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The endangered Australian sea lion extensively overlaps with and regularly becomes by-catch in demersal shark gill-nets in South Australian shelf waters

D.J. Hamer [a,b,*], S.D. Goldsworthy [b,c], D.P. Costa [d], S.L. Fowler [d], B. Page [c], M.D. Sumner [e]

[a] Australian Marine Mammal Centre, Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050, Australia
[b] Earth and Environmental Sciences, University of Adelaide, North Terrace, Adelaide, South Australia 5000, Australia
[c] South Australian Research and Development Institute – Aquatic Sciences, 2 Hamra Avenue, West Beach, South Australia 5024, Australia
[d] Ecology and Evolutionary Biology, University of California, 100 Shaffer Road, Santa Cruz, CA 95060, USA
[e] School of Zoology, University of Tasmania, Churchill Avenue, Hobart, Tasmania 7005, Australia

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A B S T R A C T

Australian sea lions (*Neophoca cinerea*) have typically small breeding colonies, many of which are genetically distinct populations due to female philopatry (i.e. breeding site fidelity). This situation may increase the vulnerability of the species to decline when anthropogenic influences increase levels of mortality, even by small amounts. Anecdotal reports from South Australian shelf waters suggest Australian sea lions become by-caught and drown in demersal gill-nets used to catch sharks, or escape with life threatening entanglements. This study explored the potential impact of the operational interaction by estimating the (i) extent of geographic overlap and (ii) level of by-catch. Monitoring of Australian sea lion at-sea movements and of the demersal gill-net fishery confirmed spatial overlap between the two in 68.7% of 4 km^2 grid cells across South Australian shelf waters and by-catch of 283–333 Australian sea lions each breeding cycle (193–227 each year). Recent changes to the management arrangements of demersal gill-netting in South Australian shelf waters are likely to have improved the situation for Australian sea lions, although it may be necessary to further refine aspects relating to (i) the effectiveness of untested electronic fishery monitoring methods, (ii) the efficacy of relatively small permanent fishery closures around breeding colonies and (iii) the efficiency in receiving, processing and responding to by-catch reports to ensure by-catch limits are not exceeded. Long-term monitoring at representative breeding colonies would be useful for determining if and where research and management should be prioritised. A recent report suggests a similar problem may exist in Western Australia, where approximately 14% of the species resides.

1. Introduction

A growing body of research conducted since the early 1990s indicates that Australian sea lions (*Neophoca cinerea*) have low fecundity and their breeding colonies are typically small and unlikely to receive female immigrants due to philopatry (Higgins, 1993; Gales et al., 1994; Gales and Costa, 1997; Goldsworthy et al., 2009; Lowther et al., 2012). These characteristics may increase the species vulnerability to decline or extinction when even small increases to the level of mortality occur (Caughley, 1994; Goldsworthy et al., 2010; Hamer et al., 2011). Since the late 1960s, a demersal gill-net fishery has operated along the southern Australian coastline (BRS, 2004; Walker et al., 2005), overlapping with Australian sea lions most apparently in waters adjacent to South Australia (SA) where the greater proportion of the species resides and forages (Fowler et al., 2007; Hamer et al., 2011; Woodhams et al., 2011; DSEWPaC, 2012a). Available reports suggest that Australian sea lions may become by-caught and drown, or occasionally become entangled and eventually succumb from related injuries (Shaughnessy et al., 2003; Page et al., 2004; Goldsworthy et al., 2010; Hamer et al., 2011). The nature, extent and impact of these events remain unclear, thus providing the impetus for this study.

1.1. Pinniped by-catch: a global perspective

Since the 1960s, the Southern Ocean has witnessed the recovery and expansion of many pinniped populations, due to the widespread cessation of commercial sealing by the mid 1800s (e.g. Taylor, 1982; Roux, 1987; Wickens, 1995; Kirkwood et al., 2010).

* Corresponding author at: Australian Marine Mammal Centre, Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050, Australia. Tel.: +61 3 6232 3357.
E-mail address: derek.hamer@aad.gov.au (D.J. Hamer).

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Commercial fishing effort has also expanded during the same period, due to advancements in fishing technology and increased demand for fish (FAO, 2009; UN, 2009). Consequently, increased overlap between these two marine consumers has resulted in the increased occurrence of direct or 'operational interactions' (e.g. Beverton, 1985; Woodley and Lavigne, 1991; Pemberton et al., 1994; Wickens, 1995; Northridge and Hofman, 1999; Hückstädt and Antezana, 2003; Shaughnessy et al., 2003; Hamer and Goldsworthy, 2006; Hamer et al., 2011). These events occur when marine mammals come into direct or close contact with fishing gear, either intentionally when depredating caught fish, or accidentally when foraging naturally (Northridge and Hofman, 1999; Shaughnessy et al., 2003; Read, 2005).

Pinnipeds may benefit energetically from depredating fish caught in the fishing gear, although they may also become by-caught and drown when doing so (Northridge and Hofman, 1999; Hamer and Goldsworthy, 2006), or may escape with life threatening entanglements from which they later succumb (Fowler et al., 1990; Page et al., 2004). The occurrence of these events in demersal gill-nets is widespread and may be the greatest contemporary anthropogenic threat to pinnipeds (Woodley and Lavigne, 1991; Wickens, 1995; Read et al., 2006; Read, 2008). In California, two gill-net fisheries have reported by-catch of four pinniped species (Californian sea lion *Zalophus californianus*, Steller sea lions *Eumetopias jubatus*, harbour seal *Phoca vitulina* and northern elephant seal *Mirounga angustirostris*; Julian and Beeson, 1998). A recent study estimated 98% of all pinniped by-catch in the United States of America (USA) commercial fisheries occurs in gill-nets (Read et al., 2006), while another estimated 9% of all California sea lions at one Mexican breeding colony exhibited gill-net entanglements (Aurioles-Gamboa et al., 2003).

Despite widespread occurrence of operational interactions between pinnipeds and fisheries, there have been few attempts to address the problem. Trawl fisheries have received some attention, with New Zealand sea lion (*Phocarctos hookeri*) by-catch mitigated to some extent by applying by-catch limits and temporary closures (Wilkinson et al., 2003), and Australian fur seal (*Arctocephalus pusillus doriferus*) by-catch mitigated by moving away when individuals were observed near the vessel and by including gear modifications (Tilzey et al., 2004; Hamer and Goldsworthy, 2006). One lobster trap fishery attempted to mitigate Australian sea lion by-catch by mandating the use of exclusion devices in some areas where the species foraged (Campbell et al., 2008). The apparent lack of effort committed to mitigating the impact of by-catch on marine mammals more widely may be in part due to resistance between the two main stakeholders, with conservationists aiming to protect marine mammals at the expense of the fisheries involved and fisheries aiming to exploit marine resources at the expense of other marine consumers. To date, there are few examples demonstrating a capacity or willingness to adopt a bipartisan approach.

1.2. Impact of demersal gill-nets on Australian sea lions

A demersal gill-net fishery has operated along the southern Australian coastline since the late 1960s, targeting benthic dwelling gummy shark (*Mustelus antarcticus*) and school shark (*Galeorhinus galeus*; BRS, 2004; Walker et al. 2005). The method used has remained virtually unchanged since its inception, with monofilament polypropylene gill-net hung between a weighted foot rope that holds it stationary on the benthos and a floated headline that holds it upright in the water column (Hamer et al., 2011). In waters adjacent to SA, Demersal gill-netting is managed by the Australian Fisheries Management Authority (AFMA) in state waters (i.e. from the coastline out to 5.56 km or 3 nm, under a bilateral agreement with the SA Government) and Australian Government waters (i.e. from 5.56 km out to a maximum depth of 183 m, pursuant to the management arrangements of the fishery), from the SA and Western Australian (WA) boarder, to the Victorian and New South Wales (NSW) border (AFMA, 2010; Woodhams et al., 2011). Waters adjacent to SA are particularly important to the fishery, with approximately 40% of effort by km of gill-net hauled occurring there in 2010 (Goldsworthy et al., 2010; Woodhams et al., 2011).

The same waters are also important for the Australian sea lion, with approximately 86% of the species by numbers of individuals and 63% by numbers of colonies residing there (Goldsworthy et al., 2009). This species is unique when compared with other pinnipeds, firstly by having slow maturation and extended breeding cycles of 17.4–17.8 months, that reduce overall fecundity by approximately 30% (Higgins, 1993; Gales et al., 1994; Gales and Costa, 1997). Secondly, colonies are generally small, with 66% of all breeding colonies in SA producing less than 30 pups. Thirdly, females exhibit philopatry, breeding exclusively at their own place of birth and thus unable to facilitate immigration at other sites, which may explain why many breeding colonies or clusters of breeding colonies are genetically distinct (Campbell et al., 2007; Lowther et al., 2012). These characteristics may increase the species vulnerability to decline or extinction when even small and unnatural increases in levels of mortality occur (Caughley, 1994; Goldsworthy et al., 2010; Hamer et al., 2011; Davidson et al., 2012).

