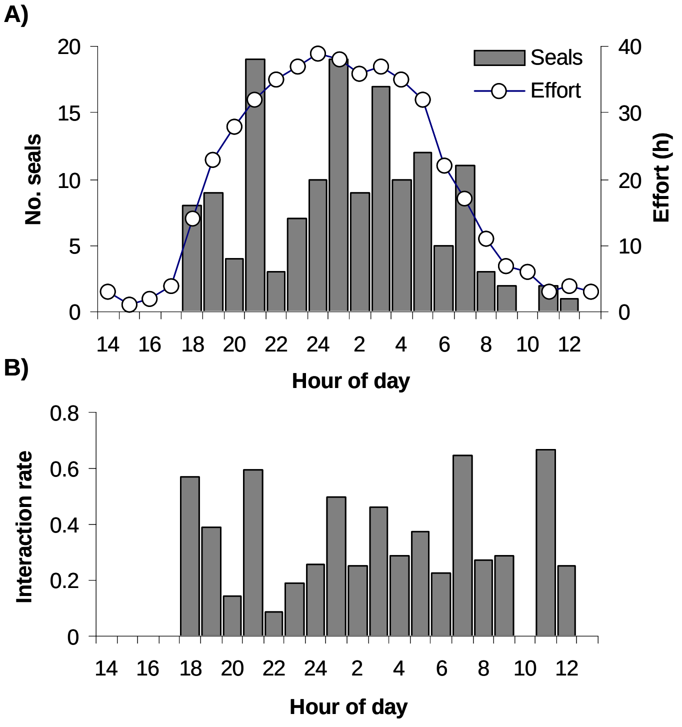

Fig. 12 Seal interactions by time of day (Eastern Standard Time). A) Number of seals and effort, based on video-hours for trawls in which interactions were observed, by time of day; and B) interaction rate (seals per trawl-video hour) by time of day.

5.2.5 Impact of SED configuration

Entrance to net

Based on the initial sighting of an individual, the mode of entrance to the net was inferred as being either via the net mouth (i.e. the seal first appeared from behind the camera FOV), or was observed entering through the SED escape opening. Approximately 87% of seals that entered the net did so via the net mouth, just 13% entered the net through the escape opening (Table 4). Comparison between the bottom opening configurations indicated that there was a significantly higher likelihood of SED entry with the small as opposed to the large opening ($\chi^2 = 5.31$; d.f. = 1, $P = 0.02$). If, however, seals that partially entered the net by the escape opening are included as a form of SED entry, then there was no difference between the two bottom opening configurations ($\chi^2 = 0.69$; d.f. = 1, $P = 0.40$).

Table 4 Mode of entrance into the net inferred from the initial interaction event for individual seals and based on SED configuration

	SED configuration			
Initial interaction	**Bottom opening, small escape hole**	**Bottom opening, large escape hole**	**Top opening**	**Total**
Net mouth	52	77	3	132
SED opening	13	6	0	19
Total	**65**	**83**	**3**	**151**
Partial SED opening	4	15	0	19

Interaction outcomes

The outcome of interactions based on the last sighting of an individual were classified as ‘swam out the net mouth’ (inferred on the basis that in the final sighting the seal swam back up the net and out of the FOV), ‘actively swam out of the escape opening’ (e.g. Fig. 13), ‘passively exited via the escape opening’, and outcome ‘uncertain’. This latter situation typically arose when the FOV was obscured by dense groups of fish for a period of time and it was not possible to be confident when and how the animal had exited the net. Overall, just 22% of the seals were judged to have exited by the mouth of the net whereas about 64% exited via the escape opening, the majority doing so passively (Table 5). Interaction outcomes for the remaining 14% were uncertain. Although proportionally more seals were observed exiting via the escape opening for the large escape hole (67%) compared with the small hole (57%), these differences were not significant ($\chi^2 = 1.74$; d.f. = 1, $P = 0.19$).

Table 5 Interaction outcome inferred from the final interaction event for individual seals

	SED configuration			
Interaction outcome	**Bottom opening, small escape hole**	**Bottom opening, large escape hole**	**Top opening**	**Total**
Swam out net mouth	17	17	0	34
Actively swam out escape opening	13	12	0	25
Passive exit via escape opening	24	44	3	71
Uncertain	11	10	0	21
Total	65	83	3	151

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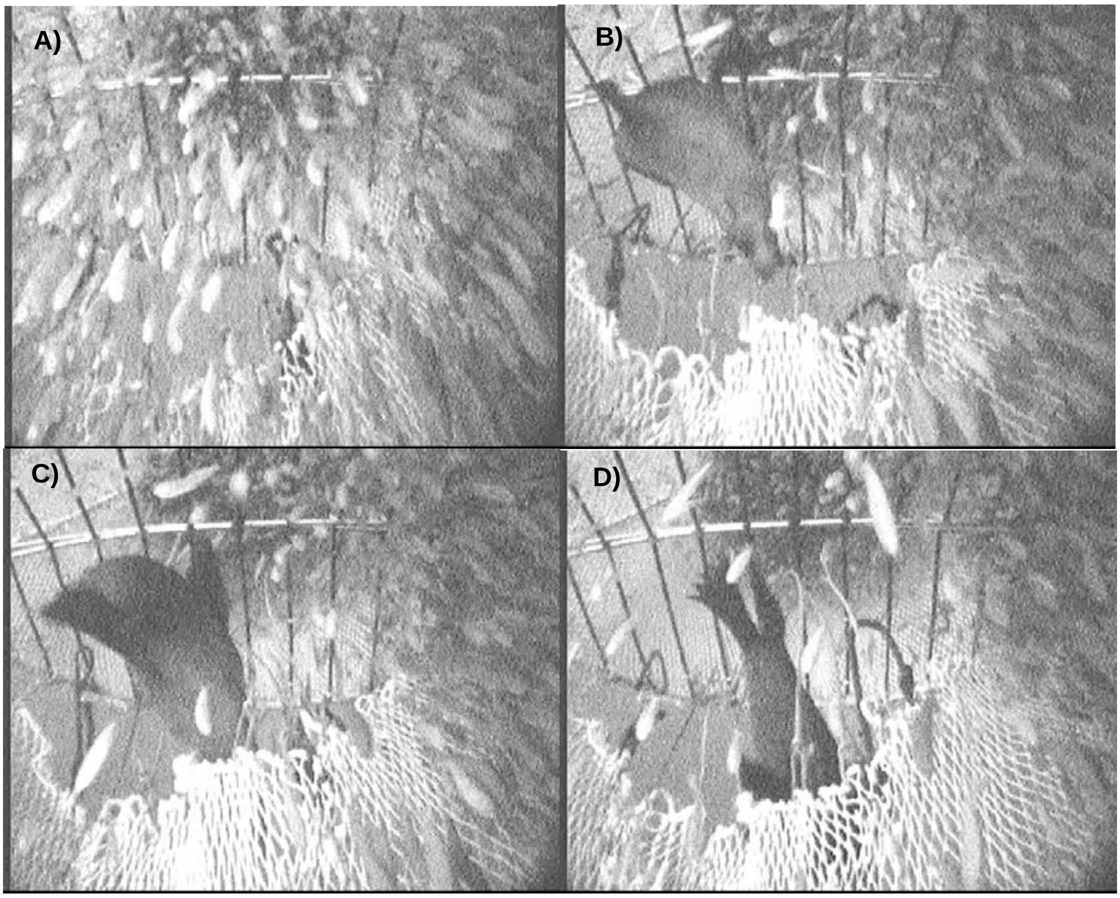

