BIOLOGICAL CONSERVATION 130 (2006) 517–529

available at www.sciencedirect.com

SCIENCE DIRECT®

journal homepage: www.elsevier.com/locate/biocon

Seal–fishery operational interactions: Identifying the environmental and operational aspects of a trawl fishery that contribute to by-catch and mortality of Australian fur seals (*Arctocephalus pusillus doriferus*)

*Derek J. Hamer**, *Simon D. Goldsworthy*

South Australian Research and Development Institute, Aquatic Sciences, 2 Hamra Avenue, West Beach, Adelaide, South Australia 5024, Australia

ARTICLE INFO

Article history:
Received 1 June 2005
Received in revised form
11 January 2006
Accepted 16 January 2006
Available online 2 March 2006

Keywords:
Australian fur seal
Operational interactions
By-catch mortality
Trawl fishery
Fisheries management
Generalised linear modelling

ABSTRACT

Australian fur seals are known to interact directly (i.e. operational interactions) with trawlers fishing in the winter blue grenadier trawl fishery of western Tasmania, Australia. The purpose of this study was to identify the environmental and operational aspects of the fishery that were associated with increased numbers of seals observed at the surface. The incidence of net entry was determined in order to establish the effectiveness of the currently used Seal Exclusion Device (SED) at reducing by-catch and mortalities. In addition, the stage and depth at which seals were at greatest risk of entering the net at depth and becoming by-catch were also identified.

An increase in seal numbers observed at the surface is assumed to be proportional to the increased risk of by-catch and mortality incidences at trawlers. The most important subset of environmental and operational factors for predicting the number of seals observed at the surface both in the fishing ground in general and during fishing operations were identified using Generalised Linear Modelling. The final model yielded a significant result ($R^2 = 0.63$, $P < 0.01$, $n = 149$) and indicated that the number of seals observed increased when weather conditions deteriorated, particularly when barometric pressure decreased and when swell height and visibility increased. Vessel operations also influenced the number of seals observed; seal numbers increased when the number of nearby vessels and trawl frequency increased, but decreased when vessel speed increased. Seal numbers also increased as the distance from the nearest breeding colony and haul-out site decreased.

Seal numbers at the surface generally increased steadily during trawling operations ($n = 475$), although brief declines were noted during shooting and hauling phases. Sub-surface net interactions were also examined using a submersible video camera unit. Seal activity at depth was converse to that observed at the surface, with increased seal numbers noted during shooting and hauling, suggesting that seals dived to forage on fish in the submerged net.

All seal by-catch occurred during the day and almost half occurred during shooting. Mortalities were significantly higher during shooting compared with hauling (Fishers exact test: coef. = 0.65, $P < 0.05$). However, mortality rates were similar between tows with the Seal Exclusion Device (SED) attached and those without (Fishers exact test: coef. = 0.07, $P < 0.99$). Only one seal was detected entering and exiting the net mouth during monitored tows, suggesting that the recently observed reduction in by-catch levels (and mortalities) may not necessarily

---

* *Corresponding author*: Tel.: +61 8 8207 5348; fax: +61 8 8207 5406.
E-mail addresses: hamer.derek@saugov.sa.gov.au (D.J. Hamer), goldsworthy.simon@saugov.sa.gov.au (S.D. Goldsworthy).

0006-3207/$ - see front matter

doi:10.1016/j.biocon.2006.01.014

be attributed to the introduction of the Seal Exclusion Device. Seal by-catch recorded during hauling typically occurred when haul speeds exceeded minimum average swimming speeds for fur seals.

Recommendations based on these findings have been made to assist with the future management of fur seal populations that interact with trawl fisheries.

1. Introduction

1.1. *Operational interactions between seals and commercial trawl fisheries*

The unintentional catch of non-target or "by-catch" species has been detected in almost all fisheries, accounting for between 17% and 39% of the catch (Alverson et al., 1994; Wickens, 1995; Alverson, 1999). In some fisheries, by-catch rates are of similar or higher proportions to the species targeted (Carbonell et al., 2003). In the past, many fisheries have regarded non-target species as economically unimportant, partly explaining the historical absence of by-catch management plans (Alverson, 1999; Harris and Ward, 1999; Bunting, 2002; Bache, 2003). Consequently, the importance of by-catch in the conservation and management of marine mammal populations in particular and the ecologically sustainable development of commercial fisheries that interact with them has only recently become a major management issue (Hall et al., 2000; Goldsworthy et al., 2003).

The occurrence of operational interactions between seals and fisheries, resulting in by-catch and associated mortalities, is now globally widespread. The recent recovery of seal species after the cessation of commercial sealing in most countries, plus the concomitant increases in fishing technology over the last five decades has likely contributed to the marked increase of this problem (Beverton, 1985; Wickens, 1995; Shaughnessy et al., 2003). Global reviews of seal–fishery interactions demonstrate an increase from 16 affected seal species in the early 1980s (Northridge, 1984, 1991; Woodley and Lavigne, 1991), to 36 in the early 1990s (Wickens, 1995), although these figures may in part be explained by a general increasing in awareness. With the advent of the conservation movement over the last four decades, seals have become 'charismatic' animals in the public domain, with perceptions and attitudes subsequently evolving from that of consumptive exploitation to conservation and welfare (Alverson et al., 1994; Hall et al., 2000; Bache, 2003).

Seals and commercial fisheries often target the same food resource. These consumer groups inevitably come together at a retracted spatial and temporal scale, thus leading to 'operational interactions' (Beverton, 1985; Shaughnessy et al., 2003; Tilzey et al., 2004). Operational interactions between seals and fisheries occur when seals come into direct contact with fishing gear, due to the spatially retracted abundance of fish (Northridge, 1991; Woodley and Lavigne, 1991; Wickens et al., 1992; Pemberton et al., 1994; Wickens, 1995; Fraker and Mate, 1999; Northridge and Hofman, 1999; Shaughnessy et al., 2003).

These foraging opportunities at or near the surface are an advantage for seals, because they negate the requirement for deep foraging dives that are energetically expensive (Hückstädt and Antezana, 2003; National Marine Fisheries Service, 1992; Williams et al., 2004). However, there are disadvantages to both the fishery and the seals; target fish are often discouraged from entering the net when seals are present and seals may risk injury or death if they also become caught (Shaughnessy, 1985; Loughlin and Nelson, 1986; Wickens et al., 1992; Wickens, 1994; Pemberton et al., 1994; Shaughnessy et al., 2003; Wilkinson et al., 2003; Tilzey et al., 2004). The extent of seal–fishery operational interactions and the associated risk of seals becoming by-catch may be dependent on the biology, ecology and behaviour of the seal species involved and the type, location and nature of the fishery concerned (Northridge, 1984).

1.1.1. *Environmental and operational variables associated with seal interactions*

Although extensive information has been compiled on seal by-catch rates in a number of fisheries, little is known about the environmental and operational variables most closely associated with the numbers of seals observed from fishing vessels. A number of variables that might be important determinants include the prevalence of animals naturally occurring in the fishing area, the time of day, the trawl duration and haul speed, although none of these have been quantitatively supported (Waring et al., 1990; Morizur et al., 1999; Shaughnessy et al., 2003). Interactions between the southern sea lion (*Otaria flavescens*) and the central Chilean purse-seine fishery indicated that the number of seals observed were generally positively correlated with the duration of fishing operations, the number of vessels in the fishing ground, commercial catch rates and the distance to the closest haul-out site (Hückstädt and Antezana, 2003; Hückstädt and Krautz, 2004). Catch weight and the presence of specific by-catch species may also influence the numbers of seals observed at the fishing vessel (Manly et al., 2002; Tilzey et al., 2004).

Determining the circumstances under which seal numbers increase at fishing vessels may be crucial for predicting when seal–fishery operational interactions are more likely to occur. Moreover, identifying a subset of important variables associated with increased numbers of seals at trawlers will facilitate a more directed management approach for mitigating future seal–fishery interactions.