Australia is home to three pinniped species (i.e. Australian fur seal, New Zealand fur seal *Arctocephalus forsteri* and Australian sea lion), all of which have had operational interactions with demersal gill-nets (Shaughnessy et al., 2003). A study during the early 1990s in Tasmania (Australia) found that 15% of entanglements on Australian fur seals involved demersal gill-net material (Pemberton et al., 1992). Entangled individuals may have been attracted to the benthic fish caught in the gill-nets that naturally occur in their diet (Arnould and Kirkwood, 2007; Deagle et al., 2009). During the early 2000s at Kangaroo Is (SA), 1% of entanglements observed on New Zealand fur seals involved demersal gill-net material (Page et al., 2004). The seemingly low incidence of entanglement may be reflect the pelagic foraging habit of the species (Baylis et al., 2008). In contrast, Australian sea lions are known to forage almost exclusively at or near the sea floor, mostly on benthic prey (Costa and Gales, 2003; Fowler et al., 2006). This may explain why the Kangaroo Is study found 55% of entanglements on Australian sea lions involved demersal gill-nets (Page et al., 2004). Given the severity of the wounds resulting from entanglement in demersal gill-nets and the low probability that the material would break away naturally (Peter Shaughnessy, personal communication), an estimated 36 Australian sea lions are likely to die from related injuries each year (modified from Page et al., 2004).

The impact of Australian sea lion by-catch in demersal gill-nets may be evident in population trends at some breeding colonies. Population growth at the Dangerous Reef breeding colony in Spencer Gulf (SA) increased from 0.6% each breeding cycle between 1975 and 2002 to 4.8% each breeding cycle between 2002 and 2007, after a moratorium of shark fishing was issued there in 2001 (SA Government Gazette, 22 March 2001, page 1060–1061; SA Government Gazette, 2 May 2001, page 1703). The Seal Bay population, which is close to an area where demersal gill-netting effort is high, declined at 1.1% each breeding cycle between 1985 and 2003 (Shaughnessy et al., 2006). These examples indicate that Australian sea lion populations are sensitive to the presence of demersal gill-netting activities, namely to the additional losses of individuals due to by-catch.

The empirical history of Australian sea lion by-catch in demersal gill-nets has been difficult to determine, because it was not mandatory to record such interactions prior to the enactment of the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) in 2000 (administered by the Australian Government Department of Sustainability, Environment, Water, Population and Communities; DSEWPaC). Nonetheless, gill-netting logbook records obtained for the years 2000 to 2007 for the area adjacent to the SA coastline contain records for only 10 drowned seals of unspecified species (Hamer, 2007). This low incidence contrasts with two anecdotal reports that suggest high levels of by-catch by individual gill-netters, one of 20 animals being by-caught each year during the 1990s in southeast SA (Shaughnessy et al., 2003) and the other of about 12 being by-caught during 2010 (Adelaide Now, 2011). A recent independent study, conducted prior to the present study, reported that 7–17 female Australian sea lions residing at Bunda Cliffs (western coastline of SA) were by-caught and drowned in demersal gill-nets set in and adjacent to the Great Australian Bight Marine Park (GABMP) each breeding cycle, with only an estimated 13 needed to suffer this fate before population decline would be imminent (Hamer et al., 2011). Therefore, by-catch of Australian sea lions in demersal gill-nets is likely to occur regularly and be geographically widespread.

1.3. Protection measures for Australian sea lions

Partial legal protection for Australian sea lions first occurred in WA in 1892 and in SA in 1919, although unregulated killing for skins and for fish bait continued into the 1970s (Thiele, 1979; Ling, 1999; Shaughnessy, 1999). Currently, Australian sea lions are listed as ‘Vulnerable’ under the SA *National Parks and Wildlife Act 1972* (SADEH, 2011) and as ‘Specially Protected’ under the WA *Wildlife Conservation Act 1950* (WA Government Gazette, 17 February 2012, page 746), forming the basis for protection inside state waters, where all breeding colonies are located. In response to growing concerns about the impact of entanglement and by-catch in demersal gill-nets in SA and adjacent Commonwealth waters, the Australian Government listed the species as ‘Vulnerable’ pursuant to the EPBC Act in 2005 and the International Union for the Conservation of Nature (IUCN) included the species as ‘Endangered’ on the Red List of Threatened Species in 2008 (Goldsworthy and Gales, 2008). Pursuant to the EPBC Act, DSEWPaC must facilitate a recovery plan for a Vulnerable species, identifying priorities and actions for mitigating the impacts of the threatening processes, or activities (DSEWPaC, 2012b).

All major fisheries in Australia are required, pursuant to the EPBC Act, to obtain a conditional Wildlife Trade Operation (WTO) permit to harvest a native fish species and thus are also required to minimise impacts on the marine environment when doing so. Renewal of the WTO permit is dependent on the permitted fishery lodging a mandated environmental assessment (EA) and on addressed recommendations arising during the previous permit period. The demersal gill-net fishery in southern Australia is part of the broader Southern and Eastern Scalefish and Shark Fishery (SESSF), which conducted its first EA in 2003. The EA highlighted the potential for operational interactions between Australian sea lions and demersal gill-netting, prompting DSEWPaC to recommend that AFMA (i) ‘‘establish a robust reporting system’’ and (ii) ‘‘if necessary, trial and implement appropriate mitigation measures such as spatial closures’’ (DEH, 2003). Based on emerging information, in 2010 DSEWPaC released new conditions on the then current WTO permit. Condition 6b required AFMA to ‘‘implement long-term management measures, including formal closures and other actions, that lead to a significant reduction of the impact of fishing activity on Australian sea lions. These measures [should] be clearly directed towards enabling recovery of the species, including all subpopulations’’ (Australian Commonwealth Government Gazette, 19 February 2010, page 1–4).

Mitigating the impact of demersal gill-nets on Australian sea lions could be facilitated by reducing the degree of spatial overlap between the two, namely by implementing spatial closures or marine protected areas (MPAs), thus excluding demersal gill-netting in areas of critical habitat for Australian sea lions. A number of MPAs in SA and adjacent Australian waters offer some protection to Australian sea lions. The GABMP, proclaimed in 1998, is the largest MPA along the SA coastline and extends up to 21 km seaward from Bunda Cliffs (Hamer et al., 2011). The remaining MPAs, such as the one adjacent to Seal Bay and proclaimed in 2009, extend only 5.6 km out to sea (DENR, 2009). These coastal MPAs are unlikely to provide adequate protection to resident Australian sea lions, because recent tracking studies indicate that females forage much further offshore at distances of 77–193 km from their home colonies (Fowler et al., 2007; Hamer et al., 2011).

1.4. Aims of this study

The available evidence suggests that Australian sea lions regularly become by-caught and drown in demersal gill-nets in areas where the two physically overlap. This phenomenon may threaten the conservation of Australian sea lion populations. As such, the use of satellite telemetry to determine the movements of pinnipeds (e.g. Baylis et al., 2008; Hamer et al., 2011) and of observers to monitor the movements and activities of commercial fishing vessels (e.g. Bastardie et al., 2010) could assist in quantifying levels of overlap and by-catch, which could ultimately be used by managers seeking to conserve Australian sea lions. Therefore, this study aimed to estimate (i) the spatial distribution and geographic overlap between Australian sea lions and the demersal gill-net fishery from satellite telemetry and fishery logbooks and (ii) the level of Australian sea lion by-catch by monitoring demersal gill-net fishery activities.

2. Methods

2.1. Australian sea lion foraging effort

The at-sea movements of adult female Australian sea lions were determined at 16 of 48 known breeding colonies across waters adjacent to the SA coastline (Fig. 1). Desirable attributes of the selected breeding colonies (SBCs) included relative ease of access and broad geographic spread across the species range. Sexually mature females were the focus of the foraging study, because they produce offspring and exhibit philopatry and thus are directly linked to the sustainability or vulnerability of populations.

To facilitate deployment of satellite linked platform transmission terminals (PTTs; Mark I and II, Sirtrack, Havelock North, New Zealand), females were captured and restrained using a purpose built cone-shaped net, then sedated with isoflorane (Isoflo™, Veterinary Companies of Australia, Artarmon, New South Wales, Australia) delivered with oxygen via a vaporiser (Cyprane Tec III, Advanced Anaesthetic Specialists, Melbourne, Victoria, Australia). A PTT was placed along the mid-dorsal line 10 cm posterior of the fore-flipper pits and attached to guard hairs using rapid curing two part epoxy adhesive. Devcon 5 Minute® (ITW Devcon, Massachusetts, USA) was used at Seal Bay and Araldite® 2017 (Huntsman Advanced Materials, Basel, Switzerland) was used at all other SBCs.