Fig. 13 Sequence of images showing: A) fishing, B) seal arriving and making contact with the SED, C) turning and D) actively exiting via the SED escape opening.

Interaction duration

The elapsed time between initial and final sightings, defined as interaction duration, was estimated for 146 individual seals and varied from less than a few seconds to several hours. Just over one third of all interactions lasted less than one minute, about half were under 3 minutes and 70% were less than 6 minutes in duration (Fig. 14). Interactions that lasted longer than 20 minutes involved situations in which seals were pinned against the SED for lengthy periods and clearly unresponsive.

By relating interaction duration to outcomes (with mortality a defined outcome), different patterns emerge. The maximum interaction time for seals that were judged to have exited via the net mouth was less than 6 min, almost half of these interactions being less than 2 min in duration (Fig. 15A). Seals which exited via the escape opening whilst still exhibiting some level of responsiveness (i.e. not considered mortalities), did so up to about 14 min after their first sighting, though active exit ceased after about 9 min (Fig. 15B). The distribution of interaction times for the uncertain outcome group was similar to that for SED exit, although proportionally fewer of these interactions were under 2 min (38% compared with 53% for escape opening exit) (Fig. 15C). By contrast, interaction times for seals judged as unresponsive and assumed to be mortalities, exceeded 20 min in the vast majority of instances, many pinned motionless against the SED for several hours (Fig. 15D). Overt responsiveness in individuals that were subsequently judged to have died ceased after an average of 8.3 min (SE 0.8, n = 12; range 4.5 -12.7 min), suggesting that this may represent a critical time limit if the seal is to exit the net and have a chance if surviving.

Giving consideration to interaction duration and outcome, we propose three categories of risk, namely low, medium and high risk. Low risk interactions, as exemplified by those in which seals swam out via the mouth of the net, were less than 6 min in duration, medium risk interactions were between 6 – 10 min and high risk interactions greater than 10 min (Fig. 15). Overall, low risk interactions accounted for 80.8%, medium risk 11.6% and high risk 17.8% of all interactions, with all assumed mortalities falling into the high risk category. It is of course implicit that interaction times do not equate to effective dive duration, which also includes descent time (in some instances to fishing depths of around 60 – 120 m), time to locate the SED (some 150 m into the net if entry was via the net mouth), and ascent time back to the surface.

Significantly, no seals (alive or dead) were brought on deck whilst the camera was in use[5]. Observed seal mortalities all occurred in trawls using bottom opening SED configurations, and in each case the seals eventually fell out through the escape opening before the net was hauled onboard. In many instances this occurred as the SED broke the surface and wave action dislodged the individual from the SED (Fig. 16).

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[5] In one trawl in which there was a malfunction of the camera, 3 deceased seals were brought aboard the vessel. In this instance the top opening SED was used, however, the mesh flap covering the escape opening had become tangled with some broken bars in the SED, effectively blocking the escape hole.

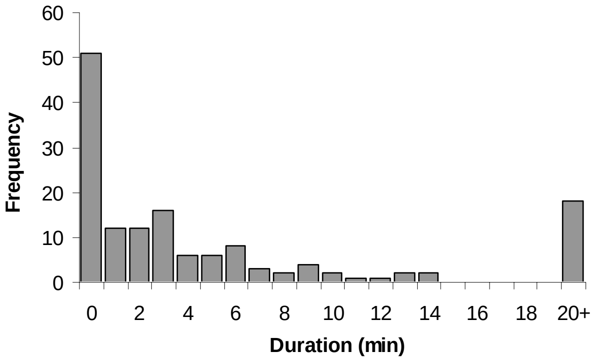

Fig. 14 Interaction duration for seals observed in the vicinity of the SED.

