

Informing risk assessment through estimating interaction rates between Australian sea lions and Western Australia's temperate demersal gillnet fisheries

*Hesp, S.A., Tweedley, J.R., McAuley, R.,
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**Fisheries Research and Development Corporation Report
FRDC Project 2009/096**

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2009/096

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OBJECTIVES:

1. Develop a tool to assist in determining the implications of the current distribution of commercial gillnet fishing for different colonies of Australian sea lions.
2. Estimate the proportion of Australian sea lions, in different colonies, that encounter commercial gillnets in Western Australian waters each year.

NON TECHNICAL SUMMARY:

OUTCOMES ACHIEVED TO DATE

A simulation model has been developed to describe the potential risks that commercial gillnet fishing poses to Australian sea lions (ASLs) in Western Australia. The study provides “proof of concept” for the development of similar models for informing risk assessments relating to marine mammal interactions with fisheries.

The model has provided a method for simulating the spatial patterns of ASL movements around all surveyed breeding colonies along the WA coast and has been used to estimate the rates at which ASLs from these colonies occurred within a chosen proximity to demersal gillnets used by commercial fishers in WA. This model is potentially beneficial for informing the design of any future programs to monitor ASL interactions with the WA commercial gillnet fishery and for evaluating any conservation benefits arising from future marine management zoning (*i.e.* marine parks).

The information produced by this study will be of value to industry and managers for at least the following reasons. Firstly, the completion of this research satisfies part of condition 5(a) of the fisheries Wildlife Trade Operation accreditation under the Environment Protection and Biodiversity Conservation Act (1999) that allows for continued export from WA’s temperate demersal gillnet fisheries, *i.e.* “to undertake a study to estimate risk of interactions between (gillnet) fishers and Australian sea lions” in WA. The information generated by this study will be used by the Department of Fisheries, WA, to investigate the appropriateness and design of a future observer program for monitoring ASL/fishery interactions and potentially for developing strategies for mitigating any risks posed to individual ASL colonies by gillnetting. Secondly, the model and information developed during this project could assist WA’s commercial gillnet fisheries to pursue Marine Stewardship Council accreditation to demonstrate the ecological sustainability of this regionally important fishery. Lastly, the information produced by this study will be relevant to imminent discussions on marine park planning in WA.

A computer model (referred to as an agent-based model) was developed to simulate movements of the Australian sea lion (ASL), *Neophoca cinerea*, around each of the 24 previously surveyed breeding colonies along WA’s coast. The model has been used to estimate the likelihoods of ASLs (“agents”) occurring within a chosen proximity of 500 m to commercial demersal gillnets. These events are referred to as “*potential encounters*” which are treated as a surrogate for interactions of sea lions with gillnets. However, as the relationship between the proximity of ASLs to a net and their risk of interacting with or being captured by that net is unknown, potential encounter rates are **not** equivalent to interaction or capture rates.

The computer model employs a “biased random walk” approach for simulating ASL movements. Movement simulations were informed (hence, “biased”) by pre-existing satellite-tracking data, gathered from a total of 41 “real” ASLs (that is, for 20 cows and 21 juveniles) across 8 WA colonies. The satellite-tracking data were used to produce “probability distributions” for five key variables, namely depth ranges for ASL movements, distances moved by ASLs from their colonies, forage trip durations, resting time between foraging trips and ASL travelling speeds. The movements of 400, computer-generated, ASLs (that is, 200 cows and 200 juveniles) were simulated for each of the 24 WA colonies by randomly sampling values from each of these probability distributions. Results were then scaled to reflect the most recently described demographics (*i.e.* numbers of cows and juveniles) of each colony. Where necessary, data for the 8 colonies from which ASLs had been satellite-tracked were extrapolated to other colonies that lacked data for colony-specific modelling. Sea lion movements were simulated as discrete movements in cardinal directions (north, east, south or west) at time intervals over a computer landscape map, generated using bathymetric (water depth by location) data.

Satellite location data for “real” ASLs from three colonies, including one at the northern most extent of the species range (Abrolhos Islands), one on the lower west coast of WA (Beagle Island) and one on the south coast of WA (Investigator Island), were visually

compared to multiple sets of simulated movement data for those colonies to evaluate the reliability of model outputs. The comparisons suggest that the spatial patterns of ASL movements predicted by the model are similar to those recorded by “real” satellite tracking. The extent to which observed and simulated distributions for different model parameters used to simulate ASL movements matched suggest that the modelling approach was sound.

The reported fishing activities by WA’s demersal gillnet fisheries were “replayed” in model simulations for each of three successive financial years (2006/07 – 2008/09, inclusive). Information from fishers’ logbooks on the locations, days and durations of gillnetting during those years, and on the dimensions of the nets they use, were used to place (computer-generated) gillnets on the model landscape at the times and locations specified for each of the three financial years.

The following points should be remembered when interpreting results from model. 1) The relationship between a sea lion’s proximity to a net and the probability of it interacting with that net is entirely unknown. Furthermore, as an interaction may result from an ASL swimming into a net purely by accident or from it being attracted to fish caught in the net, and as the probability of an interaction is likely to vary depending on differences in individual behaviours and localised environmental conditions, this relationship is likely to be highly uncertain (even if it were able to be estimated). In simulations, a “potential encounter” was recorded when an ASL occurred within 500 m of a net (as it was considered plausible that an ASL is at risk of a net encounter in such a situation). The sensitivity of results to different specified distance values was also explored. 2) Colonies with large numbers of individuals are likely to accrue relatively high numbers of potential encounters throughout the year as, for such colonies, there are many more animals in the water at any one time and thus the chance of one of their individuals encountering a net will be higher than for smaller colonies. 3) An interaction poses the greatest risk to those colonies that have the smallest numbers of ASLs. Statistics which take into account both colony size and numbers of encounters are likely to be most informative for any assessment of levels of risk.

Depending on the colony, up to 60% of cows and up to 54% of juveniles are estimated to have occurred within 500 m of a gillnet at least once in each of the three successive financial years for which fishing effort data were available. Typically, individual cows encountered gillnets more often than juveniles from the same colony. For cows, the highest estimates of per capita potential encounter rate (determined as the number of potential encounters estimated for a colony divided by the number of cows in that colony) were for Hauloff Rock and Doubtful Island, near Albany, and Beagle Island, near Jurien Bay. For juveniles, the greatest estimated per capita rates were for Hauloff Rock, Doubtful Island and Glennie Island (near Esperance). Model simulations indicated that no ASLs at the Abrolhos Islands encountered a gillnet over the three years simulated.

To the best of our knowledge, the simulation approach adopted in this study is new to research on pinniped interactions with fishing operations in Australia. Agent-based modelling is shown to provide a powerful tool for estimating potential encounter rates between ASLs and gillnets (as a basis for informing risk assessments) and potentially, the encounter rates of other Threatened, Endangered and Protected (TEP) species for which similar empirical data are available. However, the approach adopted in this study for simulating ASL movements represents one of a number of valid alternatives. As outlined later in this report, additional satellite-tracking data for ASLs in WA and refinement of certain components of the agent-based model could lead to substantial gains in accuracy and precision of estimates of potential encounter rates of ASLs with gillnets. If required, the approach used in this study would lend itself well to exploring the benefits of a range of potential bycatch mitigation measures and maximising the effectiveness of such measures for conserving ASLs.

KEYWORDS: Australian sea lions, demersal gillnet fisheries, potential encounter rates, movements, simulation modelling

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BACKGROUND

Temperate demersal gillnet fisheries in Western Australia

Commercial exploitation of sharks in Western Australia first began in 1941, with a single boat using demersal longlines in coastal waters around Bunbury (McAuley & Simpfendorfer 2003). Over the next twenty years, shark fishing started in waters near Albany, Fremantle and Geraldton (McAuley & Simpfendorfer 2003). In the 1960s, the fishery began to expand into deeper, offshore waters and monofilament gillnets were introduced (Kailola *et al.*, 1993). The main shark species targeted by fishers on the south coast of Western Australia are the gummy shark (*Mustelus antarcticus*) and the dusky shark (*Carcharhinus obscurus*). On the west coast, fishers primarily target the dusky shark and the sandbar shark (*Carcharhinus plumbeus*). The whiskery shark (*Furgaleus macki*) and a variety of teleost species are also important components of the catch in both fisheries (McAuley & Leary, 2010).

Commercial demersal gillnet fishing in the southern half of Western Australia is managed through two complementary management plans that denote the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery (JASDGDLF), which encompasses waters from 33°S to the South Australian border (at 129°E), and the West Coast Demersal Gillnet and Demersal Longline Managed Fishery (WCDGDLF), which extends northwards from 33°S to Steep Point, Shark Bay (26° 30' S) (McAuley & Leary, 2010).

Gillnets employed in both these fisheries are constructed from nylon monofilament mesh, which is hung between a negatively buoyant 'ground line', that sinks the net to the seabed, and a positively buoyant 'head line', which stands the net vertically off the bottom. Minimum permitted mesh sizes in these fisheries are 162.5 mm (6.4") in the JASDGDLF and 175 mm (6.9") in the WCDGDLF, and nets may not exceed 20 meshes in depth (~263 cm with a 7" mesh; McAuley & Simpfendorfer, 2003). Fishers generally set between one and four nets at any time, depending on their unit allocation, vessel size, area of operation, expected catch rates, and various other factors. Each individual net is typically between 1,000 m and 3,000 m long. During a fishing session, nets are sometimes set in close proximity to

each other, whilst at other times, they are separated by distances of a few kilometres. Many vessels deploy their gear overnight, although some fishers set and retrieve their gear multiple times per day. On average, fishers have traditionally “soaked” their nets for between 17 and 19 hours per day (Simpfendorfer *et al.*, 2000; McAuley & Simpfendorfer, 2003).

Commercial landings of elasmobranch species from the WA shark fishery ranged between 1,238 to 1,510 tonnes per annum between 2006/07 and 2008/09, with additional catches of between 220 and 240 tonnes of demersal scalefish also being retained (McAuley & Leary, 2010). The annual value of this fishery is estimated to be between \$6 and 7 million (McAuley & Leary, 2010).