Location data were obtained from Services Argos Inc (Toulouse, France). Class A, B and Z locations were removed from the dataset prior to analysis due to their inaccuracy (following: Sterling and Ream, 2004; Costa et al., 2010). In addition, data linked to locations within 1 km of the ‘home’ colony were excluded to account for error margins and the potential inclusion of resting animals, thus confining analyses to at-sea positions only. The remaining data were redistributed into 1 km^2 grid cells across SA shelf waters using specifically written script (*timeTrack* and *trip*) for use in the software package R (Version 2.3.0, R Foundation for Statistical Computing, Vienna, Austria). For this study, shelf waters adjacent

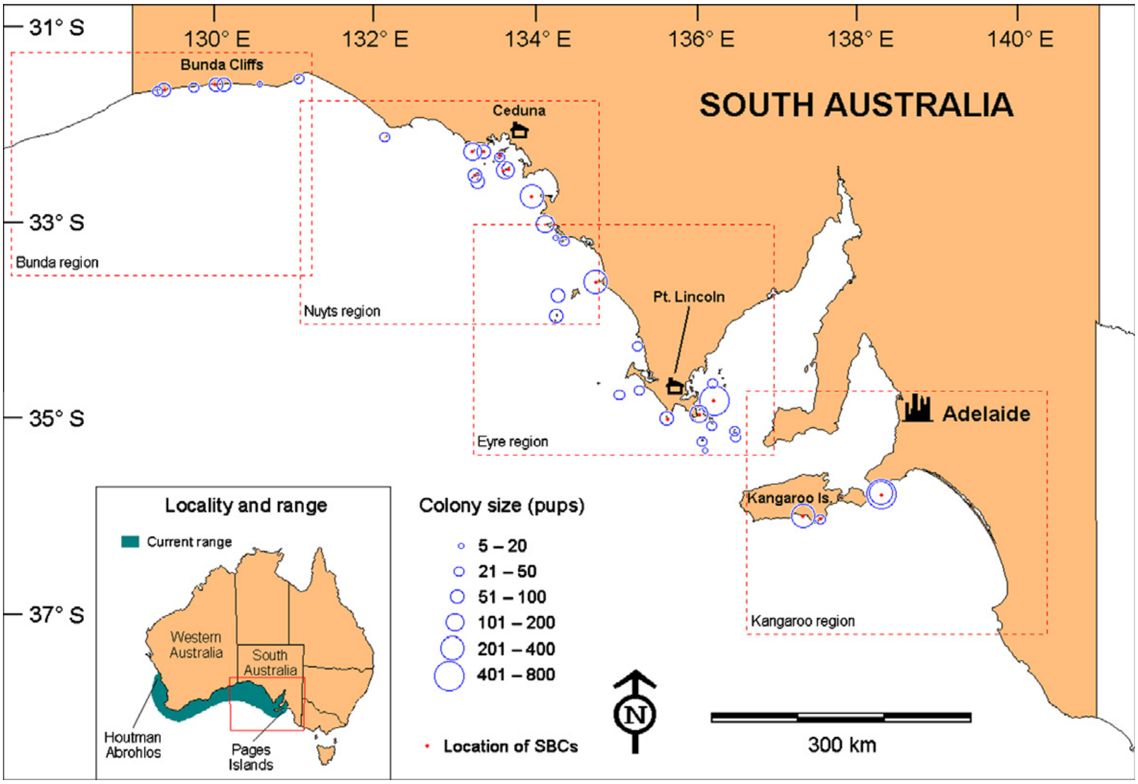

Fig. 1. *Location map*. Showing the (i) overall range of Australian sea lions (insert, green area), (ii) location and numbers of pups at known breeding sites in South Australian shelf waters (blue circles), (iii) the 16 selected breeding colonies (SBCs) that were the focus of this study (red dots) and (iv) four regions referred to in this study (red dashed boxes). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to the SA coastline are referred to as 'SA shelf waters' and defined as those waters under SA Government jurisdiction (i.e. from the coastline out to 5.6 km offshore) and those under Australian Government jurisdiction (from 5.6 km seaward to 183 m), collectively covering approximately 178,000 km^2.

The resulting values were then used to calculate the overall proportion of foraging effort in each 1 km^2 grid cell for each individual, then standardised by determining the fractional contribution of (i) each tracked individual to the overall tracking time calculated for all tracked individuals from an SBC, (ii) each SBC to the overall tracking time calculated for all SBCs and (iii) each SBC to overall pup abundance in SA shelf waters. Analysis of these values was facilitated using MapInfo Professional® and Vertical Mapper® (Versions 9.0 and 2.5, respectively, MapInfo Corporation, New York, USA) and the interpolation function (i.e. triangulation with smoothing) was used to identify areas of high, intermediate and low foraging effort.

For greater clarity, the results were presented in maps across four broad regions, referred to in this study as Bunda, Nuyts, Eyre and Kangaroo, based on geographically distinguishable regions containing clusters of breeding colonies (Fig. 1). For each SBC, summaries were presented for mean foraging distance (based on the straight line distance between each recorded location received for each tracked individual and the location of its associated SBC), mean maximum foraging distance (MMFD; based on the straight line distance between the furthest recorded location of each foraging trip received for each tracked individual and the location of its associated SBC) and mean direction of travel (based on the direction of the location of each tracked individual recorded closest to midday each day). In addition, the percentage of time spent in SA waters, in adjacent Australian waters and in each AFMA Marine Fishery Area (MFA; effectively degree by degree cells) was calculated. Effort has traditionally been recorded by MFA, thus calculations were additionally made at this coarser scale to provide fishery related context.

2.2. Demersal gill-net fishing effort

Shark gill-net fishing effort data were obtained from AFMA logbooks between 1 January 2000 and 31 December 2008. Prior to 1 July 2007, shark gill-net fishers recorded the location of fishing events by MFA. After that time, it became mandatory to more accurately record location by degrees and minutes (for latitude and longitude), although this has mostly occurred since 1 January 2006. As such, the location-based fishing effort for the 3 year period between 1 January 2006 and 31 December 2008 were used to determine areas of high, intermediate and low gill-netting effort across SA shelf waters, using MapInfo Professional® and Vertical Mapper®. This was done at an aggregated 4 km^2 grid cell scale, to account for the 1.8 km error in all directions caused by the prevalent absence of the geographic *second* value in the spatial component of the fishery logbook data. Additionally, to maintain an agreed level of commercial confidentiality in locations where the number of fishing events or fishing effort inside a given MFA was low (which occurred several times in the Bunda region), the location of fishing events was centralised to the nearest 6 min central node (i.e. one tenth of a degree). While the metric for recording Australian sea lion foraging effort was time, most of the fishery effort data recorded between 1 January 2006 and 31 December 2008 was recorded by event. Although the 'soak time' (i.e. the amount of time that the gill-net is in the water during each fishing event) could have been standardised for each event and thus made proportional to the number of fishing events, this was deemed unwise (thus not attempted), due to the wide variation in fishing strategies known to be in use in the fishery.

2.3. Overlap and by-catch estimates

The level of geographic overlap between tracked Australian sea lions and demersal gill-netting activities was calculated by multiplying the proportion of time spent by Australian sea lions by the proportion of km of gill-net set in the aggregated 4 km^2 grid cells. The results were used to calculate the percentage of cells utilised by both Australian sea lions and shark gill-netters, thus providing a simplistic indication of spatial overlap, without an index of relative effort. Based on available dive data (Costa and Gales, 2003; (Fowler et al., 2006; Goldsworthy et al., 2010), it was assumed that all of the adult females tracked had the capacity to dive to and forage on the sea floor across all SA shelf waters, thus had the potential to encounter demersal gill-nets in all the areas they visited.

Independent scientific observers accompanied demersal gill-net vessels in SA shelf waters between 1 January 2006 and 31 December 2007 to monitor fishing activities. The observers employed a novel technique described in Hamer et al. (2011) of vigilantly observing from outboard of the gunwale, as the net was hauled through the upper several metres of the water column to the surface and then onto the net roller. Specifically, records included the time and location the gear was hauled at the end of a fishing event, the number Australian sea lions by-caught and drowned in the gill-net and the number that dropped out before being hauled aboard. Where possible, the age and gender of the by-caught individual was determined by inspecting the genitalia, size and pelage colouration. The colour of the gill-net in which by-caught individuals were caught was also recorded.