1.2. *Seal by-catch in the winter blue grenadier fishery of western Tasmania*

Commercial quantities of blue grenadier (*Macruronus novaezelandiae*) are caught off western Tasmania, Australia (Fig. 1). However, only 46% (5734 metric tonnes) of the total allowable catch (TAC) of 12 409 metric tonnes was caught in 1998 (Aus-

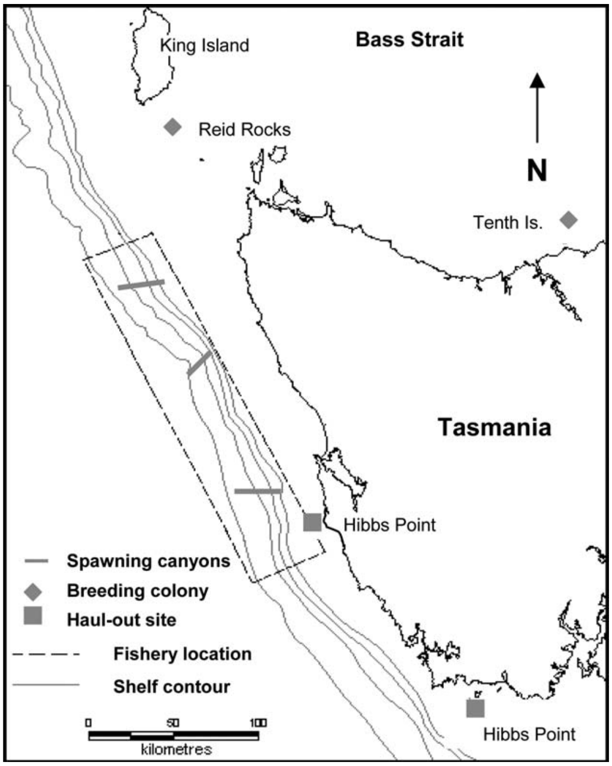

Fig. 1 – Approximate location of the winter blue grenadier fishery off western Tasmania during 2003. The location of Australian fur seal breeding and haul-out locations is also provided.

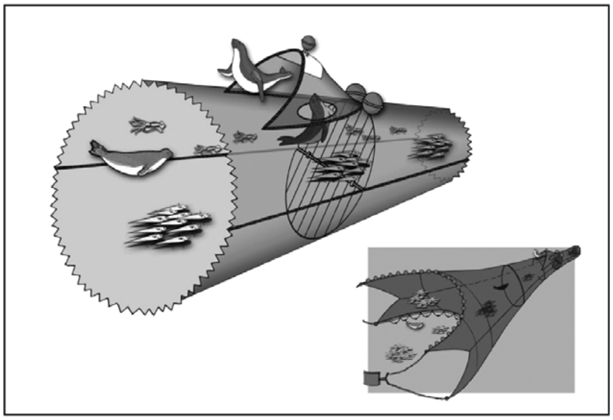

Fig. 2 – Schematic of seal exclusion device (SED) configuration used in trawl nets by factory trawlers off western Tasmania. Courtesy: Hoki Fishery Management Company NZ.

tralian Fisheries Management Authority, 1999). Notwithstanding, a strong pulse of sexually mature blue grenadier was predicted to enter the spawning stock in 1999, prompting the decision by the Australian Fisheries Management Authority (AFMA) to allow factory trawlers into the fishery to ensure the full utilisation of the total allowable catch (Australian Fisheries Management Authority, 1999).

Factory trawlers experienced a high Australian fur seal (*Arctocephalus pusillus doriferus*) by-catch mortality rate in their first year of operation, with 89 seals caught from 665 trawl events (Australian Fisheries Management Authority, 1999; Tilzey, 2002; Tilzey et al., 2004). In response, the Australian Fisheries Management Authority required factory trawlers to include the seal exclusion device (SED) in trawl nets as the principal gear modification for mitigating seal by-catch (Tilzey, 2002). The seal exclusion device comprises a stainless steel grid placed in front of the cod-end and an escape hatch some 5 m ahead of the grid (Tilzey, 2002; Wilkinson et al., 2003) (Fig. 2). In principal, the seal exclusion device allows the uninterrupted passage of fish through to the cod-end while prohibiting the entry and facilitating the escape of seals, subsequently reducing the risk to seals of drowning.

1.2.1. *The effectiveness of the seal exclusion device for reducing seal by-catch*

The inclusion of seal exclusion devices in fishing gear used by factory trawlers in this fishery and the concomitant reduction in the Australian fur seal by-catch rate over three fishing seasons between 2000 and 2002 has lead to the conclusion that Seal Exclusion Devices are responsible for the observed reduction of seal by-catch and mortality on factory trawlers (Tilzey, 2002; Tilzey et al., 2004). However, the incidence rate of sub-surface net entry is not available, making a quantitative determination impossible. The reduction in by-catch incidence may instead be due to the removal of habituated individuals through previous by-catch mortality, or changes in unidentified environmental variables leading to an overall reduction in the numbers of animals present in the region of the fishery. The concomitant reduction in the incidence of sub-surface net entry that would be expected outcomes of these two circumstances cannot be discounted as the cause for reduced seal mortalities, rather than the presence of the seal exclusion devices alone. Therefore, the perceived success of the seal exclusion devices must be validated. This may be achieved firstly by quantifying the incidence of sub-surface net entry by fur seals and secondly by comparing the incidence of by-catch and mortality that occurred during trawl events that had the seal exclusion device attached with those that did not.

1.2.2. *Stage and depth of net entry by seals*

It is difficult to determine at what stage or depth a seal is at greatest risk of becoming caught in trawl nets, although it is generally accepted that they become caught in the net during hauling while foraging on the catch. However, seal mortalities in trawl nets may also occur when the net is deployed at the beginning of the trawling event (Shaughnessy and Payne, 1979), but this has not been conclusively demonstrated. Therefore, determining when seals enter the trawl net may be useful to the further improvement of fishing practices to mitigate seal by-catch.

Blue grenadier is predominantly caught at depths between 300 m and 600 m (Smith, 1994; Tilzey, 1994). Dive data for Australian fur seals are limited, although a single record of 102 m maximum depth for an adult male (Hindell and Pemberton, 1997) and 164 m mean max depth for adult females (Arnould and Hindell, 2001) suggest that they are unlikely to forage naturally on blue grenadier due to the lack of vertical overlap. However, blue grenadier may become available during fishing operations, when they are hauled into the upper water column within the trawl net. Therefore, the period that the net is above approximately 200 m depth, during shooting and hauling, is likely to be when seals are at greatest risk of becoming caught. Confirmation of this could potentially assist in improvements to fishing practices aimed at mitigating seal by-catch.

1.3. *Aims of this study*

In summary, this study aimed to:

1. Identify a subset of environmental and operational variables most closely correlated with the numbers of seals observed at fishing vessels in general and during trawling.
2. Establish the incidence of net entry and the subsequent incidence of by-catch and mortality to determine the effectiveness of the seal exclusion device.
3. Determine the stage and depth of net entry and net interactions by seals to establish when they are at greatest risk of becoming by-catch during trawling.

2. Methods

2.1. *Description of the study site and the FV Aoraki*

The winter spawning blue grenadier fishery is located along canyons that originate at the continental shelf slope, 30–40 km off the west coast of Tasmania at approximately 144.8°E and between 40.6–42.7°S, in Australian Commonwealth waters (Fig. 1). All fieldwork contributing to this study was conducted on the New Zealand registered *FV Aoraki*, a Sealord Group owned factory stern trawler of approximately 78 m in length, with 750 metric tonne freezer storage capacity and approximately 60 crew members.

2.2. *Method used for counting seals at the surface*

Counts of Australian fur seals observed at the surface were conducted from the bridge of the vessel and became the dependent variable for all statistical analysis conducted during this study. Counts were obtained by rapidly scanning the ocean surface with horizontal sweeps, in order to avoid the possibility that seals might move, thus reducing the likelihood that animals would be missed, or counted more than once. Observations were made with both the naked eye and binoculars (Nikon 12 × 50 auto focus), out to a distance of approximately 200 m from the vessel. The mean was calculated from multiple scoring during each session.