Australian sea lions

Conservation status and distribution

Australia’s only endemic pinniped, the Australian sea lion (*Neophoca cinerea*), is one of the rarest sea lions worldwide (*ca* 14,700 individuals) and is assessed as “*endangered*” under the International Union for Conservation of Nature. This species was recently listed as “*vulnerable*” under the Commonwealth Environmental Protection and Biodiversity Conservation Act and is also listed as “*specially protected fauna*” under the WA Wildlife Conservation Act (1950) (Goldsworthy & Gales, 2008; Goldsworthy *et al.*, 2010). Furthermore, as female ASLs show extreme natal site fidelity, if a breeding colony is lost, it is believed that the site of that colony is unlikely be recolonised by this species (Campbell *et al.*, 2008a).

Australian sea lions are distributed sparsely along *ca* 3,000 km of the southern Australian coast. They are currently distributed southwards from the Houtman Abrolhos Islands (28° 44 S, 113° 49 E) off the west coast of Western Australia and then eastwards along the south coast to just past Kangaroo Island in South Australia (35° 47 S, 138° 17 E) (Gales *et al.* 1992, 1994). Although ASLs occupy very few mainland sites along this area of coast, about two thirds of its islands are used by ASLs either for breeding or as haul-out sites (*i.e.* resting areas) (Gales & Costa 1997). In the past, ASLs were also found in Bass Strait but commercial sealing

operations in the 1700-1800s resulted in this species becoming extinct in this area. There is also evidence that some ASL colonies have been lost from within the current range of this species. For example, in Western Australia, there is evidence that, in the early 1800s, ASL breeding colonies could be found on Rottnest Island, Garden Island and Carnac Island near Perth, whereas today, this is not the case (Abbott, 1979; Campbell, 2005).

Today, there are 76 known ASL breeding locations in southern Australia, of which 28 are located in Western Australia (Goldsworthy *et al.*, 2009). Moreover, the overall estimated abundance of ASLs in Western Australia is much lower (~2,000 individuals) than in South Australia (~12,700 individuals) (Goldsworthy *et al.*, 2009), which has been attributed to differences in the productivity of the marine environments between the two regions (Gales *et al.*, 1994; Dennis and Shaughnessy, 1999). Whilst productivity in eastern Australia is positively influenced by the cool, nutrient rich Flinders Current, combined with cold water upwelling (Wenju *et al.*, 1990), in Western Australia, the warm, nutrient-poor Leeuwin Current lowers productivity in this region (Pearce, 1991; Feng *et al.*, 2009).

In Western Australia, the majority of breeding colonies are located along the south coast, with most of these occurring within the Recherche Archipelago near Esperance. All of the south coast breeding colonies lie east of Albany. However, the two largest breeding colonies in WA lie off the west coast near Jurien Bay (Beagle Island and North Fisherman Island). Two other relatively large breeding colonies are situated off the West coast at the Abrolhos Islands and at Buller Island. The low population sizes of a number of ASL colonies in Western Australia, in particular, make them extremely vulnerable to localised extinctions (Campbell *et al.* 2008a). Census data are available for 24 of the 28 colonies in Western Australia (Goldsworthy *et al.*, 2009). The locations of these colonies are shown in Fig. 1 (see materials and methods).

Movements and foraging behaviour

Australian sea lions are benthic feeders. They feed on a broad range of prey, comprising mainly cephalopods, crustaceans, benthic elasmobranches and demersal teleosts (Richardson & Gales, 1987; Gales & Cheal, 1992; Costa & Gales 2003; McIntosh *et al.*, 2006; Baylis *et al.*, 2009). Dietary analyses have demonstrated that this species is an opportunistic benthic forager (Gales and Cheal 1992; Ling 1992; Costa and Gales 2003). This point is illustrated by the fact that ASLs are known to “rob” crayfish and octopus from lobster pots as well as fish from demersal gillnets (Inns *et al.*, 1979; Robinson & Dennis, 1988; Campbell *et al.*, 2008b).

Research on the foraging behaviour of cows at Kangaroo Island in South Australia indicates that the timing of foraging trips does not follow a distinct diel pattern (Costa & Gales, 2003). Studies by Fowler *et al.* (2006) on ASLs at this location indicated that juveniles and pups, likewise, show no diel pattern in foraging times. Work on ASLs in Western Australia by Campbell and Holley (2007) show that cows at Jurien Bay forage throughout both the day and night (with no diel pattern). The majority of juveniles at Jurien Bay foraged more often at night, although some juveniles showed no diel pattern in forage trip times (Campbell and Holley, 2007).

At Kangaroo Island, cows have been shown to begin diving (to the sea floor) immediately upon leaving the shore and to continue diving throughout their full trip (Costa *et al.*, 1989). Indeed, of the time that cows are at sea, about 60 % is spent diving and, of each dive, nearly 60 % is spent on or near the bottom of the sea (Costa & Gales, 2003). The overall duration of dives by ASLs increases with increasing water depth (Costa *et al.*, 2001; Costa & Gales, 2003). Adult females on Kangaroo Island have been known to dive to depths of 105 m.

Diving behaviour has also been shown to vary among locations. At Jurien Bay, on the west coast of Western Australia, pups, juveniles and adult females all typically dive to depths which are shallower than, for example, ASLs in waters around Kangaroo Island. The differences in diving depth distributions of ASLs among locations probably reflect a range of factors, including variations in local bathymetry, in the abundances of predator (*sensu* Frid *et al.*, 2007) or prey species. In the case of

prey, in Jurien Bay, for example, ASLs probably heavily target the abundant octopus, *Octopus tetricus*, and western rock lobster, *Panulirus cygnus* (Campbell *et al.*, 2008b). There is also evidence to suggest that ASLs from different colonies exhibit “site specific” foraging behaviours, with individuals from neighbouring South Australian colonies exhibiting different water depth preferences (*i.e.* shallow vs deep) (Goldsworthy *et al.*, 2009). Such differences in foraging behaviour could have a strong bearing on the relative levels of exposure of individuals from different colonies to demersal fishing operations, an issue which has recently been explored in South Australia through studies of stable isotope ratios in ASL whisker fragments (Lowther & Goldsworthy, 2011).

A number of studies have compared ontogenic differences in foraging patterns. Studies on Kangaroo Island showed that young pups (~6 months old), spend the vast majority of their time onshore and that, when at sea, they dive to a mean depth of ~7 m. The mean duration of each dive by young pups is less than half a minute (Fowler *et al.*, 2006). However, by 15-23 months, ASLs at Kangaroo Island dive far deeper (~40-45 m) and longer (~3 minutes) (Fowler *et al.*, 2006). Adult females, by comparison, were shown to dive to a mean depth of 70 m, with each dive typically lasting ~3.3 minutes.

The home range of individuals, *i.e.* the area in which ASLs spend 75% of their time, as considered in analyses by Fowler *et al.* (2007), increases with age. At Kangaroo Island, home range thus increases from ~280 km² for 15 month old pups, to ~350 km² for 23 month old juveniles and to ~600 km² for adult females (Fowler *et al.*, 2007). The maximum and average “straight line” distances that individuals travel from their colony site during a trip differs according to age. For example, at Kangaroo Island, this distance is ~21 km for 15 month old pups, compared with ~35 km for 23 month old juveniles and ~68 km for adult females (Fowler *et al.*, 2007). Although, in general, the distances travelled by ASLs increases from pups to juveniles and then adults, distances can differ markedly among individuals of the same age, particularly among individuals from different colonies. For example, satellite tracking data for both juveniles and cows at the Abrolhos

Islands indicate that these individuals typically only travel up to ~10 km from the colony site (Campbell, 2008) and thus far less than ASLs from Kangaroo Island. In the study at Kangaroo Island, there were no seasonal differences in the distances travelled by cows during foraging trips (Fowler *et al.*, 2007).

The speeds of ASL movements also increase as animals become older. From the research of Fowler *et al.* (2007), the average “travel rate”, *i.e.* the average speed of movement between locations of individual ASLs at successive tag locations, increases with age, from ~1.3 km/h for 15 month old pups, to 2 km/h for 23 month old juveniles and 3.9 km/h for cows. A range of studies have shown that the maximum travel rate of ASLs does not exceed ~11 km/h (Fowler *et al.*, 2007; Campbell *et al.*, 2008b; Goldsworthy *et al.*, 2010).

Mean trip duration, *i.e.* the average time taken by ASLs to leave and then return to the colony, for ASLs at Kangaroo Island, is estimated to increase from ~1.8 days for 15 month old pups, to 4.8 days juveniles, and then to decline slightly to ~3.6 days for cows (Fowler *et al.*, 2007). Research in Western Australia, indicates that, at Jurien Bay, mean trip times for juveniles are much less, *i.e.* between 12-15 hours, but still up to several days for cows (Campbell & Holly, 2007).

Australian sea lion interactions with fisheries

Marine mammal bycatch is a global ecological sustainability issue for many commercial fisheries. Indeed, hundreds of thousands of individual marine mammals are caught by a range of fishing gears each year (Read *et al.*, 2006). In southern Australia, the three resident pinniped species, the Australian Sea Lion, the Australian Fur seal (*Arctocephalus pusillus doriferus*) and the New Zealand fur seal (*Arctocephalus forsteri*) have been recorded to interact with trawl, line, trap and gillnet fisheries (Shaughnessy *et al.*, 2003; Page *et al.*, 2004; Walker *et al.*, 2005; Hamer & Goldsworthy, 2006; DAFF, 2007). Records of interactions between Australian sea lions and fisheries are largely confined to trap and gillnet fisheries. In WA, the problem of incidental captures of ASLs in rock lobster pots was mitigated by legislating the inclusion of “Sea Lion Exclusion Devices” to all pots in November

2006, which has proved very successful in reducing the incidence of captures (Campbell *et al.*, 2008b; de Lestang *et al.*, 2009, 2010; see also Goldsworthy *et al.*, 2010 for situation in SA).

Interactions with demersal gillnets

Research in South Australia suggests that mortalities of Australian sea lions associated with gillnet entanglement is likely to pose the greatest risk to their sustainability (Page *et al.*, 2007; Goldsworthy *et al.*, 2010). Gillnetting can potentially pose a risk to Australian sea lions if they become entangled in nets whilst deployed during fishing operations, or in lost nets (or sections of net), from past fishing operations.