The observed by-catch mortality rate for Australian sea lions was calculated by dividing the number of individuals observed drowned by the number of km of gill-net that were observed hauled. The estimated number of Australian sea lions drowned in demersal gill-nets was then calculated by multiplying the observed by-catch mortality rate by overall gill-net effort across SA shelf waters for the two calendar years, then halved to obtain the number for one calendar year. The number was then multiplied by 1.47 to obtain an estimate for a nominal 17.6 month breeding cycle. The standard error of the annual and cyclic by-catch estimates (SEE) was then calculated to deal with the uncertainty resulting from the likely low level of observer effort. This was calculated as:

$$SEE = \sqrt{1 - \left(\frac{observer\ effort}{fishing\ effort}\right)} \bullet observed\ mortalities \quad (1)$$

where the square root of one minus the sample fraction, based on kilometres of gill-net set, was multiplied by the number of observed mortalities. To achieve 95% confidence that the upper and lower level of the two by-catch estimates were accurate, the SEE was multiplied by two to reflect two standard deviations (Cochrane, 1977).

3. Results

3.1. Australian sea lion foraging effort

A total of 115 adult female Australian sea lions was tracked from the 16 SBCs (1.8% of the total number at SA breeding colonies), yielding 4590 days (individual: $\tilde{x} = 39.9$; SD = 54.0) of tracking information. Nine animals from two SBCs in the Bunda region were tracked for 1264 days (individual: $\tilde{x} = 140.4$; SD = 119.6), 41 from seven SBCs in the Nuyts region were tracked for 1500 days (individual: $\tilde{x} = 36.6$; SD = 37.5), 25 from four SBCs in the Eyre region were tracked for 714 days (individual: $\tilde{x} = 28.6$; SD = 20.5) and 40 from three SBCs in the Kangaroo region were tracked for 1112 days (individual: $\tilde{x} = 27.8$; SD = 36.3).

The MMFDs achieved by tracked animals varied widely, from 28 ± 18 km at Lewis Is to 189 ± 25 km at Bunda-8 (Table 1). The direction of travel generally ranged between south-westerly and south-easterly, with the exception of South Pages Is where some individuals travelled in a north-westerly direction (Figs. 2a, 3a, 4a and 5aa). The percentage of time spent in each MFA visited by tracked animals also varied widely, with MFA-108 being the most utilised at 86.1% after standardisation of tracking effort (Table 2). In summary, tracked animals foraged in 20 of the 29 MFAs and across 27.9% of the 4 km^2 grid cells in SA shelf waters (26.9% of SA waters and 28.3% of Commonwealth waters).

3.2. Demersal gill-net fishing effort

Over the 9 years between 2000 and 2008, 153,800 km of shark gill-net was set, with effort in all 29 MFAs across SA shelf waters, amounting to an annual average of 17,089 km (SD = 2238). Higher levels of effort occurred along the west coast of the Eyre Peninsula in MFAs 108 and 115 (12.2%) and to the south-east of Kangaroo Is in MFAs 150 and 151 (30.4%; Fig. 6). The least effort occurred within Spencer Gulf (in MFAs 122, 129 and 132) and in Gulf St Vincent (MFA 136; 0.7% collectively), where shark gill-netting has been banned since 2001. During the 3 years between 2006 and 2008, when the more accurate location data were collected, a total of 52,064 km of demersal gill-net was deployed, amounting to an annual average of 17,354 km (SD = 852). Based on the more recent and more accurate data, higher levels of effort occurred south of Bunda Cliffs, along the west coast of the Eyre Peninsula and to the south-east of Kangaroo Is (Figs. 2b, 3b, 4b and 5b).

3.3. Overlap and by-catch estimates

There was considerable overlap of Australian sea lion foraging effort and shark gill-netting effort in all four regions across SA shelf waters. In the Bunda region, the greatest level of overlap occurred offshore around 130°E, where MFAs 101, 102, 104 and 105 intersect (Fig. 2c). In the Nuyts region, overlap was more widespread and occurred throughout most of the islands of the Nuyts Archipelago, across MFAs 107, 108 and 114 (Fig. 3c). In the Eyre region, overlap was patchier and occurred in MFAs 115, 126 and 138 (Fig. 4c). In the Kangaroo region, extensive overlap occurred throughout waters to the south and south-east of Kangaroo Is, in MFAs 149 and 150 (Fig. 5c). Overall, Australian sea lion foraging effort and shark gill-net fishing effort overlapped in 68.7% of the 4 km^2 grid cells across SA shelf waters.

Observer data were collected over 146 days at sea across SA shelf waters between 1 January 2006 and 31 December 2007. A total of 994.4 km of gill-net was observed hauled (from 234 fishing events), which equates to 2.9% of the combined length of gill-nets set across SA shelf waters during the 2 year monitoring period. Twelve Australian sea lions were observed by-caught and drowned during that period, equating to an overall by-catch rate of 0.01207 individuals per km of gill-net (or 0.05128 per fishing event). Therefore, based on the calculated annual fishing effort of 17,355 ± 852 km of deployed gear recorded in fishery logbooks and taking the SEE into account, an estimated 193–227 Australian sea lions drowned annually in demersal gill-nets across SA shelf waters during the study period, or 283–333 each 17.6 month breeding cycle. The gender of 10 of the by-caught individuals was determined, with 90% being females. As such, an estimated 174–204 females were by-caught annually, or 255–299 each breeding cycle.

The mean distance of the 12 observed by-catch mortalities to the nearest breeding colony was 12.6 km (SD = 13.8), with nine occurring within 10 km. Four occurred in the Bunda region, with

Table 1
The location, mean maximum foraging distance (MMFD) and mean direction travelled by 115 adult female Australian sea lions tracked from 16 selected breeding colonies (SBCs) across South Australian (SA) shelf waters, by region and by colony.

	Regions															
	Bunda		Nuyts							Eyre				Kangaroo		
	Bunda-8	Bunda-5	Purdie	West	Lounds	Breakwater	East Franklin[a]	South Franklin[b]	Olive	West Waldegrave	Liguanea	Lewis	Dangerous	Seal Bay	Seal Slide	South Page
Colony location																
Latitude (dec. °)	31.640°S	31.585°S	32.270°S	32.511°S	32.273°S	32.322°S	32.449°S	32.462°S	32.719°S	33.596°S	34.998°S	34.957°S	34.817°S	35.997°S	36.026°S	35.777°S
Longitude (dec. °)	129.381°E	130.031°E	133.228°E	133.251°E	133.366°E	133.561°E	133.669°E	133.639°E	133.970°E	134.762°E	135.620°E	136.032°E	136.217°E	137.327°E	137.536°E	138.292°E
Foraging summary																
MMFD (km)	189	67	64	39	33	35	32	108	48	49	28	30	28	67	59	98
MMFD SD	25	11	27	27	29	11	14	38	27	23	18	3	13	15	42	30
Mean dir. (° true)	206	185	247	162	99	199	138	197	128	186	189	237	179	171	98	248
Mean dir. SD	22	18	26	66	53	110	88	27	79	90	65	38	38	25	28	59

[a] Officially named Lilliput Is in 2008.
[b] Officially named Blefuscu Is in 2008.

three close to breeding colonies at Bunda Cliffs and one 46.3 km to the south (Fig. 2c). Eight occurred in the Nuyts and Eyre regions, with six close to breeding colonies and two 20.4 km and 32.6 km away (Fig. 3c, 4c).

Ten of the 12 by-caught individuals dropped out of the gill-net before they were hauled aboard the vessel, either as they ascended above the waterline, or as they made contact with the net roller. The two individuals brought aboard the vessel were small juveniles, suggesting the weight of the 10 larger individuals increased the probability of structural failure of the meshes in the gill-net. Seven of the by-caught individuals occurred in green gill-net, four occurred in pink gill-net and one occurred in white gill-net, being 58.3%, 33.3% and 8.4%, respectively. Unfortunately fishers were not required by AFMA to record the colour of the gill-net they deployed in their log books, thus it was not possible to determine its relationship with the likelihood of by-catch.

4. Discussion

4.1. Widespread at sea distribution of Australian sea lions

The satellite tracking of adult female Australian sea lions reported in this study represents the most comprehensive investigation of at-sea behaviour of the species to date. Specifically, this study involved 1.8% of adult females from 16 of the 48 breeding locations in SA waters, across approximately 1,100 km of coastline from near the boarder with WA at Bunda Cliffs to the eastern end of the species range at South Page Is. At sea effort was geographically widespread, covering 27.9% of the approximately 178,000 km^2 area of SA shelf waters, as defined in this study. The extensive utilisation of SA shelf waters is attributable in part to the broad distribution of the 16 SBCs and to the generally diverse although individually specialised foraging strategies exhibited at a colony scale (Baylis et al., 2009; Hamer et al., 2011; Lowther et al., 2011). Individuals from some colonies foraged inshore to MMFDs of only 28 km from their natal colony, while others foraged offshore to MMFDs of 189 km, or six to seven times the distance. These greater distances confirm that Australian sea lions can travel much further than previous reports indicate (Fowler et al., 2007) . The fact that foraging tracks did not extend further than the relatively shallow SA shelf waters suggests that Australian sea lion foraging effort is probably limited by sea floor depth (Goldsworthy et al., 2010) and by the suite of prey species found there. The variation between colonies likely demonstrates cultural differences that are developed and sustained over long periods, with individuals learning where and how to forage from other individuals in older cohorts (Lowther et al., 2011). Given that 32 other breeding colonies are located in SA waters, it is likely they collectively utilise much more of the SA shelf waters in coastal and offshore regions than the results presented in this study indicate.