2.3. *Variables associated with seal numbers at fishing vessels in general*

Mean seal numbers at the surface were estimated during a 10-min counting session, conducted at the beginning of each hour between 0800 and 1700, between the 22nd of July and the 22nd of August 2003 (31 days). The counting method defined in Section 2.2 was used to calculate seal numbers. Fourteen variables possibly associated with seal numbers were recorded, based on indications from the available literature and aspects unique to this fishery (Table 1). These variables were categorised as either operational (the activity and location of the vessel), or environmental (weather, sea state and other physical aspects).

Table 1 – Summary of factors potentially influencing seal numbers observed from the FV Aoraki, off western Tasmania 2003

Factors recorded	Units measured	Equipment used
Environmental factors		
Time of day	Fraction of day	
Barometric pressure	Hp	Jaeger dial barometer
Lunar illumination	%	Lunar chart
Visibility index	6 Point scale	AMSA visibility chart
Swell height	Meters	Visual estimation
Sea floor depth	Meters	Furuno Net Monitor CN-2210
Wind strength	Knots	Beaufort scale
Operational factors		
Distance to Reid Rocks	Kilometres	Furuno GPS Navigator GP-35
Distance to Hibbs Point	Kilometres	Furuno GPS Navigator GP-35
Number of tows in last 12 h	*n*	
Time since the last tow	Minutes	
Day of fishery	Day	
Vessels within 2 nm	Nautical miles	JMA-7710 Multi-function Radar
Vessel speed	Knots	Furuno GPS Navigator GP-35

2.4. *Variables associated with seal numbers during trawling*

Seal counts were recorded during 69 of the 107 trawls conducted during the voyage, representing all daylight fishing operations, between the 22nd of July and the 21st of August, 2003 (30 days). Each trawl was defined as the entire fishing operation, extending from the time the ship began manoeuvring into position for net deployment and continued until the net was hauled on deck. Each trawl operation was divided into seven discrete phases, according to distinct changes in operational state of the vessel, outlined in Table 2. The first three phases occurred during shooting the net, followed by trawling, then the last three phases occurred during hauling. Seals were counted during each of the seven phases, using the same counting method outlined in Section 2.2.

Data collected during the most recent hourly counting session were also assigned to a trawl event, in order to distinguish the possible effects of particular variables on seal numbers during particular stages of the fishing activity. In addition, trawl duration, haul speed, the time elapsed at the beginning of each phase since the beginning of trawling operations and catch weight were also recorded during trawling, because they were suspected of affecting the number of seals interacting with the vessel.

Table 2 – The three generic stages and seven phases of a trawling event, defined by distinct changes in operational state of a stern trawler

Shooting – deployment of the trawl net	
Phase 1	5 min scan prior to shooting net (identical method to hourly counts).
Phase 2	Between cod-end entering water and release of trawl doors.
Phase 3	Between release of trawl doors and trawling (net below 200 m depth).
Trawling – fishing period	
Phase 4	Between net below 200 m depth to commencement of net hauling.
Hauling – retrieval of the trawl net	
Phase 5	Between engaging trawl winch and hauling trawl doors aboard vessel.
Phase 6	Between trawl doors aboard vessel and net at surface.
Phase 7	Between net at surface and the cod-end on trawl deck.

2.5. *Investigation of incidence, stage and depth of seal–net interactions*

Data on the incidence and stage of subsurface seal–net interactions were collected using a submersible video camera unit (Sony Digital-8® DCR-TRV130E), mounted inside a custom made waterproof housing (Underwater Video Systems, Victoria, Australia). The video unit was tied to the inside of a net during daytime operations, facing forward and immediately ahead of the seal exclusion device, allowing seals that approached internally and externally to be detected. Depth data were also recorded by a Time Depth Recorder (Mk-9, TDR, Wildlife Computers, Washington, USA) during each trawl, at a sampling rate of 5 s intervals. Recorded depths were later synchronised with the video footage to determine the stage and depth at which seals interacted with the submerged trawl net.

2.6. *Data analysis*

Generalized Linear Modelling (GLM, SYSTAT®, Version 10, SYSTAT Inc., Illinois, USA) was used to identify a subset of variables that best described the variation in the number of seals observed at the surface (the dependent variable), both in general and during trawling. This modelling technique was chosen to enable non-normal and untransformed data (particularly low rates with Poisson distribution) derived from seal counts to be analysed (Hardy, 2002; Quinn and Keough, 2002). A backward, stepwise exclusion process was used, with the least significant variable being automatically removed from the analysis after each step until the probability of each variable remaining in the final model due to chance was less than 15% ($P = 0.15$). The higher than typical P value tolerance was used to ensure that all relevant variables were included in the final model. Those variables initially omitted from the model were individually re-entered a posteriori as a precautionary measure to confirm their relative importance in the model and were retained if they improved the R^2 value of the model by 5% or more.

Those variables that remained in the final model were graphically represented as histograms. The source of variation (values within the independent variable between which the number of seals observed varied the most) for each variable included in the final model was identified using Fisher's P LSD post-hoc analysis. This process allowed the nature of individual variables to be determined so that the final model could be more informatively interpreted and intuitive decisions could be made about the inclusion or exclusion of variables from the final model.

Repeated measures were used for analysis of variation in seal numbers at the surface between each phase of the trawl. Analysis of Variance (ANOVA) was not used here, because consecutive seal counts conducted at different stages of the trawl event were unlikely to be independent of each other, due to the cumulative nature of seals congregating to forage as the trawling event progressed.

3. Results

3.1. *Variables associated with seal numbers at fishing vessels in general*

A total of 1210 seal visitations were observed at the surface during hourly counts throughout the voyage, averaging 4.6 ± 1.2 SE ($n = 262$) per session. Seal numbers fluctuated throughout the voyage and a trend was not evident between weeks, although post hoc analysis indicated that the number of seals observed during the second and fourth week was significantly higher than the first (Fig. 3a). A peak in seal numbers occurred earlier in the day at 1000, followed by a general decline thereafter, with post hoc analysis indicating that seal numbers were significantly lower between 1400 and 1700 (Fig. 3b).

A subset of 8 of the 14 variables originally investigated remained in the final model, after the backward stepwise process and a posteriori addition of excluded variables, thus producing the most parsimonious subset for predicting seal numbers at the *FV Aoraki* in general:

> *Formula 1:* Predicted number of seals observed in general = *environmental variables* [0.901 × meters swell height + 0.276 × Beaufort's visibility scale − 0.014 × hectopascals of barometric pressure] + *operational variables* [0.506 × number of vessels within 2 nautical miles + 0.760 × number of trawls in the last 12 h − 0.042 × kilometres to Hibbs Point − 0.030 × kilometres to Reid Rocks − 0.896 × knots of vessel speed].

The final model yielded a highly significant result and explained just over 63% of the variation in seal numbers observed ($F_{7,159} = 32.71$, $R^2 = 0.63$, $P < 0.01$, $n = 149$). It should be noted that the outcome values for each variable in the final model do not function independently of each other, but are co-dependent components.

According to the final model, three of the seven environmental variables were significantly associated with the number of seals observed, being swell height, visibility and barometric pressure. Individual analysis of these variables revealed that seal numbers exhibited a steady trend of increase as swell height increased, with post hoc analysis demonstrating a significant difference between swell heights exceeding 6 m, compared with swell heights of 1 m or less (Fig. 3c). Seal