Although researchers in South Australia concluded that ASL entanglements in lost fishing gear (gillnets) is a significant issue in that state (Page *et al.*, 2007), in WA, the potential risks posed by lost nets are not believed to be as significant. This view is supported by the fact that independent researchers from the WA Department of Fisheries did not observe any instance of lost demersal gillnets whilst monitoring nearly 82,000 km gillnet hours (7.4%) of commercial gillnet fishing effort between 1994 and 1999 (McAuley and Simpfordorfer, 2003). Thus, it appears very unlikely that loss of fishing gear by WA's temperate commercial gillnet fisheries poses a substantial risk to ASLs.

Evidence of mortalities of ASLs in gillnets, as presented in other studies, are as follows. Between 1999 and 2004 in South Australia, seven pinnipeds were recorded (in the log books of five commercial fishers) as having died as a result of gillnet entanglement. The individuals are likely to have been either New Zealand fur seals or ASLs (Goldsworthy *et al.*, 2007). Previously, Shaughnessy *et al.* (2003) reported that one fisher in South Australia claimed to have caught around 20 ASLs per year. An onboard independent observer program between February 2006 and January 2008 in South Australia reported 12 ASL mortalities resulting from gillnet entanglements, from 146 sea days at sea, 234 shots and 996 km of accrued net. The observer coverage in that study accounted for 2.4% of total gillnet fishing effort in the

fishery (Goldsworthy *et al.*, 2010). In Western Australia, there was only one observed death of an ASL due to gillnet entanglement during on-board research involving the temperate commercial demersal gillnet fisheries (*i.e.* the JASDGDLF and WCDGDLF), conducted by the WA Department of Fisheries between 1994-1999 (McAuley and Simpfendorfer, 2003). During those five years, 7.4% of all reported demersal gillnet fishing effort was “observed” by WA Department of Fisheries researchers, although levels of “observer” coverage varied from 1.8% off the south coast (where the single observed ASL capture was recorded) to 19.8% in the south west corner of the state. Interestingly, and perhaps importantly, observations of 8.4% of gillnet fishing effort off the lower west coast, where the largest WA breeding colonies exist, detected no ASL captures.

Based on the observer data described above for South Australia, Goldsworthy *et al.* (2010) provided several estimates of mortality for ASLs in that state. The point estimates ranged from 318 to 395 individuals per ASL breeding cycle (~17.5 months). They also estimated that 3.9% of female ASLs > 1.5 years of age die each breeding cycle as a result of being caught in gillnets. Population viability analyses (PVA) for ASLs in South Australia indicated that annual bycatch levels of 260-400 sea lions (1-2 ASLs/100 km of net) would lead to a quasi extinction of several ASL populations within ~50 years (Goldsworthy & Page, 2007). Recently, spatial closures were introduced for all 48 ASL breeding sites in South Australia (Shaughnessey *et al.*, 2011). These gillnet exclusion areas have recently been extended so that the total area of the Commonwealth Government administered Australian Seal Lion Management Zone now covers 18,500 km² of South Australian waters (AFMA, 2011).

In Western Australia, some research has been undertaken to identify the relative magnitude of risks posed to ASLs by gillnetting (Campbell, 2008). On the basis of broad resolution data (*i.e.* monthly reports of catch and effort for 1 X 1 degree reporting blocks), the distribution of commercial fishing effort between 1992/93 and 2006/07 was shown to completely overlap ASL foraging areas (Campbell, 2008). Two important points that have also been noted are that 1) as

commercial gillnet fishing activity in Western Australia has reduced markedly over the past 25 years (> 70%, McAuley and Leary, 2010), the risks posed by such fishing to ASLs in this state are likely to now be less than in the past (Campbell, 2008) but that 2) as some of the ASL colonies in WA have not recovered from commercial hunting in the eighteenth and nineteenth centuries (Campbell, 2005) and are now very small, any mortality could pose a substantial risk to the ongoing survival of such colonies (Campbell, 2008).

As the spatial and temporal resolution of the fishery data available to Campbell (2008) was broad, he recommended analyses using finer scale data for fishing effort. Campbell (2008) suggested a “random walk” approach as one way of examining the issue of interactions between ASLs and commercial gillnets. In his report on ASLs in South Australia, Goldsworthy *et al.* (2010) noted that finer scale analyses, such as that employed in the current study, could be achieved through individual-based (or agent-based) modelling studies. These authors recommended that such studies could provide “a better means to estimate distribution of foraging effort, and should be examined in the future”.

Agent-based modelling

Agent-based models (ABMs) are computer models which simulate the behaviours of, and interactions between, collections of “agents” (*i.e.* individuals, such as single animals) with each other and/or their environment (see Lomnicki, 1992; Grimm, 1999; Breckling *et al.*, 2006). Unlike traditional (state-variable) models, that are based on differential and difference equations, and classical models such as the logistic model of population growth, which describe the (mean) dynamics of a pool of individuals, ABMs focus on the lowest level entities of a system, *i.e.* the individuals (Grimm, 1999). Agent-based models have been used for a wide variety of purposes across a range of disciplines (Van Dyke Parunak *et al.*, 1998), including fisheries science (*e.g.* Rose & Cowan, 1993; Dreyfus-León, 1999; Rothschild, 2000; Little *et al.*, 2004; Hesp *et al.*, 2010). Coincident with increases in computer technology, studies employing

this computer-intensive simulation approach are becoming increasingly reported in the literature.

As ABMs are designed to explore some aspect of a real world scenario, it is crucial that the researchers have some knowledge of the agents and system that they are modelling. Field or laboratory studies are thus invaluable for constructing models of agent behaviour, and then testing those models (DeAngelis *et al.*, 1980; Grimm and Railsback, 2005; Benenson *et al.*, 2008). The variety of high resolution ASL foraging behaviour data, as outlined above, provided an excellent basis for constructing an agent-based model to simulate movements of ASLs. Furthermore, the availability of relatively fine scale data on the distribution of fishing effort in Western Australia made it possible to employ agent-based modelling to estimate rates of potential encounter of ASLs in Western Australia with gillnets used by the commercial fisheries in the southern half of the state.

Approaches for modelling animal movements

Approaches to modelling animal movements fall within two broad categories, namely Eulerian and Lagrangian approaches. Whereas the former summarises a composite of random walks in space and time, using partial differential equations, the latter provides a discrete representation of movements, based on a sequence of movement steps (Börger, 2008; Smouse *et al.*, 2010). Eulerian approaches are typically applied to population analyses, whereas Lagrangian approaches are the usual choice for agent (or individual) based models (Turchin, 1998; DeAngelis & Mooij, 2005; Grimm & Railsback, 2005; Börger, 2008; Smouse *et al.*, 2010).

Many studies of animal movements have been undertaken using random walk models (*e.g.* Codling *et al.*, 2008). The simplest random walk models are both “uncorrelated” and “unbiased”, *i.e.* the direction of movement is completely independent of any previous movement (= uncorrelated) and there is no “preferred” movement direction (= unbiased). To illustrate this point, consider an animal moving (*e.g.* whilst foraging) over a 2D grid. In the simplest form of random walk model, an animal located in a particular cell would have an equal probability of next moving to

any one of that cell's four bordering cells (*i.e.* an equidistant move up, right, down or left).

Some more complex forms of random walk approaches include correlated random walks (CRWs), biased random walks (BRWs) and biased, correlated random walks (BCRWs) (Codling *et al.*, 2008). In the first of these, movements between successive steps are correlated, with the result that each step tends to point in a direction similar to the last step taken. As the number of movement steps that follow a previous step increases, however, the overall influence of that step on directions of future movements increasingly becomes diminished (Turchin, 1998; Benhamou, 2006). In biased random walk models, a directional bias is introduced by increasing the probability of movement towards a particular direction. In such models, animal movements are often influenced by external environmental factors, such as a “preferred” water depth range, for an aquatic animal, for example (Codling *et al.*, 2008), and/or other factors, such as an “attraction” by the animal towards some focal point, such as a nest site or colony (Smouse *et al.*, 2010). Biased, correlated random walk models, as the name implies, involve movements that are both correlated and biased.

Another class of movement model, based on random walk processes, is the Lévy walk model. Lévy walks comprise “walk clusters” of relatively short step lengths (*i.e.* distances between turns, known as flight intervals), connected by substantially longer movement “jumps” (Bartumeus *et al.*, 2005; Sims, 2010). Lévy walk approaches have been considered by some to constitute a better approach for describing movements of species in environments in which resources are randomly-distributed and very sparse (*i.e.* because “Lévy flights” increase the probability of encountering new areas) (Bartumeus *et al.*, 2002; Sims *et al.*, 2008; Sims, 2010). These models have attracted some controversy, however, which appears to reside with the fact that there have been several instances where Lévy walk models have been used to describe movements of species for which their movements clearly do not conform to a Lévy walk process (Benhamou, 2007; Sims *et al.*, 2007; Edwards, 2008; Plank & Codling, 2009). With respect to pinnipeds, it may thus be relevant that

Austin *et al.* (2004) concluded that the Grey Seal *Halichoerus grypus* typically does not follow a Lévy walk pattern. As ASLs are not rapid swimmers (see above) and continuously dive (to the sea floor) throughout their foraging trips, this raises the possibility that the movements of individuals of this species do not (consistently) follow a Lévy walk pattern.

State-space models (SSM) represent yet another class of movement model. These models represent time-series methods which, via a process model, predict the position of an animal in a future system state, based on that system's current state (Jonsen *et al.*, 2003, 2005; Patterson *et al.*, 2008). These models take into account the imprecision of observation data using likelihood methods. According to Patterson *et al.* (2008), state-space models are often highly complex and thus difficult to understand and implement, with the result that ecologists often need to collaborate with statisticians in order to be able to develop such models. They can also be very computer intensive. Movement models of this type have, however, been successfully developed for several pinniped species, *e.g.* *H. grypus* and the Californian sea lion *Zalophus californianus* (Breed *et al.*, 2009, 2011; Ward *et al.*, 2009).