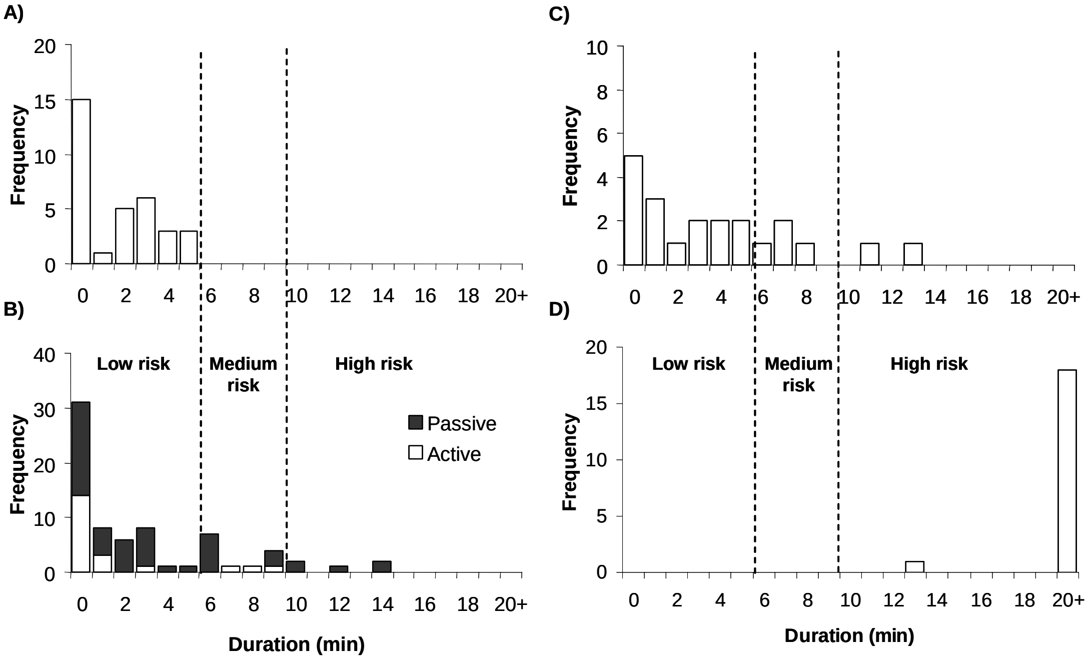

Fig. 15 Interaction duration for seals observed in the vicinity of the SED based on interaction outcome: A) escape via the net mouth; B) escape via the SED escape opening (indicating whether escape was active or passive); C) outcome uncertain; and D) mortality.

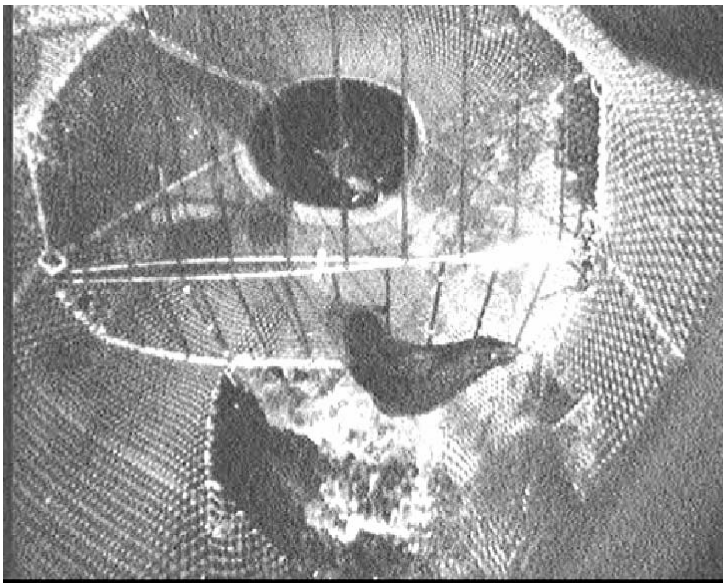

Fig. 16 Dead seal wedged through the SED bars as the net clears the water. Shortly afterwards the seal fell out through the escape opening.

Mortalities and high risk interactions

During the course of the study 19 seal mortalities were recorded by underwater video, representing a mortality rate of 12.6% based on the estimated number of seals observed the net (Table 6). In addition to mortalities, a further 5 seals were judged to have been in very poor condition (exhibiting very little responsiveness) prior to being ejected from the net, 4 of which had been in the net for more than 10 min. It is probable that the actual interaction time for the remaining individual (about 6 min) was underestimated. Interaction times for a further 3 seals fell within the high risk range, implying that there were at least an additional 8 seals for which the outcome in terms of survival was uncertain (Table 6).

Mortalities occurred during each of the trawl phases, with rates varying between 8.3 – 28.6% depending on operational phase (Table 6). Although mortality rates were about double the average level during turning and hauling phases, the trawl phase effect was not significant ($\chi^2 = 4.21$; d.f. = 4, $P = 0.38$). Similarly, the combined mortality - high risk rate did not differ significantly with operational phase ($\chi^2 = 1.27$; d.f. = 4, $P = 0.87$).

Table 6 Seal interactions by trawl phase with mortality and high risk interaction rates (proportion of seals observed in the net).

Trawl phase	No. seals	No. mortalities	Mortality rate	No. of high risk	Mortality plus high risk rate
Setting	24	2	0.083	2	0.167
Fishing	94	10	0.106	6	0.170
Turning	17	4	0.235	0	0.235
Hauling	7	2	0.286	0	0.286
Pump-out	9	1	0.111	0	0.111
Total	151	19	0.126	8	0.179

Mortality rates were, however, significantly higher for the small escape hole (20%) compared with the large escape hole (7%) configuration ($\chi^2 = 5.31$; d.f. = 1, $P = 0.02$) (Table 7). That is to say, the odds of mortality occurring were significantly higher, by a factor of 3.21 times (95% confidence interval 1.15 – 8.98), when the small escape hole was used as compared with the large opening. The combined mortality plus high risk rate was also significantly greater when the small escape hole was used ($\chi^2 = 4.86$; d.f. = 1, $P = 0.03$) (Table 7).

There was insufficient information available to evaluate the performance of the top opening SED in terms of reducing bycatch mortality.

Table 7 Seal interactions by SED configuration with mortality and high risk interaction rates.

	SED configuration			
	Bottom opening, small escape hole	Bottom opening, large escape hole	Top opening	Total
No. of shots	40	48	10	98
No. of seals	65	83	3	151
No. of mortalities	13	6	0	19
Mortality rate	0.200	0.072	-	0.126
Mortalities per shot	0.325	0.125	-	0.194
No. high risk	4	4	0	8
High risk rate	0.061	0.048	-	0.053
High risk per shot	0.100	0.083	-	0.082

5.3 Other megafauna interactions

Sunfish were observed in 5 trawl shots (e.g. Fig 17A); one occurrence involved 2 sunfish that entered the net more or less simultaneously while the remainder were represented by solitary individuals. Four of the shots were off the east coast (total of 5 sunfish) with the remaining shot off the south-west coast. All captures occurred while the net was fishing at depth at night or early in the morning (between 20:30 – 06:15). In each case the sunfish was retained against the SED until the net was hauled and the SED cleared the surface, at which time they fell out the escape hole. The fate of the sunfish was difficult to determine, though in at least one instance it was suspected that the individual had survived, despite being trapped against the SED for at least 2 hours.