4.2. Overlap of Australian sea lions and demersal gill-nets: potential impact of by-catch

Given the extensive geographic distribution of demersal gill-netting and of Australian sea lions across SA shelf waters, the extensive overlap recorded (i.e. 68.7% in 4 m^2 grid cells) seems intuitive, although this should be viewed as a minimum estimate due to the small proportion of females tracked. Predictive analyses using generic models for Australian sea lion foraging behaviour are also likely to confirm extensive overlap (Goldsworthy et al., 2010), although this study adequately demonstrates that geographic overlap is prevalent in SA shelf waters wherever gill-netting takes place, albeit to varying degrees. Although this study is limited to the 16 SBCs, it should be noted that predictive analyses using gen-

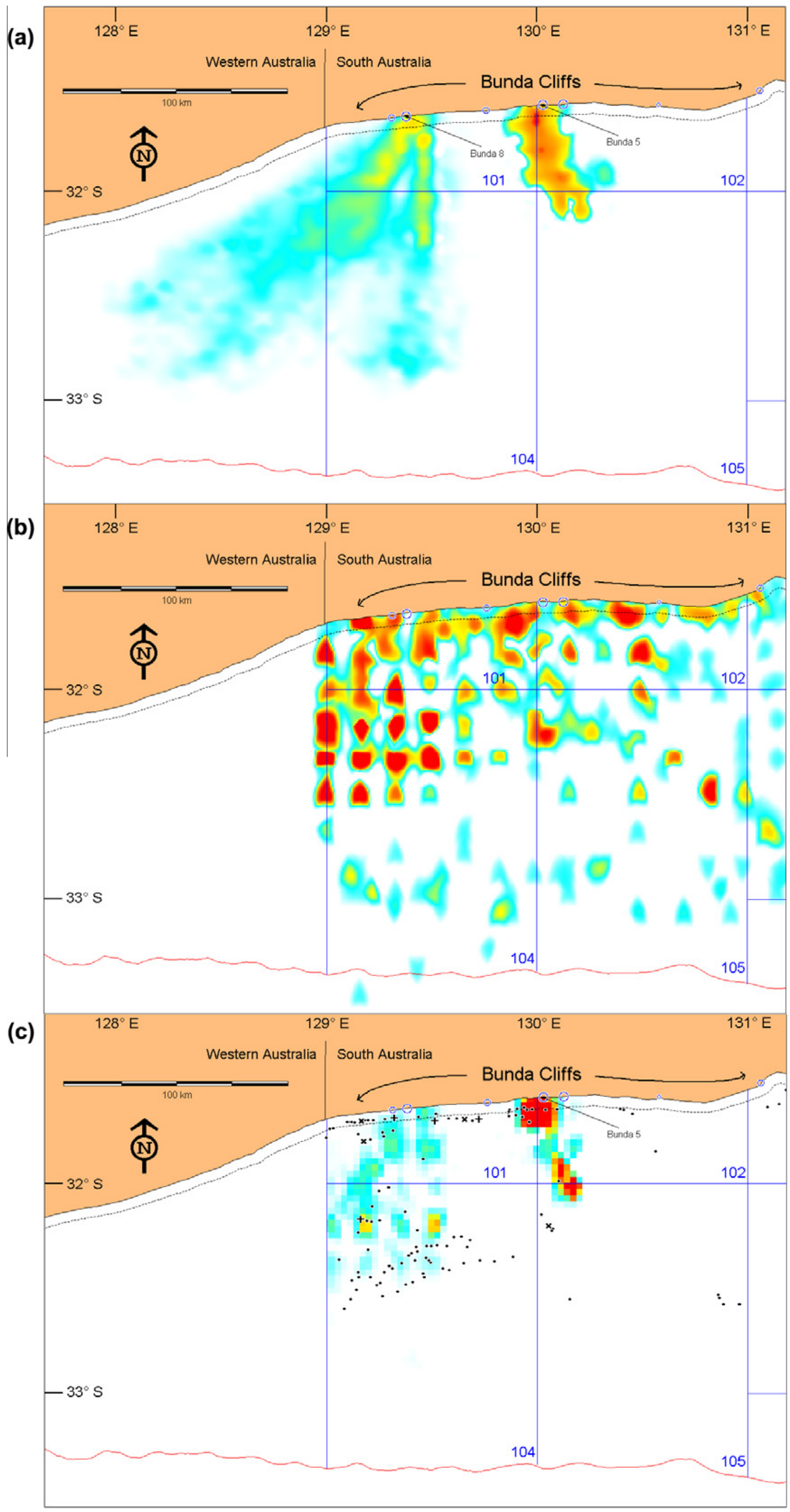

Fig. 2. *Effort distribution map in the 'Bunda region'.* Showing (a) at-sea movement of nine sexually mature Australian sea lion females tracked from two selected breeding colonies (SBCs), (b) demersal shark gill-net fishing activity in 2006–2008 and (c) overlap between the two (effort/overlap: red = high effort, orange = medium, blue = low). The location of observed fishing activity (•), presence of an Australian sea lion during hauling (x) and of by-catch mortality (+) are also marked. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

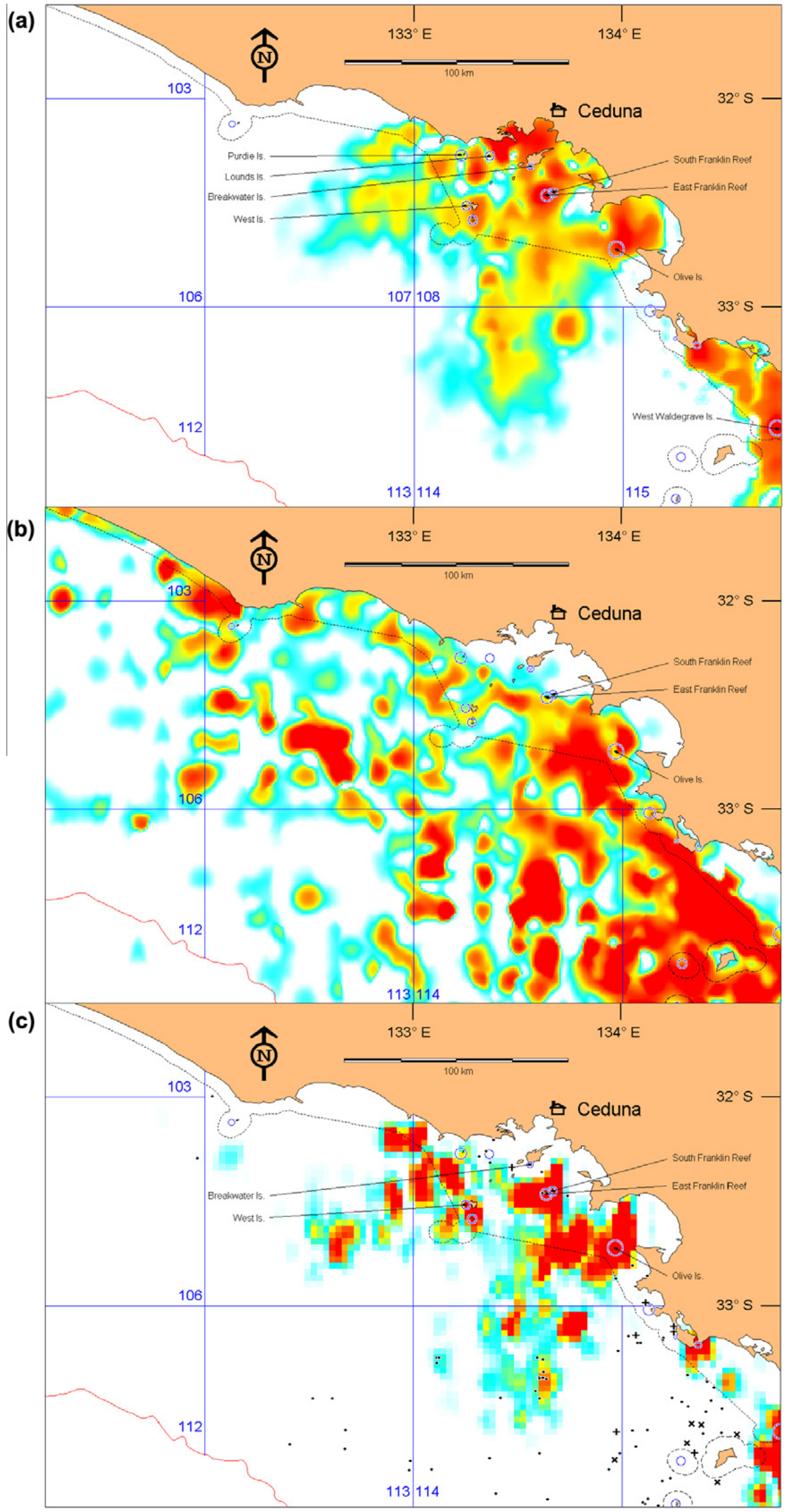

Fig. 3. *Effort distribution map in the 'Nuyts region'.* Showing (a) at-sea movement of 41 sexually mature Australian sea lion females tracked from seven selected breeding colonies (SBCs), (b) demersal shark gill-net fishing activity in 2006-08 and (c) overlap between the two (effort/overlap: red = high effort, orange = medium, blue = low). The location of observed fishing activity (•), presence of an Australian sea lion during hauling (x) and of by-catch mortality (+) are also marked. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