As pointed out by Tremblay *et al.* (2009), when selecting any model, there needs to be an acceptable trade-off between performance and complexity. Tremblay *et al.* (2009) conclude that for most applications, a biased random walk model is likely to constitute an excellent compromise between complexity, computation time and ease of implementation, and used this type of approach for modelling movements of northern elephant seals (*Mirounga angustirostris*). In this (one year) study, movements of ASLs were simulated using a biased random walk model. Distributions for depth ranges, distances travelled by ASLs from their colonies, lengths of foraging trips, time intervals between successive foraging trips and ASL travel speeds, calculated for juveniles and adult females in different colonies from available satellite-tracking data, have been used as the basis for simulating movements of ASLs in the model.

NEED

Australia's only endemic pinniped, the Australian sea lion (ASL) *Neophoca cinerea*, is one of the rarest sea lions (ca 14,700) worldwide and is listed as "vulnerable" under the Commonwealth EPBC Act and as "specially protected fauna" under the Western Australian Wildlife Conservation Act. Listing as a vulnerable species under EPBC legislation recognises that the ASL population has been depleted and requires actions to promote its recovery.

There is considerable concern among some researchers and community sectors that incidental bycatch of ASLs by commercial gillnetting may be preventing the recovery of ASL populations from their current depleted states. Goldsworthy *et al.* (2010) recently estimated that several hundred ASLs die annually in South Australia due to gillnetting, indicating that there is an urgent need to re-assess the extent to which ASLs in Western Australia are affected by commercial gillnetting.

The Western Australian Temperate Demersal Gillnet and Demersal Longline Fisheries (comprising the JASDGDLF and WCDGDLF) have recently undergone Marine Stewardship Council (MSC) pre-assessment and their members are acutely aware of the urgent need for a better understanding of ASL interactions with gillnets in Western Australia, if they are to pursue full MSC certification. Furthermore, existing risks to ASL colonies in the southern half of Western Australia will presumably be affected by the implementation of marine parks through the Commonwealth's South West Bioregional Planning process, which is due for completion in the near future. Thus, development of a quantitative model for estimating levels of risk of ASL interactions with gillnets will provide a basis for evaluating any conservation benefits to ASLs arising from the future establishment of marine parks in waters off Western Australia. Estimates of existing ASL conservation risks and the development of a modelling tool for quantifying levels of risk reduction resulting from the implementation of marine parks will assist industry, government agencies and stakeholders to manage the implications of the South West Bioregional Plan as it relates to the conservation of ASLs.

As the distribution of ASL colonies, foraging areas of ASL individuals, and dynamics of gillnet fishing in Western Australia are very different from South Australia, the results of the South Australian study cannot be directly applied to the Western Australian situation. The accuracy of ASL/gillnet interaction rate estimates has major implications for both the conservation of ASL populations and for the viability of the above-mentioned regionally important fisheries. Developing improved analytical methods for assessing levels of risk associated with protected species captures, (*e.g.* the agent-based modelling approach proposed here) and comparison of results between approaches will be key to developing effective fishery management measures that are consistent with the principles of Ecologically Sustainable Development, including the conservation of biological diversity.

OBJECTIVES

1. Develop a tool to assist in determining the implications of the current distribution of commercial gillnet fishing for different colonies of Australian sea lions.
2. Estimate the proportion of Australian sea lions, in different colonies, that encounter commercial gillnets in Western Australian waters each year.

MATERIALS AND METHODS

This section provides a detailed description of the agent-based model (ABM) developed to simulate movements of Australian Sea Lions (ASLs) in different colonies in southern Western Australia and to estimate potential encounter rates of ASLs with nets used by the commercial demersal gillnet fisheries in this region.

Description of the agent-based model

Method for describing the model

The description of the ABM developed in this study broadly follows the protocol recommended by Grimm *et al.* (2006) for describing such models.

Software platform, hardware and software requirements and simulation time

The model was developed in VisualBasic.net (version 3.5 SP1; Microsoft Visual Studio 2008, version 9.0.30729.1 SP, Microsoft 2007). The minimum hardware requirements for this software are a 1.6 GHz CPU with 384 MB of RAM. It requires the Microsoft Windows XP (Service pack 2) operating system or above. The program has the potential to be distributed to researchers as an executable file which can be run on a standard PC computer. When running simulations, data are read into the program from text files. For the purposes of this study, these files were formatted employing Visual Basic for Applications (VBA) in Microsoft Excel. Note that, to run the model, the input data files must be formatted in the same manner as those currently used to run the model. A simulation for an ASL colony (specifying 200 individuals of a certain sex, and a 1 year period for the simulation, plus a 50 day burn in period) takes ~1 hr to run on a PC with a 2.53 GHz dual core with 3.5 GB of RAM.

The purpose of the model

The purpose of the ABM is to simulate movements of individual Australian sea lions around each of the 24 surveyed WA ASL breeding colonies and estimate the number of potential encounters of ASLs with commercial gillnets during three successive financial years, *i.e.* 2006/07, 2007/08 and 2008/09. The model simulates the pattern

of ASL movements around each colony based on frequency distributions of key movement variables calculated using ARGOS satellite tracking data from previous studies. Each time an ASL moves, the model calculates its position relative to all gillnets currently set within a specified range of its colony, as described by commercial fishers' log book data.

State variables and scale

In agent-based (or individual-based) modelling, “agents” (or individuals) are considered to be “computer simulations of unique actors, capable of autonomous and adaptive actions” (DeAngelis & Mooir, 2005; Grim *et al.*, 2005; O’Sullivan, 2008, see also Hesp *et al.*, 2010). The current model consists of one type of agent, namely Australian sea lions. The state variables characterising each individual ASL are a unique integer number and “sex”, *i.e.* cow or juvenile. The study has not considered either bulls or pups, due to a lack of satellite tracking data for such individuals from WA colonies. The satellite tracking data had been collected by Dr Richard Campbell and colleagues, under projects funded by the Department of Environment Water, Heritage and the Arts, the Australian Marine Mammal Centre and the Northern Agricultural Centre. Data were provided by platform terminal telemetry (PTT) tags which operate via the ARGOS location system. These locations are associated with an estimate of precision and do not have the same accuracy as a GPS location. Each gillnet placed on the computer landscape grid during a simulation run also has a unique integer number and is associated with a particular fishing session.

During a simulation, ASLs move over a “landscape” grid constructed using data extracted from the Australian Bathymetry and Topography Grid created by Geoscience Australia in 2009 (Whiteway, 2009). The landscape grid in our model covers a total area extending from -24° S to -36° S and 112° E to 129° E. Each cell within the overall model landscape grid is ~ 1.1 km². The depth at the latitude and longitude corresponding to each corner of each cell is estimated (using the Geosciences Australia data) to the nearest 1 m (Fig. 1). Some of the model output

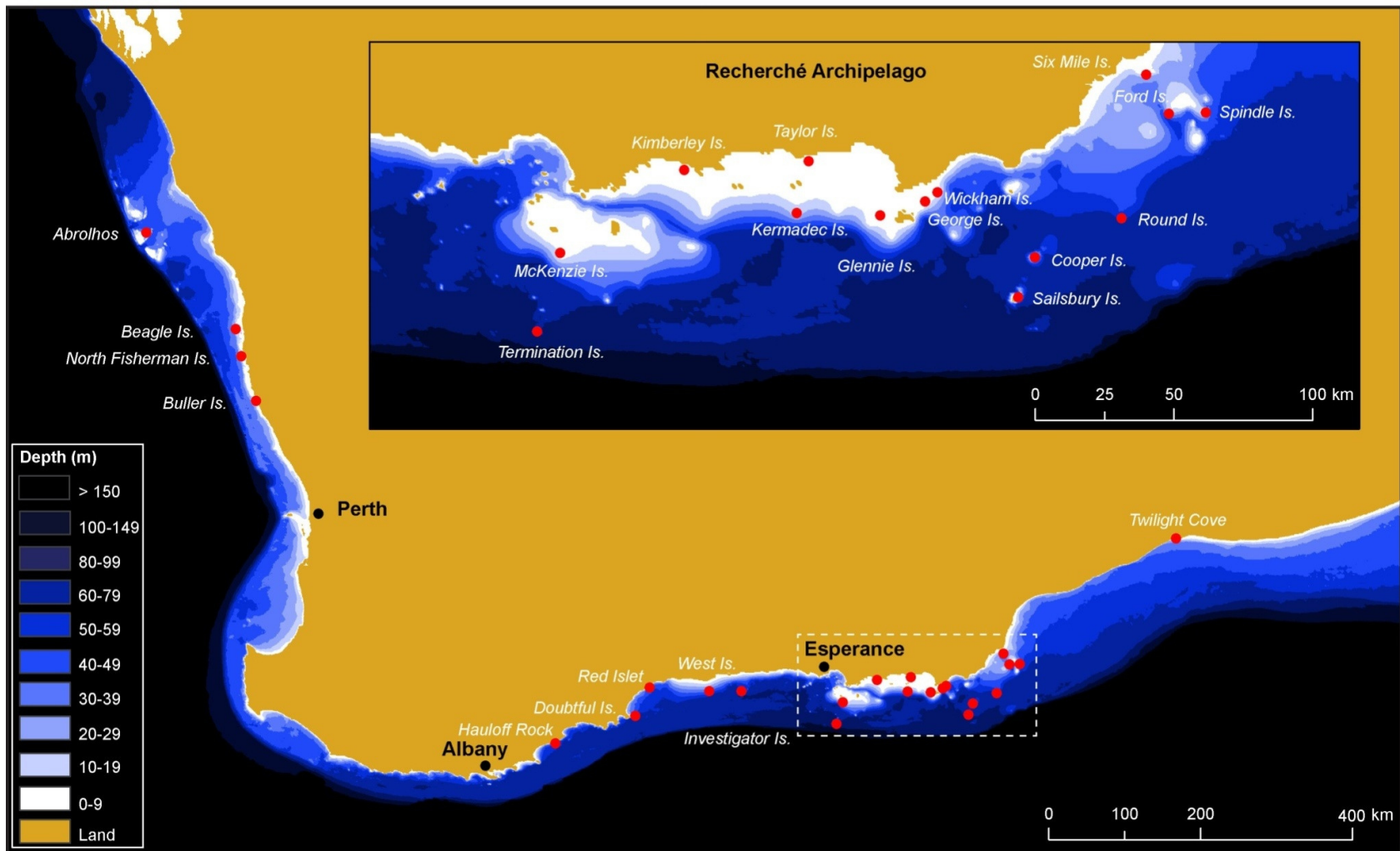


Figure 1: Map showing the locations of ASL colonies (red dots) in southern Western Australia. This map, which was produced using data from GeoSciences Australia in 2009 is used in the model.

statistics are calculated at a resolution of 10 X 10 minute blocks (~18 km²), as used by the WA Department of Fisheries for reporting catch and effort fishing statistics in the Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) logbooks. Each simulation is run for a one year period (plus an initial specified lag period of 50 days, to enable the model to stabilise before statistics start being recorded).