A total of 9 thresher shark were captured in 7 trawl shots (e.g. Fig. 17B), two incidents involved 2 sharks, although these encounters occurred at different times within the shot. All interactions occurred off the east coast at night or early in the morning (18:10 – 07:30). Most of the sharks (6) were ejected out of the escape opening within a relatively short period of making contact with the SED. In one instance a relatively small individual passed through the SED bars and into the codend, while the two remaining sharks were retained in the net until the SED broke the surface, at which time they fell out through the escape opening.

A broadbill swordfish was captured in one shot in which the top opening SED was used (Fig. 18). In this instance the individual was retained in the net and landed on deck, its dorsal spines tangled in the meshes of the net. There were 2 instances where a ray was observed pinned against the SED, in both cases they fell out through the escape opening as the net reached the surface.

A small mako shark (*Isurus oxyrinchus*) was also taken as bycatch and landed on the vessel. In that instance the shark had become tangled in meshes further up the net from the SED and was not recorded on video.

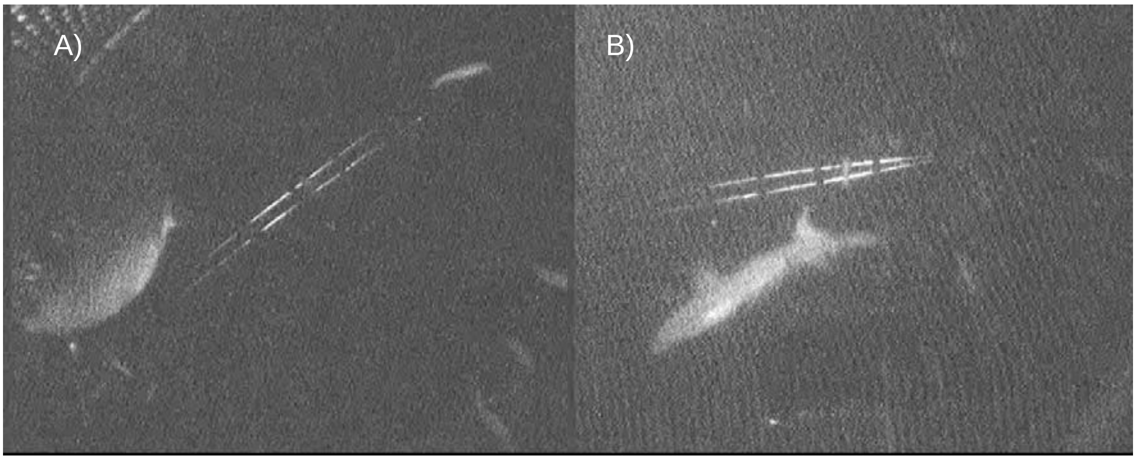

Fig 17. A) Sunfish and B) small thresher shark pinned against the SED.

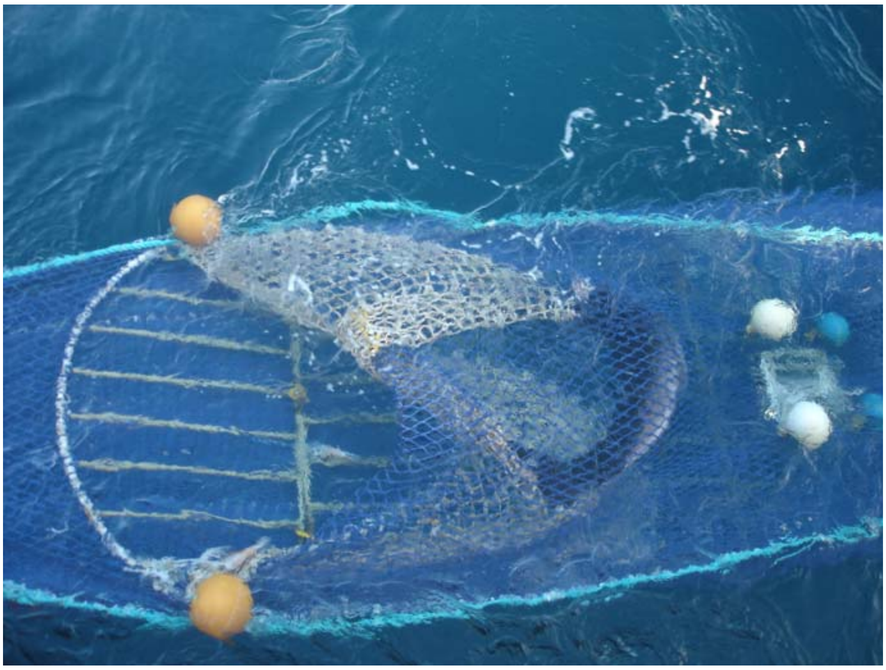

Fig 18. Broadbill swordfish lying on the top opening SED (escape opening, mesh cover and camera unit can be seen in the photograph).

6 Discussion

Exclusion devices appear to represent the only practical trawl bycatch mitigation technology for marine mammals but, in the absence of direct observations, it has been difficult to definitively evaluate their effectiveness in mitigating lethal interactions. For instance, a reduction in bycatch rates when exclusion devices are used may not necessarily imply that their introduction was responsible. Rather, information on rates of net entry and exit along with condition of the marine mammals is required if the actual impacts of any mitigation strategy is to be quantified. For example, bycatch reductions could result from the previous removal of habituated individuals or even temporal and/or spatial variability in the distribution and abundance of the marine mammals (e.g. Tilzey *et al*., 2006).

In the present study, underwater video technology was successfully utilised to evaluate the effectiveness of different SED configurations in reducing incidental mortalities in trawls. Whereas most previous studies have sought to quantify levels of bycatch (Northridge, 1991; Couperus, 1997; Wickens and Sims, 1994; Morizur *et al*., 1999; Read *et al*., 2006; Zeeberg *et al.*, 2006), few have focussed on understanding factors that contribute to interactions (Smith and Baird, 2005; Tilzey *et al.*, 2006; Hamer and Goldsworthy, 2006) and/or the effectiveness of bycatch reduction strategies (Sea Mammal Research Unit, 2004; Tilzey *et al*., 2006). Even fewer studies have addressed the behaviour of marine mammals in trawls, and where information is available, it has tended to be restricted to very few observations (Shaughnessy and Davenport, 1996; Wilkinson *et al*.; 2003; Sea Mammal Research Unit, 2004; Browne *et al.* 2005; Northridge *et al*., 2005; Hamer and Goldsworthy, 2006; Tilzey *et al*., 2006).