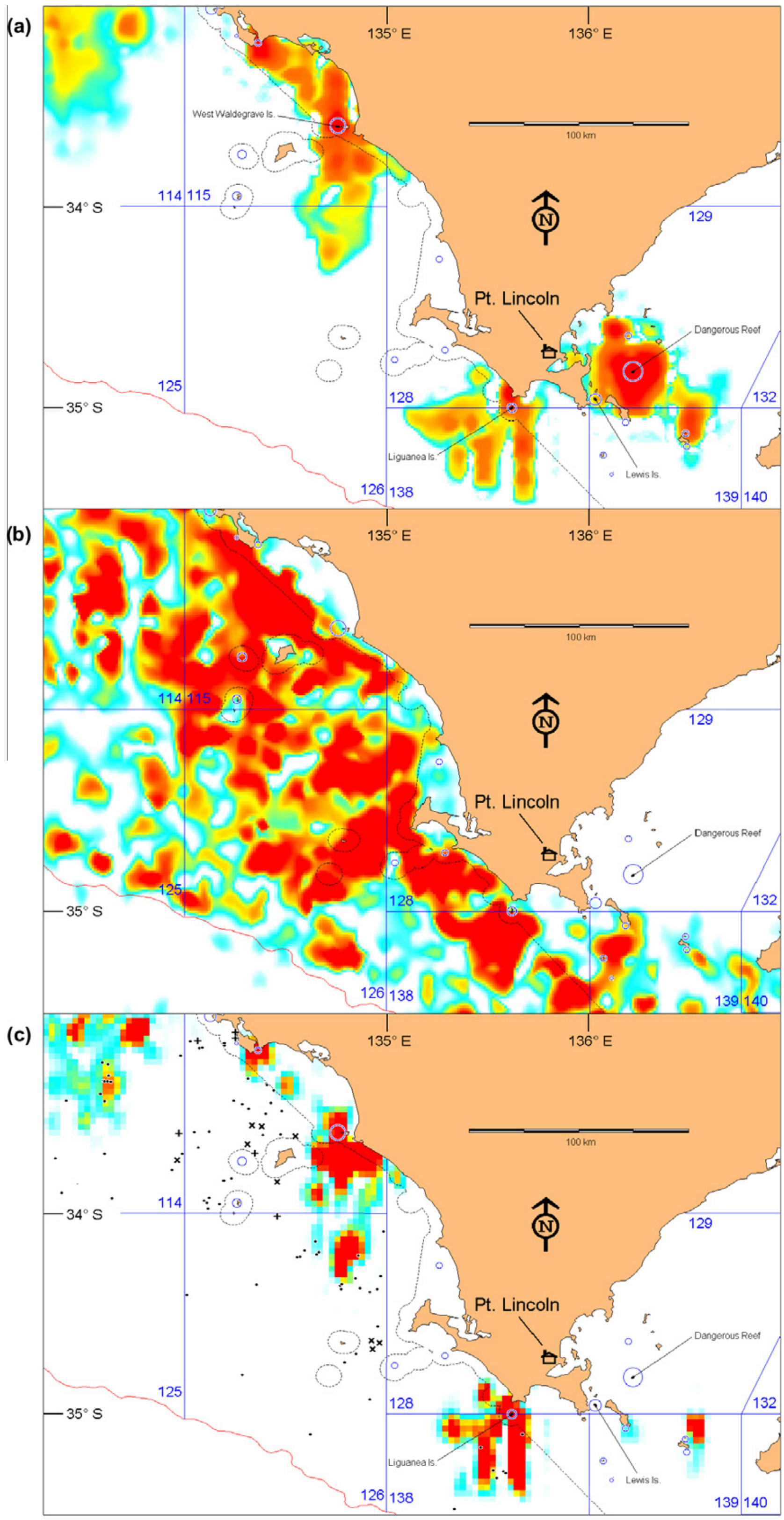

Fig. 4. *Effort distribution map in the 'Eyre region'*. Showing (a) at-sea movement of 25 sexually mature Australian sea lion females tracked from four selected breeding colonies (SBCs), (b) demersal shark gill-net fishing activity in 2006–2008 and (c) overlap between the two (effort/overlap: red = high effort, orange = medium, blue = low). The location of observed fishing activity (•), presence of an Australian sea lion during hauling (x) and of by-catch mortality (+) are also marked. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

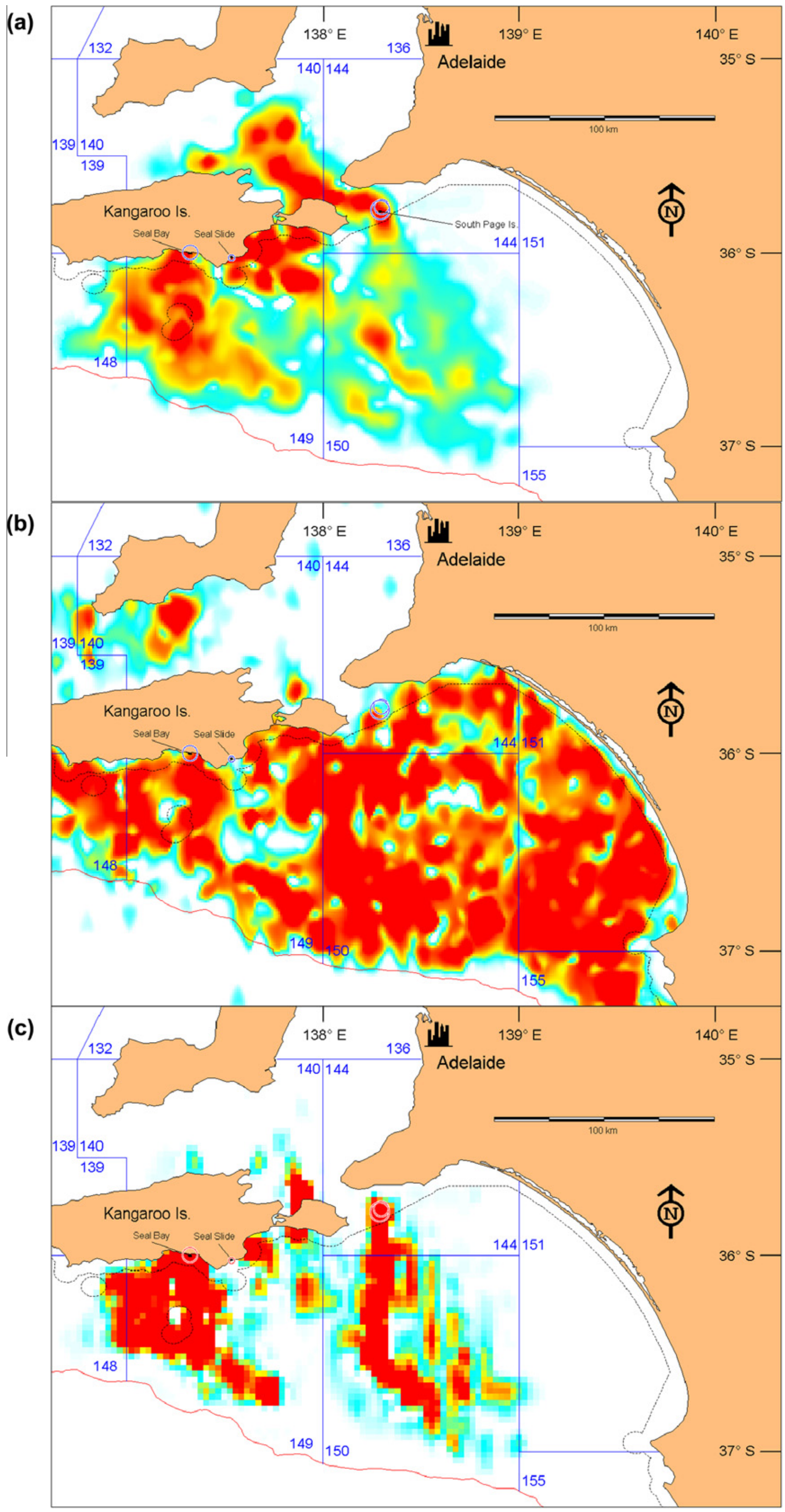

Fig. 5. *Effort distribution map in the 'Kangaroo region'*. Showing (a) at-sea movement of 40 sexually mature Australian sea lion females tracked from three selected breeding colonies (SBCs), (b) demersal shark gill-net fishing activity in 2006–2008 and (c) overlap between the two (effort/overlap: red = high effort, orange = medium, blue = low). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The percentage of time spent by 115 adult female Australian sea lions tracked from 16 selected breeding colonies (SBCs) across South Australian (SA) shelf waters, by region, by colony and by Australian Fishery Management Authority (AFMA) Marine Fishery Area (MFA).