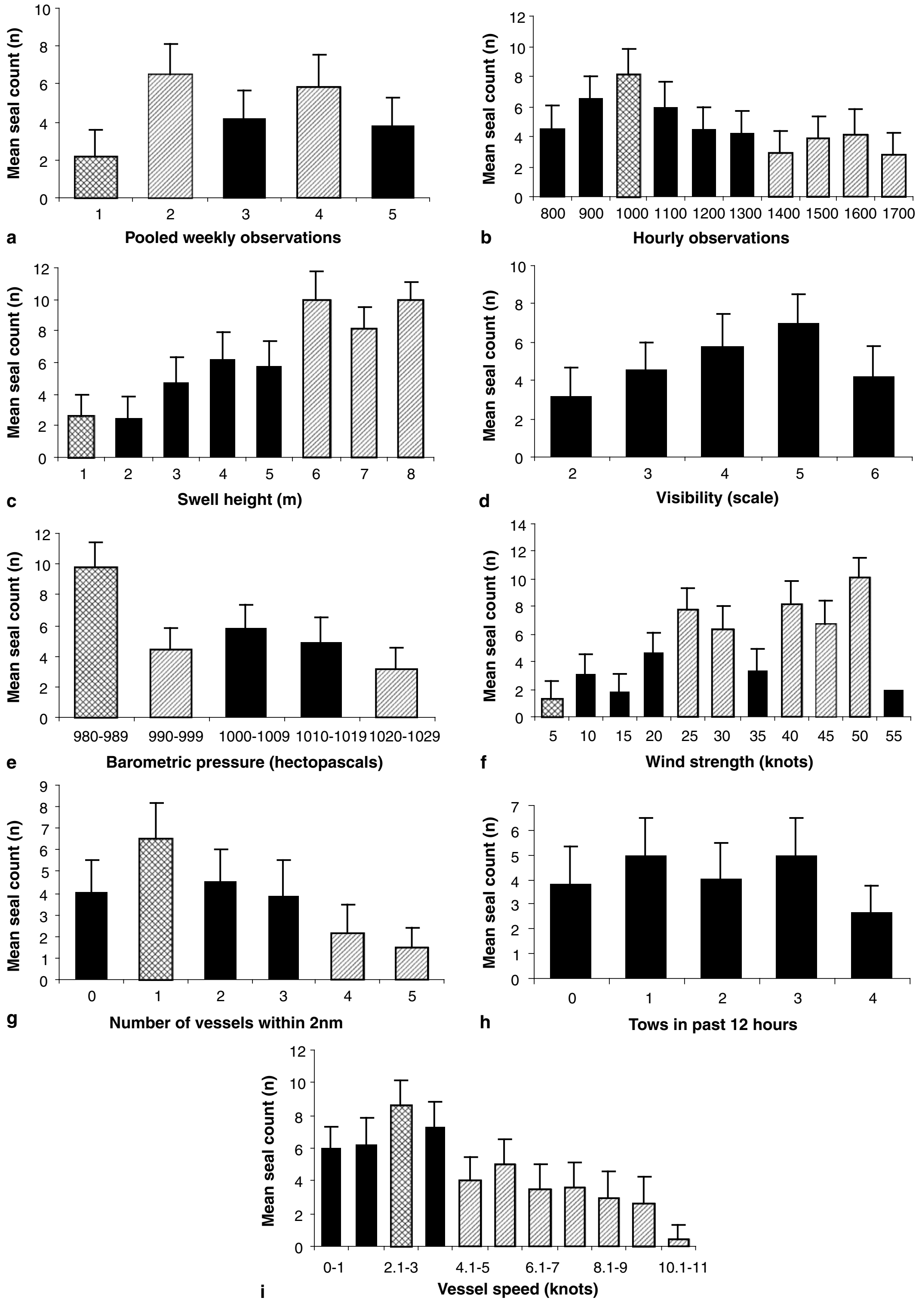

Fig. 3 – (a)–(i) Individual relationships between the mean number of seals observed from the *FV Aoraki* and: two temporal components (a) and (b), plus with those factors remaining in the final GLM for hourly observations (c)–(i). The dotted bar denotes the value of the independent variable from which seal numbers exhibited the highest frequency of significant difference with other values for the same variable (diagonally stripped bars), according to post hoc analysis.

numbers also increased with visibility, but declined slightly when the horizon was visible (full visibility), although post hoc analysis did not reveal any significant differences (Fig. 3d). Seal numbers declined as barometric pressure increased, with post hoc analysis revealing that seal numbers observed were significantly less between 1000–1009 and

1020–1029 hectopascals compared with 980–989 hectopascals (Fig. 3e). Interestingly, it was also noted that seal numbers increased with wind strength (Fig. 3f), even though it was not included in the final model, with post hoc analysis revealing that seal numbers increased significantly above 5 knots. Wind strength, combined with the three environmental variables included in the final model depicted a general deterioration in weather conditions associated with increased numbers of seals observed.

Five of the seven operational variables also remained in the final model, being the number of vessels within 2 nautical miles, the number of trawls in the last 12 h, the distance to Reid Rocks and Hibbs Point and vessel speed. Seal numbers increased with the number of vessels within 2 nm, although a decline was noted when viewed in isolation to other variables (Fig. 3g), which may be the result of autocorrelation. Seal numbers were significantly fewer when more than 4 vessels were present, compared to when only one was present. Although the number of trawls within the previous 12 hours was included in the final model, an obvious trend was not evident and post hoc analysis did not reveal a source of variation (Fig. 3h). Finally, seal numbers increased from stationary to 2.1–3 knots, but then declined steadily as vessel speed exceeded this (Fig. 3i). Post hoc analysis showed that observed seal numbers were significantly less for vessel speeds above 4.1 knots, compared with the peak at 2.1–3 knots. According to the final model, vessel speed had the strongest influence over seal numbers observed compared with other operational factors.

The combined effect of the distance between Hibbs Point (an important haul-out site adjacent to the fishery) and Reid Rocks (the closest breeding colony, to the north in Bass Strait) on seal numbers observed at the surface was investigated independently of all other variables. The longitudinal position of the fishery was fixed at 144.8°E (east–west longitudinal variation was negligible in the fishery) and the coefficients for all other variables were held constant at their respective mean values within the final model, while the latitude of the vessel was varied according to latitudinal position, allowing the number of seals to be predicted in relation to the combined effect of the distance from Hibbs Point and Reid Rocks:

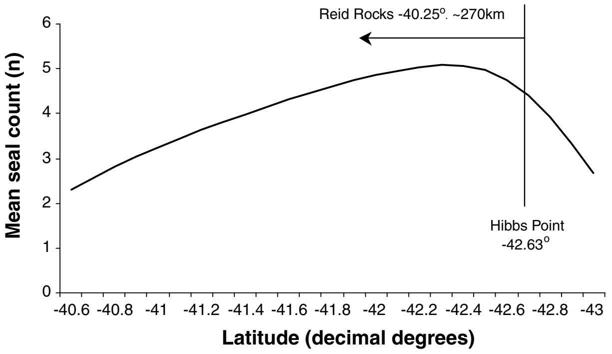

Fig. 4 – Bi-variate plot of mean numbers of Australian fur seals observed at the surface from the *FV Aoraki* in response to the combined effect of distance from both Hibbs Point and Reid Rocks.

> *Formula 2:* Predicted number of seals observed in relation to the combined effect of distance from Hibbs Point colony and Reid Rocks = [0.901(swell height coef.) × 3.081(swell height av.)] + [0.276(visibility coef.) × 5.676(visibility av.)] − [0.014(barometric pressure coef.) × 1013.929(barometric pressure av.)] + [0.506(vessels within 2 nm coef.) × 0.776(vessels within 2 nm av.)] + [0.760(trawls in the last 12 h coef.) × 1.321(trawls in the last 12 h av.)] + [−0.896(vessel speed coef.) × 6.138(vessel speed av.)] + [−0.042(distance to Hibbs Point coef.) × X^{HP}] + [−0.030(distance to Reid Rocks coef.) × X^{RR}].

where coef. is the coefficient value for each variable generated by final model, av. is the mean value of all observations for variable, X^{HP} is the specified distance to Hibbs Point (km) and X^{RR} is the specified distance to Reid Rocks (km).

The resultant bi-variate plot indicated that seal numbers increased as the vessel moved southward, away from Reid Rocks and toward Hibbs Point. Seal numbers observed peaked at a latitude of 42.3°S, approximately 44 km north of Hibbs Point (Fig. 4). The decline in seal numbers to the south of the peak was much more rapid compared to the decline to the north of the peak. These results indicate that while the breeding colony at Reid Rocks may exert some influence on the numbers of seals to the north, the proximity of the haul-out site at Hibbs Point appears to have a much greater influence on the number of seals observed.