6.1 Seal interactions

6.1.1 Interaction rates

Operational interactions between fur seals (most probably Australian fur seals, Hindell, pers. comm.) and mid-water trawls is a common occurrence in the SPF, with over half of the monitored trawls involving net entry by seals during the course of the trawl operation. This, however, represents a minimum estimate since seals that may have entered the net but did not venture as far as the SED would not have been observed. Our data compare with the results of a pilot study in which 8 out of 14 monitored trawl shots (57%) involved seals that had fully entered the net, although seals were observed in and around the net whilst it was fishing in the vast majority (93%) of shots (Browne *et al*., 2005). By design, the present study focussed on understanding the dynamics of interactions within the net, the pilot study on the other hand also included information about interactions that involved seals outside of the trawl net.

Redbait and jack mackerel, the key species targeted by the fishery, also represent major prey items for fur seals (Gales and Pemberton, 1994; Littnan *et al*., 2007). Not unexpectedly feeding was commonly observed, either by seals fully inside the net or by individuals which partially entered through the escape opening to take fish concentrated near the SED. Browne *et al*. (2005) also observed a high incidence of net feeding, with seals actively entering the net through the escape opening (at the time positioned on the roof of the net) to take fish. In addition, Browne *et al*. (2005) noted active foraging on fish as they spilled out of the escape opening (i.e. outside of the net), a behaviour not recorded in our study due to the camera system placement.

Interaction rates with seals varied markedly throughout the year. Rates exceeded 70% in monitored trawl shots between March and August but were much lower (< 25%) at other times of the year, implying a strong seasonal effect with highest rates of interactions during autumn/winter. Since mid-water operations in the SPF off Tasmania are currently limited to a single vessel, overall effort (number of trawl shots) is relatively low and sparsely distributed. Nevertheless, fishing is periodically focussed in specific areas and under such circumstances it is logical to expect that seals may become increasing adept at locating and entering the net to forage, resulting in increased interactions over time. For instance, such a trend was observed during a period of sustained fishing off the south-west coast and was also reported by Browne *et al.* (2005). It is possible, therefore, that the observed seasonality in interaction rates was influenced, to some extent at least, by learning and habituation.

6.1.2 Factors associated with net entry

Seals entered the trawl net during all phases of the fishing operation, not only as the gear was being set (descending) or hauled (ascending), as reported by Hamer and Goldsworthy (2006) and Tilzey *et al.* (2006) for the blue grenadier fishery. Operational differences in trawl depth represent the primary reason for this apparent disparity, with the SPF mainly targeting depths of less than 150 m, well within the diving range of Australian fur seals (Arnould and Hindell, 2001) and New Zealand fur seals (Page *et al*., 2005). By contrast, most trawl effort in the blue grenadier fishery occurs in depths of greater than 350 m, which is outside of the known diving capability of Australian fur seals, the species taken as bycatch in that fishery (Tilzey *et al*., 2006). Hamer and Goldsworthy (2006) reported that the greatest depths that Australian fur seals entered the trawl net in the blue grenadier fishery were 190 m during setting and 130 m during hauling phases.

Giving consideration to trawl phase, significantly higher rates of net entry, expressed as positive interactions and number of seals per 30 minute time block, were recorded during the setting phase of the trawl operation. Interaction rates for each of the other identified trawl phases, namely fishing, turning, hauling and pump-out, did not differ significantly, indicating that there was a higher probability of at least one seal entering the net whilst the trawl was descending than at other times. In absolute terms, however, well over half of all of the interactions occurred whilst the net was fishing at depth, a consequence of long trawl durations (mean > 6 hours) such that the fishing phase accounted for over 70% of the trawl operational time. Thus, with the possible exception of setting the trawl, there was no clear evidence to indicate increased vulnerability of seals becoming disorientated and passing down the net to the SED region during operational phases that involved alterations to net geometry, i.e. turning and hauling.

Interactions based on elapsed trawl duration peaked during the first hour of the shot (reflecting relatively high interaction rates whilst setting the gear), then declined sharply to a minimum level during the third hour. After this rates increased gradually during the latter stages of the trawl operation. The significance of the low interaction rate at three hours is unclear but may reflect a recovery period for individuals that had dived on the gear earlier in the shot. The majority of interactions occurred at night; to a large extent this pattern was a reflection of the distribution of trawl effort, which was heavily concentrated during the hours of darkness. However, when interactions were scaled by trawl effort, the strong diurnal pattern disappeared, implying that the likelihood of seals entering the net was largely unaffected by time of day but was more a function of trawl effort. These observations are in sharp contrast to Hamer and Goldsworthy (2006) who noted that fur seal bycatch in the winter blue grenadier fishery occurred exclusively during day shots, even though about half of the trawl events occurred at night.

In the vast majority of instances (87%) net entry was via the net mouth, only a small proportion (13%) of seals entered via the escape opening. These findings contrast Browne *et al*. (2005) who observed that out of 13 instances involving net entry, just two (15%) seals had entered via the net mouth, the remainder entered through the escape opening. However, it is possible that the use of a relatively high powered light may have attracted seals to the escape opening and influenced this behaviour. In our study a much less powerful lighting system was used and, for the majority of shots, the escape opening was located on the underside of the net and not directly illuminated. Tilzey *et al*. (2006) recorded just two instances on video where Australian fur seals entered via an escape hatch (rather than opening) but considered that over time seals would become increasingly adept at foraging in the nets, having learnt how to enter via the escape hatch.

Although interaction rates did not differ between the SED configurations tested, the proportion of seals that entered via the escape opening did differ significantly between the small and large escape openings, being higher for the small opening. This finding was unexpected but a possible explanation could be that the presence or absence of fish in the net may be more obvious from outside of the net with the larger entrance. Thus when no fish were present the incentive to enter the net in search of prey would be lower. It is also possible that the larger entrance may have better facilitated feeding manoeuvres without the necessity to fully enter the net to grasp prey. The fact that substantially more seals were observed to only partially enter the net when the large opening was in place tends to support this suggestion.