Management zone	Colony		
	Bunda-8	Bunda-5	Combined
a. Bunda region			
MFA-101	49.3	32.8	44.4
MFA-102		52.1	15.4
MFA-104	50.7	7.4	37.9
MFA-105		7.7	2.3
South Australian waters	7.5	21.0	11.5
Adjacent Commonwealth waters	92.5	79.0	88.5

Management zone	Colony							
	Purdie	West	Lounds	Breakwater	E Franklin	S Franklin	Olive	Combined
b. Nuyts region								
MFA-107	52.4	14.1	0.1					5.2
MFA-108	47.6	85.9	99.9	100.0	100.0	69.5	93.8	86.1
MFA-114						30.4	6.2	8.6
MFA-115						0.1		0.1
South Australian waters	45.3	68.9	99.9	100.0	99.6	48.5	81.5	76.9
Adjacent Commonwealth waters	54.7	31.1	0.1		0.4	51.5	18.5	23.1

Management zone	Colony				
	W Waldegrave.	Liguanea	Lewis	Dangerous	Combined
c. Eyre region					
MFA-115	94.2				30.4
MFA-126	5.3				1.7
MFA-128	0.5	43.3			9.7
MFA-129			100.0	89.9	41.4
MFA-138		56.7			12.5
MFA-139				10.1	4.3
South Australian waters	69.7	44.1	100.0	100.0	77.9
Adjacent Commonwealth waters	30.3	55.9			22.1

Management zone	Colony			
	Seal Bay	Seal Slide	S Page	Combined
d. Kangaroo region				
MFA-140			47.8	44.5
MFA-144		0.2	23.9	20.3
MFA-148	22.8			1.5
MFA-149	77.2	91.9	0.3	13.3
MFA-150		7.8	27.9	24.4
MFA-151			0.1	0.1
South Australian waters	86.2	26.8	68.4	66.0
Adjacent Commonwealth waters	13.8	73.2	31.6	34.0

eric foraging models to determine geographic overlap across SA shelf waters (Goldsworthy et al., 2010) may inaccurately distribute effort, which poses significant problems for effective conservation management on a finer scale.

Other evidence external to this study suggests vertical overlap between demersal gill-nets and Australian sea lions may also be extensive. School and gummy sharks occur close to the sea floor in temperate shelf habitats where demersal gill-nets are set (Walker et al., 2005; Hamer et al., 2011) and Australian sea lions also concentrate their foraging efforts close to the sea floor, in search of benthic prey (Costa and Gales, 2003; McIntosh et al., 2006; Fowler et al., 2007; Baylis et al., 2009; Goldsworthy et al., 2010). As such, Australian sea lions and demersal gill-nets are likely to overlap vertically in the water column, as well as geographically. This situation further highlights the increased risk of Australian sea lions becoming by-caught, because they either fail to see the gill-net while foraging naturally, or become entangled and drown while attempting to depredate fish caught in it.

Based on the most recent overall estimate of the number of Australian sea lions residing in SA waters being 14,780 (Shaughnessy et al., 2011) and the estimated range of overall by-catch being 283–333 individuals each breeding cycle, the SA component of the species could be losing 1.91–2.25% of its individuals each breeding cycle. This unnatural and additional source of mortality may serve to increase the risk of local decline or even extinction if left unabated (Goldsworthy et al., 2010). This is especially relevant when considering that Australian sea lions exhibit a comparatively low level of fecundity and have many small colonies that are probably genetically distinct populations (Higgins, 1993; Gales et al., 1994; Campbell et al., 2007; Lowther et al., 2012; DSEWPaC, 2012a). The Bunda Cliff population in the GABMP was reported to lose 7 to 17 female Australian sea lions as by-catch in gill-nets each breeding cycle, with the loss of only 13 required to exceed the intrinsic (i.e. naturally possible) rate of population growth, suggesting that local population decline could be occurring (Hamer et al., 2011). Nonetheless, small numbers have persisted

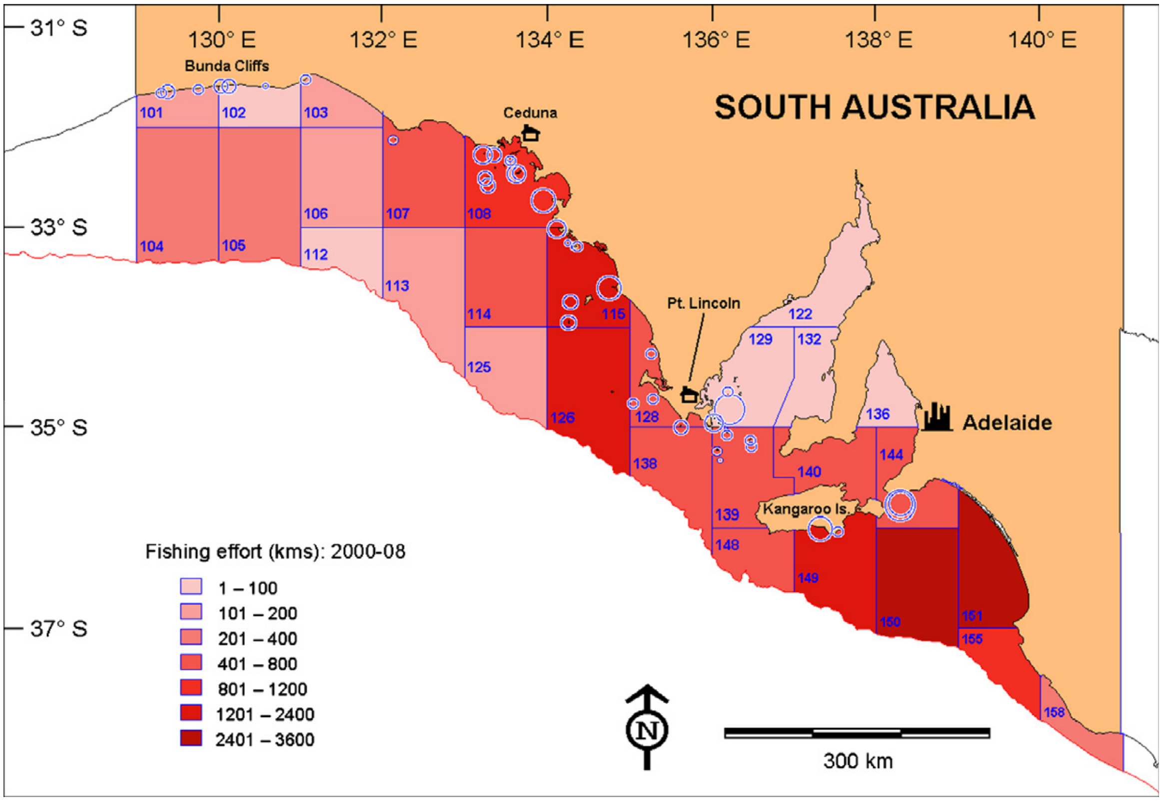

Fig. 6. *Distribution of demersal shark gill-net fishing effort by MFA.* Across South Australian shelf waters in 2000–2008, shown as blue numbered degree by degree Marine Fishery Areas (MEAs). Location of known breeding sites (blue circles) shown for reference (see our Fig 1 for size reference). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

there for at least 20 years, since at least the early 1990s (Dennis and Shaughnessy, 1996; Hamer et al., 2009). It is also possible that higher levels of by-catch may have occurred there and in other locations during the 1980s, at a time when the level of fishing effort was greater (Woodhams et al., 2011). Assuming population declines did occur earlier on due to the additional by-catch related mortalities, the level of by-catch would also have declined. Given that the likelihood of by-catch is proportional to foraging density, levels of by-catch would eventually become sufficiently low to no longer be the principal cause of decline. Alternatively though, any increase in population size would also have been prevented under a reversal of the same process, assuming all other factors remain unchanged. In a situation where gill-netting and Australian sea lion by-catch is commonplace, these two opposing forces may act to stabilise the size of the population at artificially lower numbers. This situation may explain the lack of extinction events at the many small breeding colonies in SA waters, even though they are disproportionately exposed to the effects of stochastic events, such as disease (e.g. New Zealand sea lion epizootics; Robsertson and Chilvers, 2011) and human development (e.g. recreational boating: Gales et al., 1994; aquaculture: Goldsworthy et al. 2009). As such, small and seemingly stable colonies are more likely to rapidly and unexpectedly go extinct if circumstances change even slightly for the worse. Such events are without recourse because females exhibit philopatry, thus preventing the immigration of females from other breeding sites to facilitate recolonization.