3.2. *Variables associated with seal numbers during trawling*

A total of 1620 seals were observed at the surface during trawls ($n = 475$). An average of 2.4 ± 1.4 SE ($n = 138$) fur seals were observed during shooting, 5.6 ± 1.5 SE ($n = 207$) during trawling and 7.1 ± 1.6 SE ($n = 130$) during hauling. Seal numbers varied significantly between the three stages (repeated measures: $F_{2,474} = 22.15$, $P < 0.01$) and post-hoc analysis demonstrated that seal numbers increased significantly between shooting and trawling, but not between trawling and hauling.

More specifically, the numbers of seals observed also varied significantly between the seven phases of the trawl (repeated measures: $F_{6,474} = 19.68$, $P < 0.01$), with post-hoc analysis demonstrating a significant increase in the number of seals observed from phase 1 compared with phase 5 and 7 (Fig. 5). In general, an overall trend of increase occurred throughout the trawl, although a small decrease in seal numbers occurred during phase 3, and a marked decrease occurred during phase 6, before increasing again in phase 7.

During shooting, the amount of time that the net was open above 200 m (phase 3) ranged between 5 and 15 min, averaging 7.6 min ($n = 49$). During hauling, the net was also open above 200 m (phase 5) for between 5 and 15 min, averaging 9.2 min ($n = 49$). The combined total time that seals were at risk of becoming caught in the trawl net during shooting was 370 min and during hauling was 448 min.

Trawl data were also examined using Generalised Linear Models for each phase to determine which variables were most closely associated to the number of seals observed at the surface. Highly significant models were produced for all phases, explaining between 70% and 99% of the variation observed,

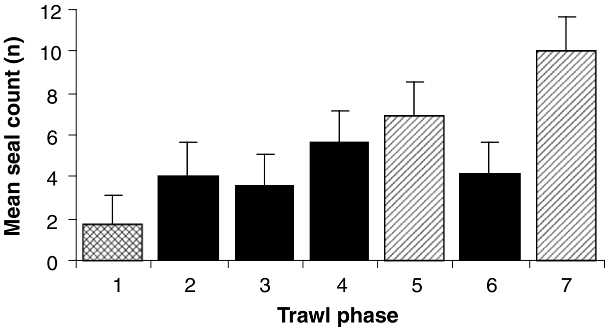

Fig. 5 – Variation in the mean number of Australian fur seals observed at the surface for the seven phases throughout trawling operations on the *FV Aoraki*. The dotted bar indicates that the value of phase 1 was significantly less than phases 5 and 7 (striped bars), according to post hoc analysis.

with the exception of phase 5, which only explained about 46% of the variation. A slightly different set of environmental variables featured in the final models produced for trawling operations, being swell height, visibility, barometric pressure and moon phase. Most of the operational variables remained in the final models for each phase during trawls, the most notable being an increase in seal numbers with increased trawl duration (phase 4) and decreased haul speed (phase 5).

Values for all other variables appeared to fluctuate non-intuitively between phases, casting doubts on the use of generalised linear models for this particular application. The rapid temporal change between phases may have been responsible for this, because there was insufficient time for seal numbers to adjust in response to the change in operational state. Therefore, analysis and interpretation of final models for each trawl phase will not be considered further, with the exception of trawl duration and haul speed, because of their relatively consistent appearance.

3.3. *Incidence, stage and depth of seal–net interactions*

Thirteen seals were caught and seven of these died during the voyage, generating a catch rate of 12.1 seals per 100 trawls (12.1%) and a mortality rate of 6.5 deaths per 100 trawls (6.5%). All seals were caught during daylight hours, with nine of the 13 seals (69%) caught after 1300 h. Six of the 13 seals caught entered the net during shooting and all of those died. Four of these deaths were confirmed by viewing the sub-surface video footage obtained during the trawls, while the remaining two were verified by the advanced stage of rigor mortis. Seven seals were caught during hauling, but only one died with all entering the trawl net shortly before it breached the surface and was hauled aboard. The incidence of mortality was significantly lower during hauling compared with shooting (Fishers exact test: contingency coefficient = 0.65, $P < 0.05$).

The net speed was 7.2–8.0 km h^{-1} (maximum haul speed) for six of the seven seals caught during hauling, with the remaining seal caught during a trawl with a haul speed of 6.9 km h^{-1}. An additional seal was recorded entering the net during shooting (shot 47) at a depth of about 120 m, but escaped via the net mouth. This was the only seal during the voyage to be recorded entering the net that avoided becoming by-catch. Two trawls also contained multiple seal by-catch.

The seal exclusion device was attached to 24 of the 49 trawls conducted in daylight hours during the voyage. Six seals were caught while the seal exclusion device was in place and 3 of those died, while seven seals became by-catch when it was not attached and 4 of those died. There appeared to be no difference in mortality rates between trawls with the seal exclusion device attached and those without it (Fishers exact test: contingency coefficient = 0.07, $P = 0.99$).

The mean number of seals observed outside the submerged net for the 49 trawls was 0.5 ± 1.1 SE during shooting and 0.9 ± 1.3 SE during hauling. Mean depth of seals observed inside the net was 165.5 ± 2.0 SE meters ($n = 4$) during shooting and 97.0 ± 2.3 SE meters ($n = 5$) during hauling, while depths outside the net were 91.4 ± 2.1 SE meters ($n = 7$) during shooting and 65.4 ± 2.3 SE meters ($n = 13$) during hauling. The deepest recorded depth for seals entering the net during shooting was 190 m. The deepest recorded depth of seals during hauling was 130 m, which occurred during trawl 89 when three were caught in the net, indicating that more time may have been available for seals to interact with, or enter the net. No seals were observed outside the net during trawling (phase 4).

4. Discussion

This study represents a comprehensive analysis of seal–fishery operational interactions, although it is not exhaustive. During this study, the mean number of Australian fur seals observed at the fishing grounds was 4.6, which is within the broad range of South African fur seals observed from commercial hake trawlers in southern and western South African waters, where numbers typically ranged between 3 and 10 per count (Shaughnessy and Payne, 1979; Ryan and Moloney, 1988; Wickens et al., 1992). Mean fur seal numbers in this study increased during the day, between 0800 and 1000 h, then declined significantly as the day progressed. Comparable findings were recorded for the same fishery during 2001, when seal numbers peaked at 1100 h, although those calculations were based on pooled data across the factory trawler fleet (Tilzey et al., 2004).

4.1. *Variables influencing the numbers of seals at fishing vessels in general*

The final model for interpreting seal activity at the *FV Aoraki* in general identified swell height, visibility and barometric pressure to be the most important environmental variables. In particular, an increase in swell height and visibility and a decrease in barometric pressure, which combined constitute a general deterioration in weather conditions, were found to be correlated with an increase in seals observed at the surface from the vessel. Although wind strength was not included in the final model, a steady increase in seal numbers with wind strength was also noted and further supports this theory.

Visibility appeared to increase during deteriorated weather conditions, which may be responsible for the apparent rise in seal numbers observed at the surface (Wilkinson et al., 2003). Animals at greater distances would be more visible during clearer conditions and thus included in counts, compared with observations undertaken during calm conditions when sea mists enveloped the vessel more frequently. Alternatively, the rise in seal numbers during rough conditions may be due to a real influx of seals into the commercial fishing grounds. It is likely that seals attain a considerable energetic advantage by utilising shallow dives to forage from fishing gear, thus avoiding deep dives and the associated recovery time at the surface (Hückstädt and Antezana, 2003; Williams et al., 2004). Although untested, foraging from trawlers may be a particularly attractive option during rough weather, because foraging close to the benthos in shallow waters may become difficult due to reduced prey availability and increased turbidity (Dunstone and O'Connor, 1979). However, before causation can be attributed to this theory, the at-sea movements of Australian fur seals that forage in the region of this fishery need to be determined during fine and rough weather conditions.