Process overview and scheduling

The ABM consists of three key components, *i.e.* 1) a model for simulating ASL movements, 2) a component for scheduling net set and retrieval events and 3) a component for estimating the rate of potential encounters of ASLs with commercial gillnets.

Events scheduled in the model belong to three broad categories, including i) simulation events, ii) ASL events and iii) net events (Table 1). Further details regarding the scheduling of each event are provided below.

Table 1: List of the possible event types for each of the three broad event categories in the model.

Simulation events	ASL events	Net events
Termination event Display grid event	Decision to go foraging Tag location recording event ASL movement event	Net set event Net retrieval event

The method used to schedule the various events during model simulations broadly follows the approach described by Hampton and Majkowski (1987). At the beginning of a simulation run, an event belonging to each of the event types for each of the three broad event categories (and for each ASL and net) are scheduled and added to an event queue. The model processes each event in the queue according to the order in which they were scheduled. As each event is processed, new events are scheduled until the simulation is terminated. The details of how each event is scheduled and the consequences of each event are described below.

The agent-based model program employs an efficient algorithm and data storage structure (AVL Tree) to store and retrieve details required to process the

simulation events. The algorithm, created by Adelson-Velskii and Landis (1962), was downloaded from <http://www.planetsourcecode.com/vb/scripts/>. The AVL classes within this algorithm were attributed to Jim Harris.

The scheduling of events is also dependent on the pseudo-random number sequence. To generate random numbers, a Visual Basic implementation of the Mersenne Twister algorithm (MT19937ar), translated by Ron Charlton (see <http://www.math.sci.hiroshima-u.ac.jp/~m-mat/MT/efaq.html>), was used. The algorithm had initially been designed and coded in C by Matsumoto and Nishimura (1998) and then translated to VBA by Pablo Mariano Ronchi.

Design concepts

Agent interactions

During model simulations, ASLs respond to their environment in several ways. The movements, *i.e.* the probabilities of individuals moving to a particular location on the grid, are influenced by whether an ASL is currently foraging and, if so, i) the distance between its current location and colony, ii) its current speed of movement, iii) the time that has elapsed since the start of its current foraging trip and iv) water depth.

The model assumes that the spatial distributions of all of the individual ASLs in a colony of the same sex are influenced in the same manner by key environmental variables, *i.e.* water depth and distance from colony. Although agent-based models provide a platform that is well suited for exploring the consequences of interactions between individual agents, the current model assumes that individual ASLs act independently of each other. It is also assumed that ASLs do not, for example, alter their movements to follow vessels to fishing grounds.

Model outputs

At run time, the following statistics are displayed on the default tab of the user interface, called “Landscape”: 1) financial year, 2) ASL colony for which movements are currently being simulated, 3) coast on which the colony is located (*i.e.* west or south coast of Western Australia), 4) current simulation time (d), 5) number of ASLs

currently on the grid, 6) number of nets currently on the grid, 7) average time (h) between simulated PTT locations, 8) average time (h), ASLs have spent “resting” at the colony site, 9) number of encounters recorded for the colony and 10) number of encounters for all colonies that have been simulated during the current model run (Fig. 2). As simulations progress, the positions of the individual ASLs and gillnets are displayed every 0.2 d.

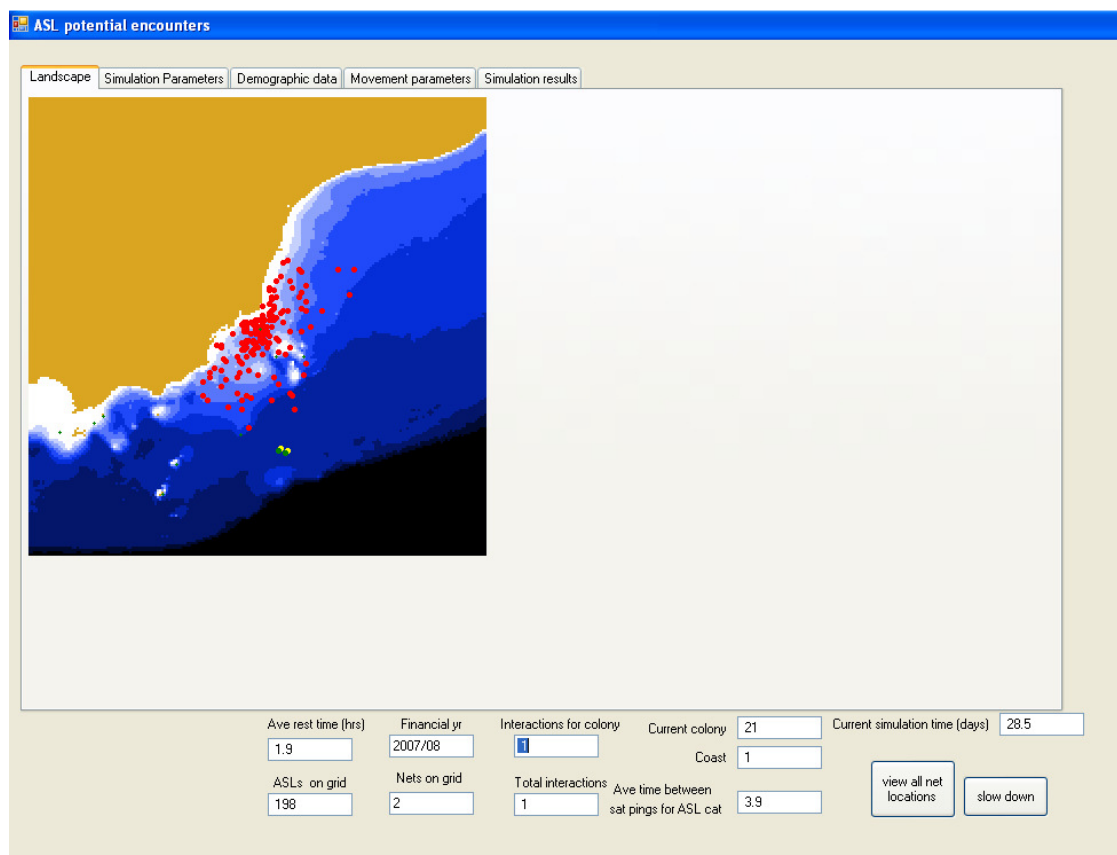


Figure 2: Diagram of the “Landscape” tab of the user-interface displayed during runtime. Each red dot represents an ASL moving over the grid. Each yellow dot represents the start of a gillnet and each green dot represents the end of a gillnet. Light brown areas indicate land. Different water depths are displayed as colours ranging from white (< 10 m depth) to black (> 150 m depth).

During simulations, further data relating to ASL movements are displayed on a tab called “Simulation results”. These include the total number of foraging trips and total number of movements undertaken by female and juvenile ASLs from the specified colony. For both female and juvenile ASLs, plots are displayed of the

distributions for 1) ASL travel speeds (km/h), 2) water depths (m) occupied by ASLs, 3) distances (km) of ASLs from the colony site when “foraging” and 4) durations (hrs) of ASL “foraging trips”. The plots show the distributions for ASLs calculated directly from available ARGOS satellite tracking data, and those determined from simulated movements.

At the end of each simulation for a colony, two text files are produced. The first provides the positions, depths and distances of ASLs from the colony for a specified number of moves. The second data file provides details of the times and locations of ASL encounters with gillnets.

Initialisation

Initialisation of a model run involves i) setting up the landscape grid, ii) reading the available commercial gillnet data, iii) creating the specified number of gillnets for the financial year and scheduling a set and retrieval time for each net, iv) determining expected frequency distributions for the five factors considered to influence the movements of ASLs (*i.e.* travel speed, forage time, rest time, depth and distance from colony), v) creating a specified number of ASLs and scheduling a new foraging trip for each individual, vi) setting the simulation clock to zero at the beginning of the simulation and vii) setting a termination event for the simulation.

Creation of ASL agents

At the beginning of each simulation, a specified number of ASLs of each sex (for specified colonies) are created. They are then placed on the landscape grid at the colony location. ASLs first leave the colony at the scheduled time of the next foraging event for that individual.

Creation of gillnets

Before the commencement of a simulation, all gillnets specified as being used in fishers’ logbooks during the financial year of the current simulation (2006/07, 2007/08 or 2008/09) are created. Note that, for ease of programming, “new nets” are created

for each fishing session and that, in a given fishing session, between 1 and 5 nets may have been used, as specified in the fisher's logbook record. See below regarding the scheduling of net set and retrieval times.

In fishers' logbook data, the locations of net sets are recorded as either a GPS position, or as a block number (based on degrees, and 10 minutes of latitude and longitude), *i.e.* a 10x10 minute area (~18 km²). The "start" position of each net for which a GPS co-ordinate was provided was placed on the grid at that location. If a block number was specified for a recorded fishing session, 200 random locations within that block were generated and the one that most closely matched the recorded depth for that fishing session was chosen.