The escape opening also provided an opportunity for seals to enter the net during the pump-out phase, at a time when the forward part of the net had been retrieved onto the net drum[6]. In such instances most of these seals were able to get to an area of the net which had emerged from the water and were able to breathe and survive until the pump-out finished and the net was streamed ready for winding the codend on board. At this time they were swept down the net and out of the escape opening.

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[6] Video footage during this phase was often over-exposed, influenced by vessel lights and ambient lighting levels (pump-out frequently occurred during daylight hours).

6.1.3 Outcomes of interactions

While there was uncertainly about the outcomes for a small proportion of individuals, it was evident that the majority (> 64%) of fur seals that had entered the net eventually exited via the SED escape opening. Comparatively few (> 12%) animals swam back out of the net mouth. An escape opening was therefore crucial in determining the fate of individual seals and the application of video technology has enabled us to determine its effectiveness in a non-destructive manner. Wilkinson *et al*. (2003) on the other hand estimated the proportion of New Zealand seal lions (*Phocarctos hookeri*) in the NZ squid trawl fishery that were ejected through an escape hatch by placing a cover over hatch (resulting in their death by drowning). They established that over 90% of seals were ejected and, based on visual assessment of vitality for three individuals using underwater video, concluded that most would have survived. However, autopsies revealed severe internal trauma suggesting that not all would in fact have survived (Gibbs *et al*., 2001; cited in Wilkinson *et al*., 2003). The fact that seals exit the net does not, therefore, in itself imply that all will survive.

In many instances we were able to estimate the time that individual seals had spent in the net and visually evaluate their condition. Being air breathing mammals, breath-hold duration is a critical determinant of survival potential. In about half of the recorded interactions, seals were observed within the net for less than 3 minutes, with about 70% exiting after 6 minutes. Significantly, the maximum interaction duration for individuals that were judged to have actively exited the net by swimming back out the mouth was about 6 minutes. Individuals that actively swam out via the escape opening did up to a maximum interaction time of about 9 minutes, whereas passive expulsion, whilst still exhibiting some overt level of responsiveness, occurred in some individuals up to 14 minutes. Responsiveness in individuals that were subsequently judged as mortalities ceased after an average of 8.3 minutes, with a maximum of 12.7 minutes. In the pilot study the longest times recorded for seals within the net were 6.5 and 8.7 minutes, in both instances the individuals became progressively lethargic, spending extended periods resting against the SED, prior to escaping out of the escape opening (Browne *et al*., 2005). Under natural conditions, maximum dive durations of 6.8 and 8.9 minutes have been recorded for male and female Australian fur seals, respectively (Hindell and Pemberton, 1997; Arnould and Hindell, 2001). New Zealand fur seals have reported dive durations of up to 14.8 min, the longest recorded for otariids (fur seals and seal lions) studied to date (Page *et al*., 2005).

As the mean descent rate for New Zealand fur seals is just under 1.5 m s^{-1} (Harcourt *et al*., 2002), and it is likely that a similar rate would apply for Australian fur seals (M. Hindell, pers. comm.), it would take about one minute to dive to a depth of around 100 m, with additional time required to locate and enter the net and return to the surface. Based on our observations and the understanding of the dive capabilities of fur seals, in particular Australian fur seals, we conclude that the potential for survival would be high for interactions lasting less than about 6 minutes, but for times exceeding about 10 minutes in the net, particularly at fishing depth, the probability of survival, even if the individual was ejected from the net, would decline progressively. This remains a significant uncertainty for any bycatch mitigation strategy, that is to say even if marine mammals can be directed out of the trawl gear, survival is not guaranteed.

6.1.4 Mortalities

Over the course of this project 19 seal mortalities were recorded on video, with individuals observed to become progressively less responsive over time, eventually being pinned against the grid for long periods prior to dropping out through the escape opening. Mortalities occurred during each of the trawl phases and, although no significant effect of trawl phase was detected, the highest mortality rates were associated with turning and hauling. SED configuration represented a significant factor, with the odds of a mortality occurring increasing by a factor of over three times when the small, as opposed to the large, escape opening was used. Owing to operational difficulties we were not able to validly compare mortality rates for a top opening configuration.

In the context of the SPF mid-water trawl fishery, our data suggest an overall mortality rate of 0.194 seals per shot, or 0.325 and 0.125 per trawl using the small and large bottom opening configurations, respectively. The equivalent rates when high risk interactions (i.e. > 10 minutes in the net) are included as potential mortalities were 0.276, 0.425 and 0.208 seals per shot, respectively. In the South East Trawl fishery, bycatch rates of 0.019 seals per trawl, about two thirds resulting in mortalities, have been reported (Knuckey *et al*., 2002). For the winter blue grenadier fishery, incidental capture rates have ranged between 0.046 - 0.132 seals per trawl (mortality rate 0.031 - 0.123) depending on year (Shaughnessy *et al*., 2003; Tilzey *et al*., 2006). By comparison with these other Australian trawl fisheries, the mortality rates when the large escape opening was used were comparable with the upper levels experienced in the winter grenadier fishery, which involves a mix of demersal and mid-water trawl activity (Tilzey *et al*., 2006). By contrast, mortality rates were an order of magnitude higher than those estimated for the South East Trawl fishery, which is primarily a demersal trawl fishery. Wickens and Sims (1994) noted that mortality rates tend to be higher in mid-water rather than bottom trawls, a phenomenon that compounded by the larger net opening of mid-water trawls.

Based on these bycatch rates and numbers of trawl shots by SED configuration (bottom opening small escape hole, N = 124; bottom opening large escape hole, N = 115; top opening, N = 12) for the study period (January 2006 –February 2007), the total number of seal mortalities was estimated as 54.7 (95% CI 32.7 – 78.1), which, if interactions judged to be high risk are added, increased to 76.2 (95% CI 48.0 – 107.2). Had the large bottom opening configuration been used throughout the period we estimate that mortalities would have been halved in number (26.8).

The observation that all of the seals that died in the net ultimately dropped out through the escape opening before the net was retrieved onboard has obvious ramifications for reporting of marine mammal bycatch. Thus, even with a high level of observer coverage most, if not all, of the interactions may have gone undetected, a situation exacerbated by the presence of the open escape hole on the underside of the net. Similarly, Bisack (1997) cautioned that marine mammals entangled in gillnets may drop out of the nets as they are being retrieved, and as such would not be detected by even comprehensive observer coverage.