Several operational variables were also found to be associated with the number of seals observed at the vessel. Seal numbers at the surface increased with the number of shots in the last 12 h, the number of vessels within 2 nautical miles and with declining distance from Reid Rocks breeding colony and Hibbs Point haul-out site. However, seal numbers declined when vessel speed increased above 5.6 km h^{-1} (3 knots), possibly influenced by the maximum swimming capacity of fur seals. The only published study of Australian fur seal swimming activity reported an average speed of 2.2 km h^{-1} (1.2 knots) over a 243 h period, although maximum sprint speeds and periods when the animal remained stationary were not taken into account (Hindell and Pemberton, 1997). Notwithstanding, an average optimal swimming speed of 7.2 km h^{-1} (3.9 knots) has been calculated for Antarctic fur seals (*A. gazella*) and Galápagos fur seals (*A. galapagoensis*) (Gentry et al., 1986; Williams and Worthy, 2002), indicating that Australian fur seals may be capable of faster speeds. Seals may also attain sprint speeds of up to 12.6 km h^{-1} (6.8 knots) over short distances (Williams and Kooyman, 1985; Williams and Worthy, 2002), which may partly explain why seals continued to be observed at higher vessel speeds. Alternatively, the vessel may have passed stationary seals and seals following other vessels nearby were also included in counts. Therefore, future studies may benefit from only counting seals that are in active pursuit of the vessel and within a prescribed distance.

The proximity of the vessel to Reid Rocks and Hibbs Point also influenced the number of seals observed, with a marked decline occurring with distance from Hibbs Point in particular (Fig. 4). In support of these findings, a recent study revealed that animals originating from Bass Strait breeding colonies and captured at the *FV Aoraki* (using a large, baited dip net) regularly use Hibbs Point as a haul-out site when the commercial blue grenadier season is operating (Simon Goldsworthy and Roger Kirkwood, unpublished data).

Previous studies provide conflicting findings with regard to the effect of distance to colonies on the number of animals observed. Similar to this study, seal numbers observed at salmon farms in south-eastern Tasmania in the early 1990s were shown to decline with increasing distance from haul-out sites (Pemberton and Shaughnessy, 1993). However, anecdotal reports suggest that this relationship later diminished as large numbers of seals became habituated to foraging in association with the salmon farms.

Contrary to this study, South American sea lions observed in a central Chilean fishery increased with distance to colonies (Hückstädt and Antezana, 2003). The authors indicated that the sea lions travelled to the most distant commercial fishing grounds due to a greater abundance of fish stocks, or greater opportunity to forage at those locations. This observation is consistent with the principle that a foraging predator should travel greater distances in search of food if those patches offer a net gain in energy above the added cost of getting there (Hassell and May, 1974; Krebs, 1978). In doing so, the individual should forage minimally in transit, which may explain why fewer animals were observed when closer to Reid Rocks, compared with Hibbs Point.

Seal numbers increased as the number of trawls in the previous 12 h (i.e. fishing intensity) increased. Factory trawlers operating in the South East Fishery are able to achieve continuity of processing operations and minimal spoiling of fish when approximately three trawls are conducted every 24 h (Tilzey et al., 2004). Notwithstanding, more trawls were conducted when less fish were caught per trawl, thus providing increased opportunities for seals to forage on the net in the upper water column.

As the numbers of vessels within 2 nautical miles increased, the number of seals also increased according to the final model, although graphical representation of this variable in isolation showed the contrary (Fig. 3g). More vessels may provide improved foraging opportunities for seals, thus adhering to the theories proposed by Stevens and Krebs (1986), which suggest that more seals should be present during times of increased fishing intensity. A similar trend occurred between South American sea lions and purse-seine vessels in Chile, although the relationship was not statistically significant (Hückstädt and Antezana, 2003).

4.2. *Variables influencing the numbers of seals at the surface during trawls*

Due to the foraging opportunities presented to seals during trawling operations, mean seal numbers observed increased from 4.6 during times when no fishing activity was taking place to 5.6 during trawls. The use of Generalised Linear Modelling for each phase of the trawl proved problematic, due to the short and variable time periods within each phase. In particular, the short amount of time taken to complete the three phases during shooting and three phases during hauling (as little as 5 min for each) made it difficult to interpret seal activity in response to the changes in operational state of the vessel. However, two operational variables included in the final models for each phase, namely trawl duration and haul speed, may be important for determining seal numbers present at fishing vessels in general during fishing.

Seal numbers increased significantly as the trawl progressed. The typically well developed directional hearing ability of fur seals (Gentry, 1967; Riedman, 1990) is likely to enable them to detect the low pitched noise produced by fishing vessels from considerable distances, particularly when the hydraulic pumps are in operation during fishing activity. This theory supports anecdotal evidence that Australian fur seals interacting with this fishery are attracted by distinctive sounds emitted by vessels during fishing operations (Tilzey et al., 2004).

The speed of the trawl net through the water as it was hauled from trawling depth was also important throughout trawl operations according to the models produced, with seal numbers typically decreasing as haul speed increased. Haul duration ranged from 5 to 15 min, thus providing marked variation in the time available for seals to arrive astern of the vessel. Assuming that Australian fur seals were capable of attaining swimming speeds of 7.2–12.6 km h^{-1} (3.9–6.8 knots) (Williams and Worthy, 2002), individual seals should have been able to cover between 600 and 3150 m for the combined range of hauling speeds and times recorded. Therefore, with less time available during faster hauls, fewer seals were able to reach the stern of the vessel.

The speed of the trawl net during hauling also appeared to influence the likelihood of seal by-catch. Haul speeds typically ranged between 3.3 and 8.0 km h^{-1} (1.8–4.3 knots) and it is likely that higher haul speeds make it more difficult for seals to outswim the net as it moves through the water column, thus increasing the probability of seals that are present inside the net becoming by-catch. Interestingly, on 4 of the 5 occasions when seals became by-catch during hauling, the haul speed was in excess of 7.2 km h^{-1} (minimum average fur seal swimming speed), while the remaining seal by-catch incident occurred when the net was hauled at 6.9 km h^{-1}. The importance of haul speed for determining seal by-catch has not been investigated prior to this study, although its potential importance has been acknowledged (Waring et al., 1990; Morizur et al., 1999; Shaughnessy et al., 2003).

4.2.1. *Seal numbers observed at the surface*

A significant reduction in seal numbers at the surface was observed during shooting, coinciding with the release of the trawl doors and the descent of the net below the surface (phase 3). Video footage confirmed that seals dived to forage on ‘stickers’ caught in the meshes of the descending trawl net from the previous trawl events. Although not addressed during this study, the removal of stickers (and the food source) may help to reduce the number of seals that put themselves at risk of becoming by-catch, because they would be less inclined to dive on the net to forage. Furthermore, the fishery endorsed *Code of Fishing Practice* recommends the removal of stickers, thus highlighting the need to review the effectiveness of sticker removal to assist in the reduction of interactions with seals. The occurrence of seals diving on trawl nets during net deployment has only been reported once before, for South African fur seals interacting with trawl fisheries, based on the advanced stage of rigor mortis of dead animals (Shaughnessy and Payne, 1979), rather than videographic confirmation.

Seal numbers also reduced significantly in phase 6 during hauling. This was preceded by seals congregating approximately 150m astern and in the wake of the vessel during phase 5, possibly in response to the markedly increased noise produced by the hydraulic trawl winches, which may act as an audio cue for seals to move to the position where the cod-end typically breaches the surface. Similar behaviour was noted for harp seals in the Grand Banks cod trawl fishery and was attributed to ‘prior learning’ that the net (and thus fish) would eventually surface at a specific distance astern of the vessel soon after the winches began operating (Pemberton et al., 1994). During phase 6, the trawl doors of the *FV Aoraki* (weighing approximately eight tonnes) were hauled out of the water, emitting a loud noise as they came into contact with the ‘bash plates’ at the stern of the vessel. The resultant audio cue likely signified that the ascending net was within the diving range of the seals, prompting synchronous diving on the net by the fur seals (again confirmed by video footage) and a reduction in the number of seals visible at the surface.

The mean depth of the headline (the top of the net mouth) was 96 m at the time of the audio cue, while the mean depth of all diving seals observed during hauling was 81 m. The depth difference indicates that seals did not typically reach the ascending net until shortly after the trawl doors were aboard, accounting for the time taken for the seals to leave the surface and reach the net. Pemberton et al. (1994) also noted that harp seals used the audio cue produced by trawl doors in a similar way, diving on the net in synchrony as the net ascended toward the surface during hauling.