The set direction of the first net used in any fishing session was specified as a random bearing, α . The "end" position of each net (when set) was determined according to the length of the net and the specified bearing. Thus, the latitude of the end of a net, λ_2 , was calculated as

$$\lambda_2 = \sin^{-1}(\sin(\lambda_1) \cdot \cos(d) + \cos(\lambda_1) \cdot \sin(d) \cdot \cos(\alpha)), \quad 1$$

where λ_1 is the latitude of the start of the net and d is the net length divided by the equatorial radius of the earth (6,378.1 km). The longitude at the end of the net, θ_2 , was determined as

$$\theta_2 = \theta_1 + \tan^{-1}(x, y) \quad 2$$

where θ_1 is the longitude at the start of the net, and where x and y are calculated as

$$x = \sin(\alpha) + \sin(d) + \cos(\theta_1) \quad 3$$

$$y = \cos(d) - \sin(\lambda_1) \cdot \sin(\lambda_2) \quad 4$$

If multiple nets were used in a single fishing session, the nets were set 1-3 km apart, *i.e.* by sampling from a uniform distribution to produce a random value between 1 and 3 for the distance between the starting positions of the various nets used in that session. Multiple nets in a session were positioned approximately

parallel to each other, *i.e.* each on a different bearing, but within 15° degrees of the bearing specified for the first net in the session, to avoid simulated nets bisecting each other. See Fig. 3 for a conceptual diagram of the net placement algorithm.

Input data

Input data are required to i) generate the landscape, ii) create the ASL agents and simulate gillnet sets, and iii) parameterise the decision rules influencing the movements of ASLs over the landscape.

The data required for generating the landscape are a subset of values extracted from the Australian Bathymetry and Topography Grid (Geoscience Australia, June 2009), produced using the World Geodetic System (WGS) 84. The data were extracted to text files using routines written in Visual Basic for Applications (VBA) in Microsoft Excel.

The ARGOS satellite tracking data for ASLs were provided as Microsoft Excel files. Prior to analyses in this study, the location data were accessed via the web-based ARGOS monitoring system (<https://www.argos-system.org/>). All locations that were obviously erroneous (*i.e.* points on land or well off the continental shelf) and locations recorded by the ARGOS system as invalid (class Z) were removed (Argos User's Manual, 2011). Velocity was calculated for travel between all pairs of successive PTT derived locations. The data were then filtered removing locations which resulted in speeds of > 10 km/hr for 5 min, > 100 km/hr for 1 minute or > 500 km/hr for any duration.

Information for each recorded PTT location included an individual ASL identification number, sex, initial tag location (and colony) and time and location of each satellite position (often referred to as a "ping"). The water depth associated with each PTT location was estimated using the same GeoSciences bathymetric data employed to generate the model landscape grid. Note that the average duration between PTT locations was ~ 4 h and that PTT locations are only received by a satellite if the animal to which it is attached is at the surface within the satellite's

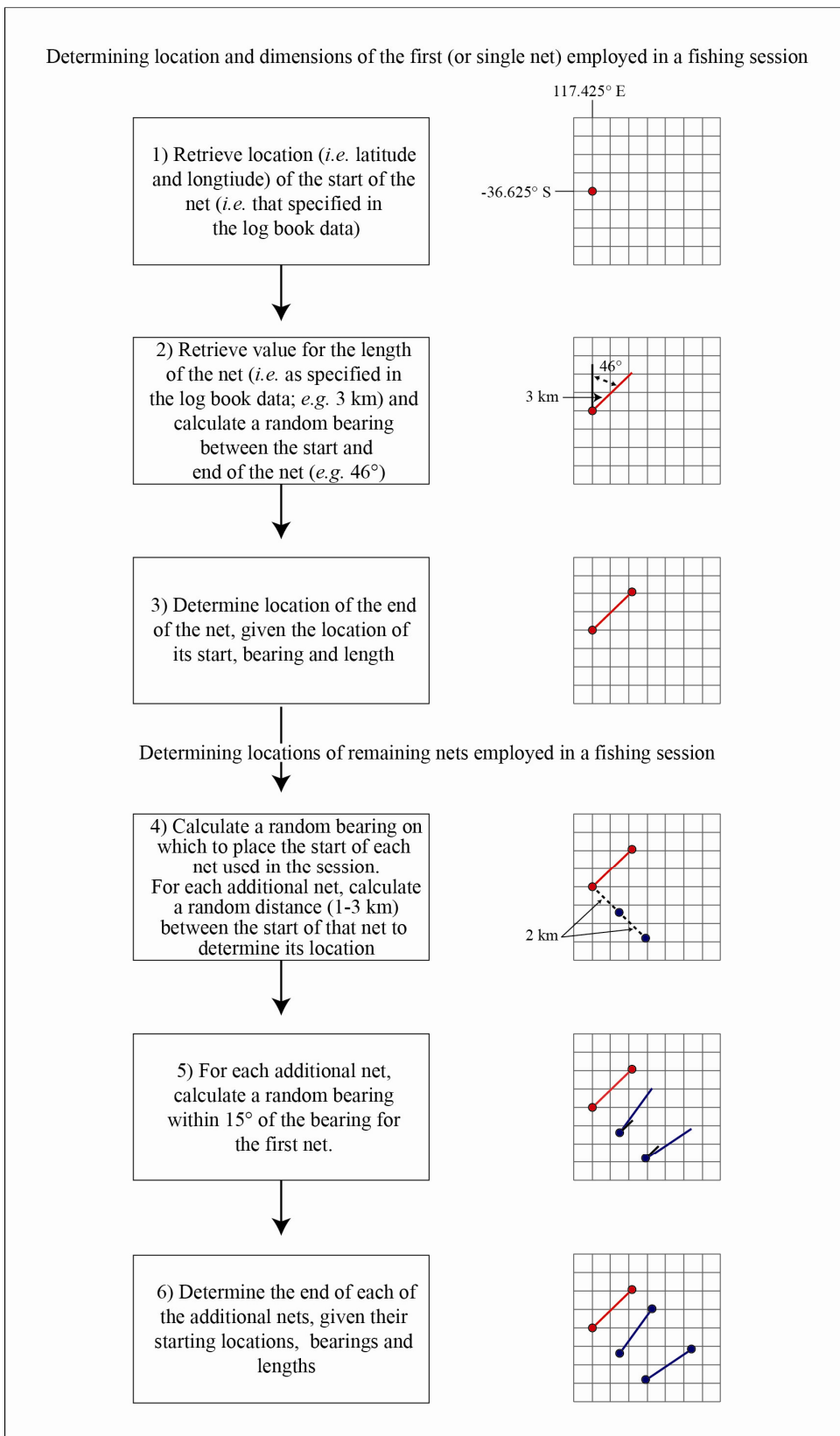


Figure 3. Schematic diagram showing how nets were placed on the computer landscape map during simulation runs. Dots represent the beginning and end of each gillnet, and coloured solid lines represent the “body” of the net. Red has been used to denote the first (or single) net used in a session, and blue for the remaining nets.

“footprint” for sufficient time and in suitable environmental conditions. Data were provided for 42 individuals from eight colonies, including 20 cows, 21 juveniles and a single pup (Table 2). In total, location data for 6,492 PTT detections were provided, including 2,425 for cows, 3,877 for juveniles and 190 for pups. Given the paucity of data for pups, the movements of these individuals were not modelled in this study. These PTT data were used to derive relative cumulative frequency distributions for i) “forage” trip duration (where a single trip was defined as an ASL moving more than 1 km away from its colony before returning, 2) rest time (*i.e.* the time between successive trips, when an individual is located to within 1 km of the colony site), 3) distance from colony (when not resting), 4) water depth (when not resting) and 5) speed (when not resting). Details of how these distributions have been used for simulating ASL movements are provided below.

Table 2: Summary of available ARGOS tracking data for Australian sea lions in WA. The numbers of cows, juveniles and pups that were tagged at each studied colony in Western Australia, and the number of PPT detections for ASLs belonging to each of those colonies are presented. For simulation modelling, data were pooled for the lower west coast and for the south coast.

Colony	Tagged cows	PPT detections (cows)	Tagged juveniles	PPT detections (juveniles)	Tagged pups	PPT detections (pups)
Abrolhos Islands	2	170	2	157	0	0
Abrolhos Islands (total)	2	170	2	157	0	0
Beagle Island	3	416	4	1,395	0	0
North Fisherman Island	3	219	10	1,318	1	190
Buller Island	0	0	1	30	0	0
Lower west coast (total)	6	635	15	2,743	1	190
Red Islet	2	177	2	142	0	0
Investigator Island	3	625	2	835	0	0
Kimberley Island	2	347	0	0	0	0
Six Mile Island	5	471	0	0	0	0
South coast (total)	12	1,620	4	977	0	0

Demographic data for each of the 24 ASL breeding colonies in Western Australia were also supplied. The years for which demographic information for each colony was produced, ranged from 1990 for one colony, to 2005, for 13 of the colonies. For 18 of the colonies, census data had been recorded in 2002 or later.

Although demographic information for ASLs was not used for simulating ASL movements, it was employed in analyses for estimating per capita rates of potential encounter for each colony.

The logbook data recorded by commercial gillnet fishers operating in Western Australia contain a range of details about their fishing activities. Information used to “replay” the fishing activities by these fishers during model simulations included the date of each fishing session, the total time each net spends in the water (*i.e.* the “soak time”) during a fishing session, the total net length used in a session, the number of individual nets used per session (treated as equal sub-units of total net length) and the location and water depth for each net set. The location of each net set was specified either as a GPS position or as occurring within a particular reporting block (see above for details on how nets were positioned over the grid). The fishers’ logbook data, which provided records of fishing activities for the two demersal gillnet fisheries in 2006-07, 2007-08 and 2008-09, were supplied by the Department of Fisheries under strict confidentiality conditions that made it impossible to identify individuals’ fishing operations.

ASL movement model

The movements of ASLs over the landscape grid are controlled by three event types, which include a decision to go foraging event, a tag location recording event and an ASL movement event.

1. Decision to go foraging event

Scheduling: Scheduled to occur approximately hourly, *i.e.* a random time within 15 minutes of each hour whilst resting.

The time of the next decision to go foraging, T_F , is scheduled as

$$T_F = T_C + (1/24) + (-0.5 + r).(1/24).(15/60), \quad 5$$

where T_C is the current time (d) of the simulation clock and r is a random number from a uniform distribution ranging between 0 and 1.