Independent observer programs are widely accepted as the most practical method for monitoring by-catch, from which rates and estimates can be calculated (e.g. Read, 2005; Gilman, 2011). In this study, monitoring occurred in approximately half of the 29 MFAs available to demersal gill-netters across SA shelf waters and by-catch occurred in approximately half of those where monitoring occurred, in both coastal and offshore environments. More by-catch data is needed confirm if the probability of an Australian sea lions becoming by-caught is greater in coastal waters (i.e. close to breeding colonies) than in offshore waters, because these central place foragers need to regularly return to feed nutritionally dependent pups (e.g. Chilvers et al., 2011). However, spatial overlap in SA shelf waters between Australian sea lions and demersal gill-netting was found to be extensive in both coastal and offshore waters, suggesting that the few individuals by-caught in offshore waters may not be an anomaly. It should also be noted that the extent of the problem may be underestimated, because only observed by-catch was included in the calculations. The novel monitoring technique used by observers during this study confirmed that the majority of drowned animals dropped out of the gear as they breached the surface before they could be hauled aboard the vessel. These events would normally go undetected and thus unreported by crew, thus not recorded by conventional fishery observers who tend to focus their attention on the deck where caught fish are processed. It seems likely that the weight of the drowned animal and a sudden increase in gravity as it emerges from the water may cause the gill-net meshes to break, thus allowing the by-caught individual to fall back into the water where it remains unnoticed. This phenomenon also raises questions about the proportion of drowned individuals that may drop out of the net as it is hauled up off the sea floor, which cannot be detected using the technique developed for this study. This problem affects many fisheries that have problems with marine mammal by-catch (Warden and Murray, 2011). However, at present there are no reliable or practical methods of observing what occurs in a demersal gill-net while it is actively fishing on the sea floor. Therefore, it must be assumed that individuals observed by-caught and drowned are only a portion of the actual level of by-catch.

Reports of Australian sea lions observed entangled at breeding sites confirm some by-caught individuals manage to break free of actively fishing demersal gill-nets with an entanglement, without drowning immediately (Shaughnessy, 1999; Shaughnessy et al., 2003; Page et al., 2004). Other studies have suggested that individuals observed with entanglements at breeding sites are a very small portion of the true number entangled, (Fowler, 1987; Fowler et al., 1990). This may be due to entangled individuals seeking to avoid interactions with other individuals at breeding colonies that may result in further injury and to the need to forage for longer periods to compensate for the energetic inefficiencies caused by the entanglement. Given that demersal gill-nets are made of thin but durable monofilament polyamide or polypropylene (Walker et al., 2005) and that entanglement related injuries are typically extensive (Raum-Suryan et al., 2009), it is probable that many individuals that initially escape with an entanglement will eventually die a slow and painful death. This eventuality also has implications for nutritionally dependent pups, which are likely to starve and die if their mother is lost as by-catch or from associated entanglement injuries.

4.3. Current management approaches to mitigating Australian sea lion by-catch

In response to the findings documented in this study and to preliminary PVAs conducted in another recent study (Goldsworthy et al., 2010), AFMA implemented the Australian sea lion Management Strategy (MS), which focuses on three elements for mitigating the impact of the demersal gill-net fishery on Australian sea lions in SA shelf waters (AFMA, 2010). Firstly, observer coverage was increased from negligible levels to 100%, to more accurately determine the level of Australian sea lion by-catch (AFMA, 2011). However, the extensive use of electronic camera systems as part of the monitoring effort may be premature, because their accuracy has not yet been adequately compared with human observers. This process is unlikely to be a swift, because a sizeable dataset would be required to facilitate pair wise statistical comparisons. Secondly, AFMA implemented year-round area closures that extend 7.3–20.7 km in all directions around the 48 breeding sites in SA (AFMA, 2011). However, the tracking results of this study demonstrate they are unlikely to reduce geographic overlap sufficiently to prevent by-catch, thus some small populations may remain at risk of decline, or even extinction. Thirdly, if the by-catch limits of 1–5 allocated in each of the seven large AFMA designated zones across SA shelf waters are reached, then much larger closures are implemented out to the boundary of the fishery in the associated zone (i.e. the 183 m depth line) for a period of 18 months, which approximates one breeding cycle (AFMA, 2011, 2012a). However, recently compiled information suggests by-catch limits are being exceeded (AFMA, 2012b), presumably due to delays in receiving, processing and responding to by-catch reports. Despite the need for continued improvement in AFMAs MS, the changes made to date are substantial and are likely to improve the conservation situation for Australian sea lions.

Comparable approaches toward managing the impact of major commercial fisheries on a pinniped species are scarce in the published literature. One example from New Zealand is relevant, where by-catch limits of New Zealand sea lions and associated area closures have formed part of the management plan for the Auckland Is arrow squid (*Nototodarus* spp.) trawl fishery since the early 1990s (Wilkinson et al., 2003). However, a recent proposal to remove by-catch limits was justified by citing negligible by-catch in recent years (MAF, 2011). This decision seems incongruous when the reduction in by-catch would have been linked, at least in part, to the by-catch limits, the use of exclusion devices and the associated area closures. This example highlights the need to properly interpret the reduction in recorded by-catch, by first determining if it is caused by the mitigation strategies originally implemented, or by an overall decline in the population.

4.4. Summary and suggestions for improved conservation management

This study demonstrates that Australian sea lions forage across a large proportion of SA shelf waters and have extensive geographic overlap with shark gill-netting activities. Given that both target prey species at or near the benthos, it is not surprising that Australian sea lions regularly become by-caught and drown in demersal gill-nets. The level of by-catch reported in this study is likely to represent a fraction of the overall occurrences, with many drowned animals dropping out of the net and going unobserved and many escaping with entanglements only to die later from related injuries. It is possible, with time, that small colonies or populations that are already affected (and thus reduced in size) by by-catch related losses may be exposed to a stochastic event that could cause further declines and possibly even extinction.

The key aspects of Condition 6b of the WTO for the demersal shark gill-net fishery ostensibly called for its impact on Australian sea lions to be addressed and mitigated. While AFMA has taken considerable steps to address these recommendations through the implementation of the MS, further improvements may include:

1. Determining the accuracy of electronic camera monitoring systems in detecting Australian sea lions, before permitting their widespread use on demersal gill-net vessels fishing in SA shelf waters.
2. Expanding the permanent closures currently implemented around 48 breeding sites to further reduce the degree of overlap between Australian sea lions and demersal gill-nets, thus further reducing the likelihood of by-catch.
3. Ensuring that reports of by-catch are more swiftly received, processed and responded to in order to minimise the chance that specified by-catch limits are not exceeded.

Although outside the scope of the MS, long-term monitoring of Australian sea lion population levels and trends at key breeding sites would also be useful in tracking the overall status of the species and its populations into the future. Making decisions about which sites to monitor should be based on region and size representation, although the potentially adverse impact of monitoring activities should be a consideration when developing survey strategies and when conducting activities in small breeding colonies. Nonetheless, population status and trajectories should not be used as a tool to assess the effectiveness of management changes to the demersal gill-net fishery, because many other external and possibly unquantifiable factors are likely to influence recovery rates. A good example of this is the continuing non-recovery of formerly abundant populations of dolphins in the eastern tropical Pacific, where there have been substantial (orders of magnitude) reductions in the by-catch mortality of intentionally targeted dolphin pods by purse-seiners in search of associating tunas (Wade et al., 2007). Therefore, long-term monitoring would be used most effectively to inform conservation and fishery managers about where and when to prioritise Australian sea lion conservation efforts at a colony, region, population, or species scale, rather than a tool for assessing the effectiveness of fishery management arrangements.

Future research opportunities that may enhance the management of Australian sea lions include more thorough investigation of gene flow (especially of males) between colonies and regions to identify possible management units (Lowther et al., 2012) and of PVA using density dependent factors and different spatial management scenarios (Goldsworthy et al., 2010). A recent report confirms that low levels of Australian sea lions by-caught in demersal gill-nets in WA may have reduced the population size of many colonies there to low levels and may put them at further risk of decline and extinction (Campbell, 2011). Therefore, the broader conservation of the Australian sea lion may benefit from determining the impact of demersal gill-net activities on populations in WA.

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