4.2.2. *Fur seal by-catch*

All seal by-catch occurred during the day, even though about half the trawl events occurred at night. These findings are in accordance with the weakly inverted diurnal foraging patterns reported for Australian fur seals (Hindell and Pemberton, 1997; Arnould and Hindell, 2001). Most by-catch on the *FV Aoraki* occurred during the late afternoon, even though seal numbers were higher in the morning, suggesting that the numbers of seals observed on the surface may not reflect a direct relationship with seal by-catch. Thirteen fur seals were taken as by-catch, six of which were taken during shooting, confirming the assumption by Shaughnessy and Payne (1979) that seals are able to enter the net at the beginning of the trawl event. Mortality rates were significantly higher during shooting compared with hauling, with 6 seals dying during shooting, compared with only one during hauling, because seals caught at the end of the trawl event were able to breath through the net at the surface.

A similar by-catch incidence occurred between trawls with the seal exclusion device attached and those without, being 6 and 7 respectively. This result does not support findings by Tilzey et al. (2004) that seal exclusion devices reduced seal by-catch and mortalities by-catch by 6.9%, indicating that the current design may be ineffective, or unutilised by those seals entering the net. Instead, the low incidence of net entry by seals indicated in the video footage and the fact that only one seal was detected exiting the net without becoming by-catch during video monitored trawls suggests that a reduced incidence of net entry by seals, rather than successful escape through seal exclusion devices may explain a reduction in seal by-catch over the last few years. Notwithstanding, the incidence of net entry by seals and the number of trawls observed was low, making it difficult to quantitatively establish if these findings are truly representative.

4.3. Recommendations

These results highlight the need for additional modifications to fishing practices conducted by factory trawlers in this fishery. In particular, we recommend that commercial fishing activity cease during rough weather when seal numbers appear to be greatest, particularly if the number of seals observed at the surface is considered as a reliable surrogate indicator of the number of animals potentially interacting with the trawl net beneath the surface. A buffer zone that prohibits or restricts fishing activity within a specified proximity to Hibbs Point should also be considered as a precautionary approach, although it is impossible to determine from this investigation what an appropriate distance would be.

Even though a reduction in seal by-catch has been recorded in the factory trawler component of this fishery since 1999, attributing this to the introduction of seal exclusion devices seems unlikely considering that all but one net entry resulted in by-catch. During this study, the reduction in seal by-catch was more likely due to the a reduction in the incidence of seal–net interactions. Nonetheless, the seal exclusion device has become the principal seal by-catch mitigation tool on factory trawlers in the winter blue grenadier fishery and the possibility of introducing them to the wet-boat fleet in the South East Fishery has also been proposed (Knuckey et al., 2002). We recommend that further trials of seal exclusion devices effectiveness be conducted in conjunction with sub-surface video equipment, so that the incidence of net entry can be directly compared with seal by-catch and mortalities in order to calculate rates.

This study confirmed that seal by-catch mortality on the *FV Aoraki* also occurs during shooting and is likely to be representative of trawl fishing activity in the South East Fishery in general. Most previous studies have assumed that seal by-catch occurs exclusively during hauling, because seals are attracted to the catch at the end of the trawl event. While this study indicates that seals are equally as likely to become caught in the trawl net during shooting, the low incidence of by-catch recorded emphasises the need to continue investigating subsurface interactions. Nonetheless, we recommend that future research should also focus on seal by-catch reduction during shooting, by trialling devices that hold the net mouth closed until the net reaches the fishing depth.

This study suggests that seal by-catch is reduced when haul speeds are kept low, which contravenes the recommendation in the *Code of Fishing Practice*, that the net should be hauled as quickly as possible to reduce the time that it remains within the diving range of fur seals (South East Trawl Fishing Industry Association, 2000). The results of this study suggest that net hauling should be as fast as possible below the maximum dive depth of the seals (about 200 m) to reduce the length of time available for Australian fur seals to reach the vessel, but should then proceed at speeds that are slower that the minimum average swimming speeds for fur seals (about 7.2 km h^{-1}) to reduce the likelihood of seals becoming by-catch in the upper water column. In order to facilitate this hauling procedure, an improved method of determining net velocity through the water column is also necessary. However, changes to the *Code of Fishing Practice* would be unwise until a dedicated investigation of the relationship between haul speed and seal by-catch incidence is undertaken.

Acknowledgements

Firstly, our sincere thanks is extended to the Petuna Seafood/Sealord cooperative for permitting access to the *FV Aoraki* and also to Garry Courtney (master) and the crew for their assistance during the voyage. We also wish to thank Richard Tilzey (Bureau of Resource Sciences) for accommodating this work within a broader project aimed at mitigating seal by-catch in the same fishery. Thanks are also extended to Peter Shaughnessy, Roger Kirkwood and Martin Cawthorn for editing manuscripts and providing advice.

REFERENCES

Alverson, D.L., 1999. Some observations on the science of bycatch. Marine Technology Society Journal 33 (2), 6–12.

Alverson, D.L., Freeberg, M.H., Murawski, S.A., Pope, J.G., 1994. A global assessment of fisheries bycatch and discards, FAO Fisheries Technical Paper, vol. 339.

Arnould, J.P.Y., Hindell, M.A., 2001. Dive behaviour, foraging locations and maternal-attendance patterns of Australian fur seals (*Arctocephalus pusillus doriferus*). Canadian Journal of Zoology 79, 35–48.

Australian Fisheries Management Authority (AFMA), 1999. Australian South East Trawl Fishery: inquiry into incidental seal bycatch. Australian Fisheries Management Authority, Canberra. 21pp.

Bache, S.J., 2003. Marine wildlife bycatch mitigation: global trends, international action and the challenges for Australia. Ocean Publications, Wollongong.

Beverton, R.J.H., 1985. Analysis of marine mammal-fisheries interactions. In: Beddington, J.R., Beverton, R.J.H., Lavigne, D.M. (Eds.), Marine Mammals and Fisheries. George Allen and Unwin, Sydney.

Bunting, J., 2002. Draft bycatch action plan for the Shark Bay prawn managed fishery (full report). Fisheries Management Paper No. 147. Department of Fisheries, Government of Western Australia, April, 2002. 82pp.

Carbonell, A., Alemany, F., Merella, P., Quetglas, A., Román, E., 2003. The by-catch of sharks in the western Mediterranean (Baltic Islands) trawl fishery. Fisheries Research 61, 7–18.

Dunstone, N., O'Connor, R.J., 1979. Optimal foraging in the amphibious mammal. I. The aqualung effect. Animal Behaviour 27, 1182–1194.

Fraker, M.A., Mate, B.R, 1999. Seals, sea lions and salmon in the Pacific northwest. In: Twiss, J.R., Reeves, R.R. (Eds.), Conservation and management of marine mammals. Melbourne University Press, Melbourne.

Gentry, R.L., 1967. Underwater auditory localization in the California sea lion (*Zalophus californianus*). Journal of Auditory Research 7, 187–193.

Gentry, R.L., Costa, D.P., Croxall, J.P., David, J.H.M., Davis, R.W., Kooyman, G.L., Majluf, P., McCann, T.S., Trillmich, F., 1986. Synthesis and conclusions. In: Gentry, R.L., Kooyman, G.L. (Eds.), Fur seals: maternal strategies on land and at sea. Princeton University Press, Princeton.

Goldsworthy, S.D., Bulman, C., He, X., Larcombe, J., Littnan, C., 2003. Trophic interactions between marine mammals and Australian fisheries: an ecosystem approach. In: Gales, N.J., Hindell, M.A., Kirkwood, R. (Eds.), Marine Mammals: Fisheries, Tourism and Management Issues. CSIRO Publishing, Melbourne.

Hall, M.A., Alverson, D.L., Metuzals, K.I., 2000. By-catch: problems and solutions. Marine Pollution Bulletin 41, 204–219.

Hardy, I.C.W., 2002. Sex Ratios: concepts and research methods. Cambridge University Press, Cambridge.

Harris, A., Ward, P., 1999. Non-target Species in Australia's Commonwealth Fisheries: A Critical Review. Bureau of Rural Sciences, Canberra.

Hassell, M.P., May, R.M., 1974. Aggregation of predators and insect parasites and its effect on stability. Journal of Animal Ecology 43, 567–594.