The probability of an ASL deciding to start a new foraging trip (at each decision to go foraging event), P_F , is dependent on T_D , the duration (hrs) between the current time, T_C , and T_{LT} , the time at the end of the previous trip. T_D , is calculated as

$$T_D = T_C - T_{LT} \quad 6$$

The probability of starting a new foraging trip, P_F , is calculated as

$$P_F = 1/\{1 + \exp[-\ln(19) \cdot (T_D - T_{50})]/(T_{95} - T_{50})\}, \quad 7$$

where \ln is the natural logarithm and T_{50} and T_{95} correspond to the lengths of time (spent resting) after which 50 and 95% of ASLs of a given sex commence a new foraging trip. The T_{50} and T_{95} for a given sex and colony are estimated by fitting a logistic curve to the relative cumulative distribution for rest time for that sex and colony derived from the observed ASL satellite data. The curves were fitted employing least squares regression in Microsoft Excel, using Solver.

A random duration in hrs, F_D , for each foraging trip undertaken by an ASL is calculated by drawing random values from the observed relative cumulative distribution for trip duration, for the corresponding sex and colony of each individual.

2. *Tag location recording event*

The frequency between recordings of successive PTT locations in the ARGOS tracking data for an ASL is variable. Thus, many of the calculations for simulating the movements of ASLs in the model are made at intervals corresponding to simulated *tag location recording events*. The times between such events were calculated by drawing random values from the frequency distribution for times between successive PTT locations in the observed data.

3. ASL movement event

Scheduling: Dependent on an individual's speed of movement

In the model, ASL movements were simulated using a biased random walk process, where the probabilities of an animal moving in a particular direction were modified by several factors for which empirical data were available (see below). At each move, an ASL agent relocates from one cell to an adjacent cell, *i.e.* one cell immediately to the north, west, south or east of its current position. Note that, unless resting, an ASL will always move from its current position at an *ASL movement event*. The time taken for an ASL to move to the next position (*i.e.* one cell away) is dependent on the timing of the next movement event, calculated according to the ASL's current speed. More precisely, in the model, an ASL agent moves (in a cardinal direction) between the intersection of one set of four grid cells and that of an adjacent set of grid cells. These locations, corresponding to intersections between grid cells, have associated depths, which correspond directly to the depths recorded by Geoscience Australia at those locations. Note that a more complex model could allow for a movement in any direction, rather than just in a cardinal direction – see section on future directions.

The time taken for an ASL to move from one grid cell to another is dependent on its current speed. The speed at which an ASL travelled whilst “foraging” was calculated by drawing a random value from the observed relative cumulative distribution for travel speed (for the corresponding sex and colony). The travelling speeds for an individual during a foraging trip were re-calculated at each *tag location recording event*.

Before an ASL undertakes any move, the model checks to determine whether the current trip should end, *i.e.* if the individual has returned back to the colony and the duration of the current trip is close to, or has exceeded the scheduled duration for that trip. If the trip has ended, a new *decision to go foraging event is scheduled*.

If the current trip has not been terminated, a series of calculations are undertaken to determine, based on its current position, the neighbouring cell to which the animal is most likely to move. These calculations take into account the probabilities, for ASLs of a given sex and colony, of occurring at a location based on

its associated depth and distance from the colony site, and also the time that has elapsed since the beginning of the current trip, *i.e.* whether the ASL is likely to be returning back to its colony.

In the simplest random walk model, the probabilities of an individual moving a cell to the north, east, south or west, would each equal 0.25. To more accurately model the movements of ASLs, the probabilities of movement in each direction are adjusted (*i.e.* “biased”) according to three main factors, *i.e.* water depth, distance from colony, and trip duration.

Adjustment of probabilities of movement based on depth

The probability of an individual moving from its current position one cell across (north, south, east or west), P_{DE} , is set to zero if the depth (m) of that cell exceeds zero. If the next cell is not located on land, P_{DE} is determined from the observed relative cumulative distribution for ASLs (of a given sex and colony) occurring in different water depths, as determined from the ARGOS satellite location data, and using the Geoscience Australia Bathymetric and Topographic Grid to determine the water depths at the corners of each cell. The probabilities of the ASL moving north, east, south or west are then adjusted so that they sum to 1.

Adjustment of probabilities of movement based on distance from colony

D , the great circle distance (km), *i.e.* “as the crow flies,” between two locations may be estimated as

$$D = R * \{2 * \sin^{-1}[x + \cos(\lambda_1) * \cos(\lambda_2) * y]\}, \quad 8$$

x is determined as

$$x = \sqrt{[\sin(\lambda_1 - \lambda_2)/2]^2} \quad 9$$

and y is calculated as

$$y = \sin[(\theta_1 - \theta_2)/2]^2 \quad 10$$

and where R = the equatorial radius of the earth (6,378.1 km), λ_1 is the latitude and θ_1 is the longitude of the current position of the ASL. λ_2 and θ_2 are the corresponding measures for the colony location. The probability of the ASL moving to each adjacent cell (intersection) based on distance from colony, P_{DI} is determined from the relative cumulative frequency distribution for an individual (of a given sex and particular colony) being a certain distance from the colony, as estimated from the ARGOS tracking data. As is the case with depth, the probabilities are adjusted so they sum to 1.

The overall probabilities of the ASL moving to each neighbouring cell, based on depth and distance from colony, P_C , was calculated as

$$P_C = (P_{DE} + P_{DI})/2 \quad 11$$

Adjustment of probabilities of movement based on trip time

At some moment during a foraging trip, an ASL must start moving back towards the colony to complete its journey. The (default) arbitrary value used in the model to correspond to that moment is the value of time equalling 95% of the scheduled trip duration, T_{95} . It is also assumed that, as an individual returns homeward, its path towards the colony will become increasingly direct as time continues to elapse. The degree to which successive ASL movements are directed towards the colony is dependent on its “strength or return”, S_R , determined as

$$S_R = [1 - (1 - T_E)/(1 - T_{95})], \quad 12$$

where T_E is the duration of time that has elapsed since the commencement of the trip.

On estimating the influence of trip time on the probabilities of an ASL moving to an adjacent cell, the bearing of the cell currently occupied by that individual to the colony, in radians, β , is first determined as

$$\beta = \tan^{-1}(x, y) - [2\pi * (\tan^{-1}(x, y)/2\pi)], \quad 13$$

where x is calculated as

$$\sin(\theta_2 - \theta_1) \cdot \cos(\lambda_2) \quad 14$$

and y is determined as

$$[\cos(\lambda_1) \cdot \sin(\lambda_2)] - [\sin(\lambda_1) \cdot \cos(\lambda_2)] \cdot \cos(\theta_2 - \theta_1) \quad 15$$

and where λ_1 and θ_1 are the latitude and longitude of the current cell and λ_2 and θ_2 are the latitude and longitude of the colony site. The bearing (in degrees) towards the colony, α , is thus

$$\alpha = \beta * 180/\pi \quad 16$$

When an ASL is returning directly towards the colony (*i.e.* when $S_R = 1$), the probability of moving north, P_N is

$$P_N = \begin{cases} |\cos[\sin(\delta)]| & \text{if } B < 90 \\ 0 & \text{if } 90 < B < 180 \\ 0 & \text{if } 180 < B < 270 \\ |\sin(\delta)| & \text{if } 270 < B < 360 \end{cases} \quad 17$$

where δ is the angle to the colony relative to north (in radians). P_R , the probability of moving either north, east, south or west when $S_R = 1$ was calculated by using the same equations (*i.e.* as in 17) but, depending on the direction, re-arranging their order.

If an ASL is returning to the colony but S_R is < 1 , the probability of moving to each adjacent cell, after adjusting for trip duration, P_A , is

$$P_A = P_C + S_R(P_R - P_C) \quad 18$$

P_A is then rescaled to sum to 1. Note that, to ensure ASLs are able to return to the colony site, individuals are allowed to cross land when $S_R > 0.5$, as may occur during a simulation if there is an island or headland in the direct path of the ASL towards the colony.

Further adjustments to probabilities of ASL movements

When using the random walk approach described above to simulate ASL movements, the distributions for water depth, distance from colony and speed calculated from the simulated movement data did not always match the corresponding observed distributions determined from the satellite data. However, it is possible to improve the match between the simulated vs observed data for these distributions, and thus accuracy of the overall spatial pattern of movement, by modifying the probabilities of movements of ASLs according to each of the three factors (depth, distance from colony and speed) considered by the model. In other words, as the simulation progresses, the model can be “tuned” to more reliably simulate movements of ASLs.

To improve the match between the distributions for simulated depths vs observed depths, the observed distribution for depth is modified after a set number of movements (default value = 1000 moves) during the simulation by a scaling factor, S , calculated according to the differences between the two distributions in the proportions of ASLs at each depth, *i.e.*

$$S = (P_{sim} - P_{obs}) * DE \quad 19$$

where P_{sim} and P_{obs} are the proportions of ASLs at each depth, DE , as described by the simulated data and observed data, respectively.

Similarly, a scaling factor, D_{SF} , was calculated to match the distributions for simulated vs observed distances from the colony, using the above equation, but substituting distance from colony for depth. A scaling factor to modify the observed cumulative distribution for speed, S , was calculated as

$$S = F_{sim} - F_{obs} \quad 20$$

where F_{sim} and F_{obs} are the cumulative frequencies of ASLs moving at each speed, as described by the simulated and observed data, respectively.

In summary, the processes for simulating ASL movements may be depicted as in the schematic diagrams in Fig. 4a,b.

Scheduling of net set and retrieval events

Scheduling: As specified in fishers logbook data.

Each net that is created at the beginning of a simulation, *i.e.* each net to be set during the year as recorded in fishers' logbook data, is set and retrieved once. The time of net retrieval, T_{NR} , is calculated as

$$T_{NR} = F_D + r \quad 21$$

where F_D is the date that a net was hauled, as specified in the fisher's data, and r is a random number between 0 and 1.

For a given session, the soak time for each net, T_S , was assumed to be the same, *i.e.* equal to the net soak time recorded in the fisher's log book. The time for setting that net, T_{NS} , was determined by subtracting T_S from T_{NR} .