6.2 Other interactions

The primary impetus for this project was to investigate the behaviour of dolphins in the midwater trawls, with a view to identifying factors that might reduce the likelihood of mortalities occurring. From the outset it was understood that such interactions were likely to be rare and sporadic and therefore a high level of coverage would be necessary. To this end we have been successful but, significantly, did not detect any interactions with dolphins. Furthermore, there been no reports of dolphin bycatch since May 2005. While we can not completely dismiss the possibility that there may have been dolphin bycatch in shots that were not monitored with the camera system, we can conclude that the incidental capture of dolphins is extremely rare and sporadic in this fishery.

In relation to the bycatch of other megafauna, this study has established that interaction rates are very low, with pelagic sharks, principally thresher sharks, sunfish, rays and billfish occasionally captured. Bycatch of megafauna such as sharks, billfish, and sunfish, in addition to marine mammals, has been identified as an important issue in other trawl fisheries worldwide, along with the need to develop strategies to reduce the levels of bycatch (Lewison *et al*., 2004; Zeeberg *et al*., 2006).

6.3 SED design

Operating within the context of a commercial fishing operation, we had intended to evaluate the performance of top and bottom opening SED configurations. However, logistic and crew safety considerations meant that it was not possible to fully evaluate the performance of top opening designs.

Two bottom opening SED configurations were trialled successfully, with seal mortality rates significantly reduced by enlarging the escape opening. To be effective, exclusion devices need to facilitate the exit of marine mammals, taking account of the fact that the less time animals are in net the more likely they are to survive. Seals became progressively less active over time, spending increasing periods resting against the grid. Grid angle therefore has an important function in directing animals towards the escape exit while the design of the exit, whether open or a hatch, will be important in determining how easy it is for the animal to escape from the net. In relation to the former, Wilkinson *et al*. (2003) recommended that the grid should be angled at about 45^o which is substantially greater than that used in the SPF. It was beyond the scope of the present investigation to compare the effect of grid angle on survival rates but further work could be useful. Exit design has relevance since many of the seals were ejected rather than actively swam out through the escape hole. The large opening provided a less impeded point of exit than the small opening by effectively removing barriers in the floor in the net. Rates of net entry via the bottom escape exit were relatively low compared with the top opening configuration used in the pilot study, though it is possible that the lighting system used in that study may have influenced the seal behaviour (Browne *et al*., 2005).

Tilzey *et al*. (2006) considered that a top opening SED represented a considerable advancement over a bottom opening design because it better facilitated both seal exit (seals being more likely to swim upwards) and reduced the likelihood of seal entry via the escape hatch. In relation to net access, they assumed that the top hatch would be less accessible since in the blue grenadier fishery most seal entry occurred while the net was being hauled. However, very limited observational information was available to support their assertions which, along the inadequate coverage achieved in our study, suggest the need for further assessment of relative performance of top opening SED configurations, both in terms of facilitating exit and potential impact on net entry rates. It was perhaps significant that relatively few SED contacts (just 13%) occurred in the lower third of the SED, close to the escape exit. Just over half of all contacts occurred in the mid-region, with a third in the upper region of the SED. In addition, seals were occasionally observed actively resisting being forced down towards the bottom exit or, once expelled, actually fighting to re-enter the net. These observations tend to support the supposition that seals would be more inclined to head for the surface after foraging and that a top opening escape exit may act to reduce interaction times and thereby enhance survival potential.

Fish loss out of the escape opening, along with providing a potential access route for marine mammals into the net, represent important issues for industry. Modifications including flaps, “hoods” or escape hatches have been applied in trawl nets (e.g. Wilkinson *et al*., 2003; Sea Mammal Research Unit, 2004; Tilzey *et al*., 2006) to reduce both fish loss and net entry rates. There is a clear opportunity and need for such refinements to be applied in the SPF.

Ultimately the design of successful exclusion devices cannot rely on the ‘problem solving’ or sensory capabilities of marine mammals to navigate to the escape opening. Rather, animals must be directed to exit the net, whether actively searching/swimming or not, and the orientation of the grid, and the location and size of the escape opening will assist in this.

6.4 Recommendations

The very nature of mid-water trawl operations in the SPF, i.e. targeting key prey species at depths well within the diving range of seals, mean that operational interactions with fur seals are inevitable. Our data suggest that there are no clear strategies or changes to fishing practices that could be employed to eliminate interactions. For instance, the Code of Practice developed to reduce seal bycatch in the winter blue grenadier fishery specifies that vessels steam at 10 – 12 knots for at least 40 minutes prior to shooting the gear, thus reducing the likelihood that seals enter the net whilst setting the gear (Tilzey *et al*., 2006). While similar practices in the SPF might reduce interactions whilst the gear is being set, interactions are still likely to occur throughout the remainder of the trawl operation, noting that in absolute numbers more seals enter the net while it is fishing than at other stages. Sustained trawl activity within a restricted area may also increase the probability of interactions as seals appear to progressively learn how to forage from the trawl. Limiting the time spent fishing in specific areas may reduce interaction rates but, given the often patchy distribution of the target species, moving away from productive grounds would have significant economic consequences for the operators.

Mitigation strategies, therefore, need to focus on how to get individuals out of the net and maximise the likelihood of their survival. Exclusion devices offer the most practical solution and the large escape opening represents a significant improvement over the small opening option. There is, however, considerable scope to further refine the SED design used in the SPF. SED orientation, size and type of escape opening are refinements that could be examined.

- A key requirement for the exclusion grid is that it is angled sufficiently to readily deflect megafauna towards the exit, other studies have recommended an angle of around 45^o, which is substantially greater than currently used in the fishery.

- The effectiveness of a top opening escape option requires further investigation, both for its potential to better facilitate the exit of marine mammals (towards the surface) and to address the issue of bycatch drop-out. In the absence of underwater observations, bycatch will be under-reported with the current bottom opening configuration, regardless of the level of observer coverage.