Hindell, M.A., Pemberton, D., 1997. Successful use of a translocation program to investigate diving behavior in a male Australian fur seal, *Arctocephalus pusillus doriferus*. Marine Mammal Science 13 (2), 219–228.

Hückstädt, L.A., Antezana, T., 2003. Behaviour of the southern sea lion (*Otaria flavescens*) and consumption of the catch during purse-seining for jack mackerel (*Trachurus symmetricus*) off central Chile. Journal of Marine Science 60, 1003–1011.

Hückstädt, L.A., Krautz, M.C., 2004. Interaction between southern sea lions *Otaria flavescens* and jack mackerel *Trachurus symmetricus* commercial fishery off Central Chile: a geostatistical approach. Marine Ecology Progress Series 282, 285–294.

Knuckey, I.A., Eayrs, S., Bosschietter, B., 2002. Options for reducing incidental catch of seals on wet-boats in the SETF: a preliminary report. Marine and Freshwater Resources Institute. Report to the Australian Fisheries Management Authority. ARF Project R01/0887. 59pp.

Krebs, J.B., 1978. Optimal foraging: decision rules for predators. In: Krebs, J.B., Davies, N.B. (Eds.), Behavioral ecology: an evolutionary approach. Sinaur, Massachusetts.

Loughlin, T.R., Nelson, R., 1986. Incidental mortality of northern sea lions in the Shelikov Strait, Alaska. Marine Mammal Science 2, 14–33.

Manly, B.F.J., Seyb, A., Fletcher, D.J., 2002. Bycatch of fur seals (*Arctocephalus forsteri*) in New Zealand fisheries, 1990/91–1995/96, and observer coverage. Department of Conservation (DOC) Science Internal Series 41, Department of Conservartion, Wellington. 40pp.

Morizur, Y., Berrow, S.D., Tregenza, N.J.C., Couperus, A.S., Pouvereau, S., 1999. Incidental catches of marine-mammals in pelagic trawl fisheries of the northeast Atlantic. Fisheries Research 41, 297–307.

National Marine Fisheries Service (NMFS), 1992. Final recovery plan for Steller sea lions *Eumetopias jubatus*. National Marine Fisheries Service internal report, National Oceanic and Atmospheric Administration. Silver Spring, Maryland. 29pp.

Northridge, S.P., 1984. World review of interactions between marine mammals and fisheries. FAO Fisheries Technical Paper, vol. 251. 190pp.

Northridge, S.P., 1991. An updated world review of interactions between marine mammals and fisheries. FAO Fisheries Technical Paper, vol. 251(Suppl. 1). 58pp.

Northridge, S.P., Hofman, R.J., 1999. Marine mammal interactions with fisheries. In: Twiss, J.R., Reeves, R.R. (Eds.), Conservation and Management of Marine Mammals. Melbourne University Press, Melbourne.

Pemberton, D., Merdsoy, B., Gales, R., Renouf, D., 1994. The interaction between offshore cod trawlers and harp *Phoca groenlandica* and hooded *Cystophora cristata* seals off Newfoundland, Canada. Biological Conservation 68, 123–127.

Pemberton, D., Shaughnessy, P.D., 1993. Interaction between seals and marine fish-farms in Tasmania, and management of the problem. Aquatic Conservation 3, 149–158.

Quinn, G.P., Keough, M.J., 2002. Experimental Design and Data Analysis for Biologists. Cambridge University Press, Melbourne.

Riedman, M., 1990. The Pinnipeds: Seals, Sea Lions and Walruses. University of California Press, London.

Ryan, P.G., Moloney, C.L., 1988. Effect of trawling on bird and seal distributions in the southern Benguela region. Marine Ecology Progress Series 45 (1), 1–11.

Shaughnessy, P.D., 1985. Interactions between fisheries and Cape fur seals in southern Africa. In: Beddington, J.R., Beverton, R.J.H., Lavigne, D.M. (Eds.), Marine Mammals and Fisheries. George Allen and Unwin, Sydney.

Shaughnessy, P.D., Kirkwood, R., Cawthorn, M., Kemper, C., Pemberton, D., 2003. Pinnipeds, cetaceans and fisheries in Australia: a review of operational interactions. In: Gales, N.J., Hindell, M.A., Kirkwood, R. (Eds.), Marine Mammals: Fisheries, Tourism and Management Issues. CSIRO Publishing, Melbourne.

Shaughnessy, P.D., Payne, A.I.L., 1979. Incidental mortality of cape fur seals during trawl fishing activities in South African wasters. Fisheries Bulletin, South Africa 12, 20–24.

Smith, A.D.M., 1994. Blue grenadier *Macruronus novaezelandiae*. In: Tilzey, R.D.J. (Ed.), The South East Fishery: A Scientific Review with Reference to Quota Management. Bureau of Rural Sciences (BRS). Australian Government Publishing Service, Canberra.

South East Trawl Fishing Industry Association (SETFIA), 2000. Code of fishing practice to minimise incidental by-catch of marine mammals in the South East Trawl Fishery, South East Trawl Fishing Industry Association, Canberra. 16pp.

Stevens, D.W., Krebs, J.R, 1986. Foraging theory. Princeton University Press, Princeton.

Tilzey, R.D.J., 1994. Introduction. In: Tilzey, R.D.J. (Ed.), The South East Fishery: A Scientific Review with Regard to Quota Management. Bureau of Resource Science (BRS). Australian Government Publishing Service, Canberra.

Tilzey, R.D.J., 2002. Interim report to FRDC on seal exclusion device trials in the winter 2002 blue grenadier fishery program. Bureau of Resource Sciences (BRS), Canberra.

Tilzey, R.D.J., Goldsworthy, S.D., Cawthorn, M., Calvert, N., Hamer, D.J., Kirkwood, R., Russell, S., Shaughnessy, P.D., Wize, B., 2004. Assessment of seal–fishery interactions in the winter blue grenadier fishery off west Tasmania and the development of fishing practices and Seal Exclusion Devices to mitigate seal bycatch by factory trawlers. Report to the Fisheries Research and Development Corporation (FR & DC), Project no. 2001/008, May 2004. 61pp.

Waring, G.T., Gerior, P., Payne, M.P., Parry, B.L., Nicolas, J.R., 1990. Incidental take of marine mammals in foreign fishery activities off the northeast United States, 1977–1988. Fisheries Bulletin 88, 347–360.

Wickens, P., 1994. Interactions between South African fur seals and the purse-seine fishery. Marine Mammal Science 10, 442–457.

Wickens, P., 1995. A review of operational interactions between pinnipeds and fisheries. FAO Fisheries Technical Paper, vol. 346, 86pp.

Wickens, P., Japp, D.W., Shelton, P.A., Kriel, F., Goosen, P.C., Rose, B., Augustyn, C.J., Bross, C.A.R., Penney, A.J., Krohn, R.G., 1992. Seals and fisheries in South Africa – competition and conflict. South African Journal of Marine Science 12, 773–789.

Wilkinson, I., Burgess, J., Cawthorn, M., 2003. New Zealand sea lions and squid: managing impacts on a threatened marine mammal. In: Gales, N.J., Hindell, M.A., Kirkwood, R. (Eds.), Marine Mammals: Fisheries, Tourism and Management Issues. CSIRO Publishing, Melbourne.

Williams, T.M., Fuiman, L.A., Horning, M., Davis, R.W., 2004. The cost of foraging by a marine predator, the Weddell seal *Leptonychotes weddellii*: pricing by the stroke. Journal of Experimental Biology 207 (6), 973–982.

Williams, T.M., Kooyman, G.L., 1985. Swimming performance and hydrodynamic characteristics of harbor seals *Phoca vitulina*. Physiological Zoology 58, 576–589.

Williams, T.M., Worthy, G.A.J., 2002. Anatomy and physiology: the challenge of aquatic living. In: Hoelzel, A.R. (Ed.), Marine Mammal Biology. Blackwell Publishing, Oxford.

Woodley, T.H., Lavigne, D.M., 1991. The incidental capture of pinnipeds in commercial fishing gear. International Marine Mammal Association Inc., Technical Report 91–01. 51pp.