- Considerable refinement in grid design is required to overcome operational issues relating to implementing a top opening system. For factory trawlers with extensive trawl deck space it is feasible to have relatively large and sophisticated SED configurations which can be stowed safety on deck. For smaller vessels or those with very limited trawl deck space, such as the FV *Ellidi*, the SED typically must be wound onto the net drum. Flexible plastic mesh grids (e.g. Anon., 2006) are available and, being similar to the cargo mesh barrier used initially in the fishery (Browne *et al.*, 2005), may overcome some of the logistic and safety problems experienced when using the backwards orientated excluder grid.

- As evidenced in the pilot study and to a lesser extent here, an open escape exit can provide a ready point of access for seals. This coupled with issues of fish loss suggest that further refinements are required to the exit and there are a range of hood and exit hatch designs available that have been trialled in other fisheries.

- For bottom opening configurations there is a need to investigate options to reduce the likelihood that seal and other megafauna mortalities fall out of the net prior to being identified and recorded. Any such options must not impede the exit of healthy specimens.

In order to properly evaluate the benefits of any future refinements in SED design, underwater monitoring will be necessary. Furthermore, as mid-water trawling is expected to expand in the SPF there will be a need to undertake camera trials on other vessels and in other areas of the fishery. The underwater camera system and data analysis protocols developed for this project have yielded an unprecedented amount of information about the nature of marine mammal interactions and should be adopted and/or refined for this purpose.

7 Benefits / Management Outcomes

This study has provided a comprehensive assessment of marine mammal bycatch in the mid-water trawl sector of the SPF operating off Tasmania, including modifications to the exclusion device that have resulted in a significant reduction in seal mortality. While cetacean bycatch has been identified as a major issue for the SPF, our data demonstrate that incidents involving dolphins are extremely rare and unpredictable. By contrast, operational interactions with fur seals are a common and unavoidable occurrence in this fishery. Mortality rates are relatively high by comparison with other trawl fisheries, though comparatively low trawl effort at the present stage of the fishery development means that, in absolute terms, the number of mortalities are low and unlikely to pose a significant threat to seal populations.

Traditionally, bycatch monitoring has been undertaken by observers, although in this fishery fixed onboard cameras have also been trialled and are considered to represent a cost-effective monitoring strategy. Both approaches are only effective if bycatch is sighted, usually as it is brought onboard the vessel. This study has demonstrated that the bottom opening SED in current use is effective in expelling the vast majority of the megafauna that enters the net in a healthy condition but when mortalities occur, they invariably drop-out of the net and thus would not be detected.

There are obvious implications from this work for the development of the Bycatch Action Plan and requirements under the Environment Protection and Biodiversity Conservation Act, relating to reporting interactions with protected species. As a minimum requirement in the SPF, mid-water trawl nets should incorporate an effective marine mammal exclusion device to mitigate potential lethal interactions. Consideration should also be given to developing a Code of Practice to address the issue of seal as well as cetacean interactions, though as noted above, any such strategy could only serve to reduce the number of interactions.

8 Conclusion

The incidental capture of dolphins during 2004 and 2005 focussed attention on the issue of marine mammal bycatch in the SPF. While interactions with cetaceans were of greatest concern, a pilot study and the current investigation have established that fishery interactions with fur seals are far more common. As such, this study represents the most comprehensive assessment of the nature of operational interactions between marine mammals and mid-trawls available, including information on net entry and exit, and potential rates of survival.

Fur seals, most probably Australian fur seals, entered the body of the trawl in over half of all monitored shots, though interaction rates peaked at over 70% during autumn and winter and were below 25% at other times of the year. This seasonality may, in part at least, be the result of habitation, since seals appeared to become increasingly adept at entering the net to forage during periods of sustained fishing activity within a localised area.

Seals were observed entering the net during each phase of the trawl operation, the vast majority via the net mouth. Only a small proportion entered through the escape opening. Conversely, the greatest majority of seals exited the net via the escape opening, relatively few exited out of the net mouth. Although the highest rate of interactions occurred whilst the net was being set, numerically the majority of seals entered the net whilst it was fishing at depth, this particular operational phase accounting for the bulk of the trawl duration. Since trawling typically occurs in shelf waters, at depths that are within the dive capability of fur seals, the trawl effectively remains accessible to seals throughout the entire operation. Furthermore, most interactions occurred at night, reflecting the concentration of trawl effort during the hours of darkness. When standardised for effort, this diurnal pattern was no longer evident, suggesting that the probability of interactions occurring was unaffected by time of day.

The performance of bottom and top opening SED configurations were examined during this study, though due to operational limitations we were unable to adequately trial the top opening design. We were able to demonstrate that by increasing the size of the escape opening, such that there was no floor in the net immediately in front of the excluder grid, a significant reduction in lethal interactions was achieved. By comparison with other Australian trawl fisheries the overall seal mortality rate is high in this fishery, around 0.19 seals per shot, though when the large escape opening was used this dropped to 0.12 per shot, which is comparable to the upper range for the winter blue grenadier fishery. During the 13 month study period, we estimated that there were 55 fishery induced seal mortalities, with the survival of a further 20 seals considered uncertain.

An important observation from the study was that all seal mortalities eventually fell out of the escape exit prior to the net being brought onboard the vessel, suggesting that many would not have been observed without the camera system and hence the scope of the bycatch issue would have been understated, even with a high level of observer coverage.

No interactions with dolphins were observed or reported over the entire study period, highlighting that such interactions are rate and unpredictable. Other megafauna, mainly thresher sharks and sunfish, were very occasionally caught in the net. There was evidence that some of this bycatch was ejected in a healthy condition.

This study has clearly demonstrated that seal bycatch in mid-water trawls is an issue that needs to be addressed in the SPF. The implementation of exclusion devices that optimise the probability that animals escape in a healthy condition represents the key to a successful mitigation strategy. In this respect there is considerable scope for further refinement in SED design, including a clear need to further examine the suitability of a top escape opening and to investigate options to reduce the ingress of marine mammals and loss of fish out of the escape opening. Such refinements as the inclusion of an escape hatch and/or a hood over the escape hole warrant consideration.

Significantly, this study also provides a model for other marine mammal bycatch studies, whereby through the full engagement of industry as a research partner it has been possible to achieve a high level of fishery coverage in a cost-effective manner as well as working collaboratively to mitigate the bycatch of marine mammals.

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