Estimating the rate of potential encounters of ASLs with gillnets

In this model, an ASL is considered to have potentially encountered a gillnet either when it has moved to within a specified proximity to a net (500 m), or when a net is placed in a location that is less than that distance to the ASL (Fig. 5). As the relationship between a sea lion's proximity to a net and the probability of it interacting with the net is unknown, the model was run using a proximity-to-net value of 500 m to describe potential encounters. This distance was chosen as it was considered to represent a plausible distance over which there is a risk that a sea lion might either accidentally encounter or be attracted to the net. However, the model could be re-run with any other given proximity-to-net value, *e.g.* if a more defensible, empirically-derived estimate was able to be obtained. Until such time, it should be reiterated that the relationship between ASLs' proximity to nets and their risk of interacting with or being captured by those nets has been assumed and the potential encounter rates described in this study are **not** equivalent to actual interaction or capture rates.

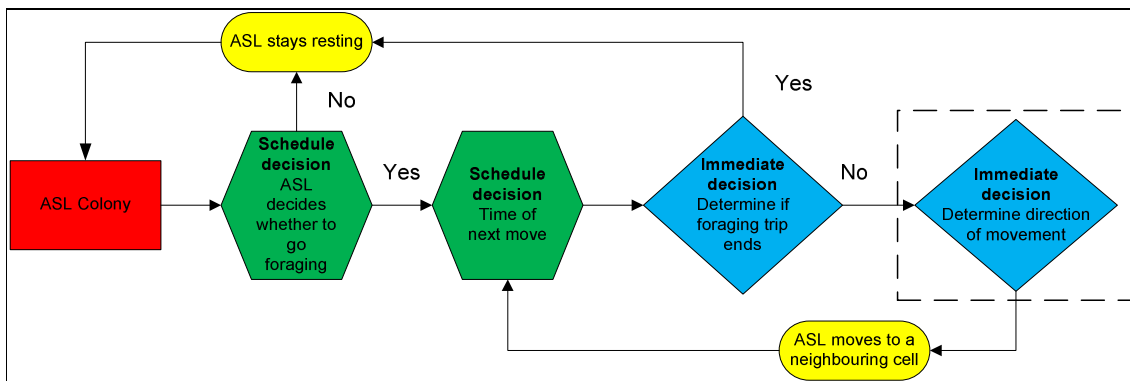


Figure 4a. Schematic overview of the processes undertaken in the model for simulating movements of Australian sea lions.

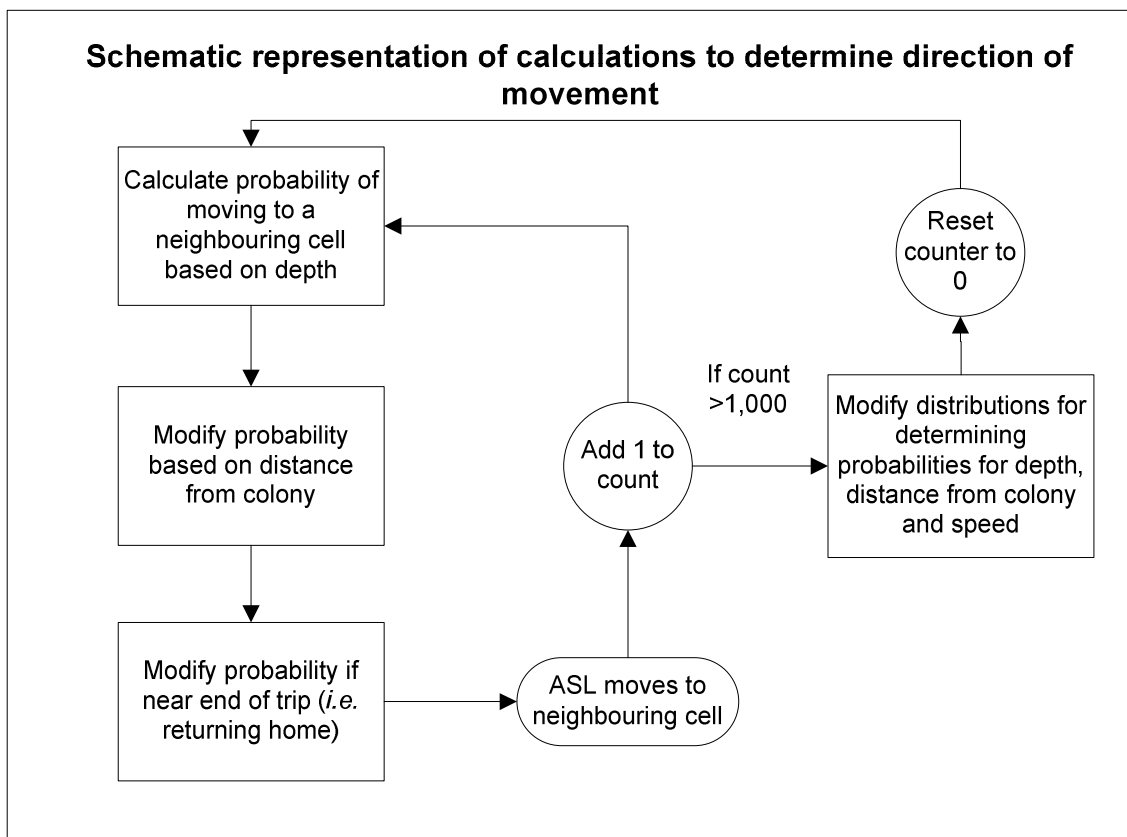


Figure 4b. Schematic overview of the processes associated in determining the directions of movements for Australian sea lions, *i.e.* the processes associated with the blue diamond in the dashed box in Fig. 4a.

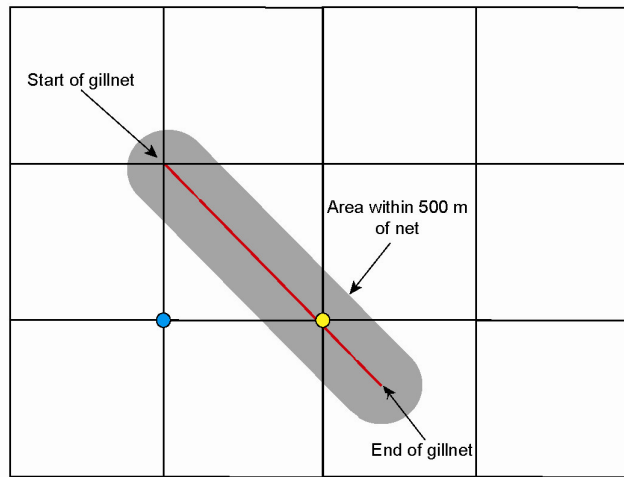


Figure 5: Schematic diagram showing the positioning of a gillnet (red line) across several grid cells, and the assumed proximity-to-net distance that is used to estimate potential encounters (grey shading). One ASL (yellow circle) has moved to within the chosen proximity-to-net distance and thus a *potential encounter* would be recorded by the program, whereas another ASL (blue circle) is currently positioned outside the proximity-to-net distance.

The program checks to determine whether an ASL’s position lies within a set distance of a gillnet when it has just been placed on the grid (*i.e.* net set event), and after each move by an individual ASL (*i.e.* ASL movement event). In the case of a net set event, the position of each ASL currently on the grid (for a given colony) relative to any position along each net currently on the grid is calculated. The equations for determining the distance of an ASL from a particular location along the net are the same as those used for determining the distance of an ASL to the colony site (see equations 8-10). A bisection algorithm is employed to determine the closest distance of the ASL to any location along the net. In the case of each ASL movement event, the same process is employed, but the distance to the net is only evaluated for the individual that has just moved.

For each foraging trip by an ASL, the program only records up to one potential encounter of the ASL with a gillnet during a foraging trip. Note that, in real life, if an ASL detects a net, it is possible that it may interact with several parts of that net at intervals during the net set, *e.g.* to feed on new fish caught in the net. To reduce complexity, the model considers each of these as a single “potential encounter.”

Note that the algorithms employed by the model to estimate encounter rates provide an approximation that might slightly under-represent the actual rate at which ASLs move to within the specified proximity-to-net, as the distance to the net is currently only evaluated in the model at the end of each move. This component of the model can be refined, *e.g.* by evaluating the distances at multiple intervals between an ASL's movement from one cell to another (although this would greatly increase the number of computations required, and thus reduce program speed).

Simulations undertaken for this study

The agent-based model has been used to undertake simulations for each of the 24 surveyed WA breeding colonies in each of three successive financial years. Separate simulations were undertaken for cows and juveniles. Each simulation involved "creating" 200 individuals, *i.e.* a large number, to produce robust information on the movements of ASLs around each colony (and thus also on potential encounter rates). Note that the results presented on potential encounters for each sex, colony and year, represent those derived from a single simulation run (with a run representing several million movements of ASLs).

RESULTS

Visual comparisons of observed vs simulated ASL locations

Visual comparisons of the locations of the two cows from the Abrolhos Islands, recorded by ARGOS satellite tracking, with sets of simulated movement data for cows at that location (of the same sample size and same number of individuals), show that the spatial movement patterns predicted by the model were broadly similar to those determined from the observed data (Figs 6a-c). Although the movement patterns would not be expected to match completely (because of random stochasticity and as all movements by ASLs in the model are exactly 1 grid cell apart and thus plotted points more often overlay each other), it is clear from the observed data that cows did occasionally travel further than predicted by the model (Figs 6a-c). For example, from the observed data, it is clear that cows did occasionally cross a channel (the Zeewijk Channel) between the “Easter Group” of Islands (where most positions were recorded) and the “Pelsaert Group” of Islands (to the south of the Easter Group of Islands), but this never happened in simulations. The observed vs simulated locations for juveniles at the Abrolhos Islands were very similar and, unlike the situation for cows, locations for juveniles were always recorded around the Easter Group of islands (Figs 6d-f).

The observed and simulated locations for cows belonging to the Beagle Island colony (near Jurien Bay) were similar (Figs 7a-c). In contrast with the situation at the Abrolhos Islands, where cows moved no further than ~ 30 km, the observed data show that cows at Beagle Island tend to move much further from the colony site, *i.e.* to a maximum of ~ 70 km, with individuals often travelling a substantial distance along the coast (north or south). Although the observed and simulated locations for juveniles at Beagle Island were similar, with the majority of recorded locations lying close to the colony site, the satellite data show that juveniles do sometimes move a substantial distance away from the colony, which was not evident in the subsets of simulated data extracted for this analysis (Figs 7d-f).

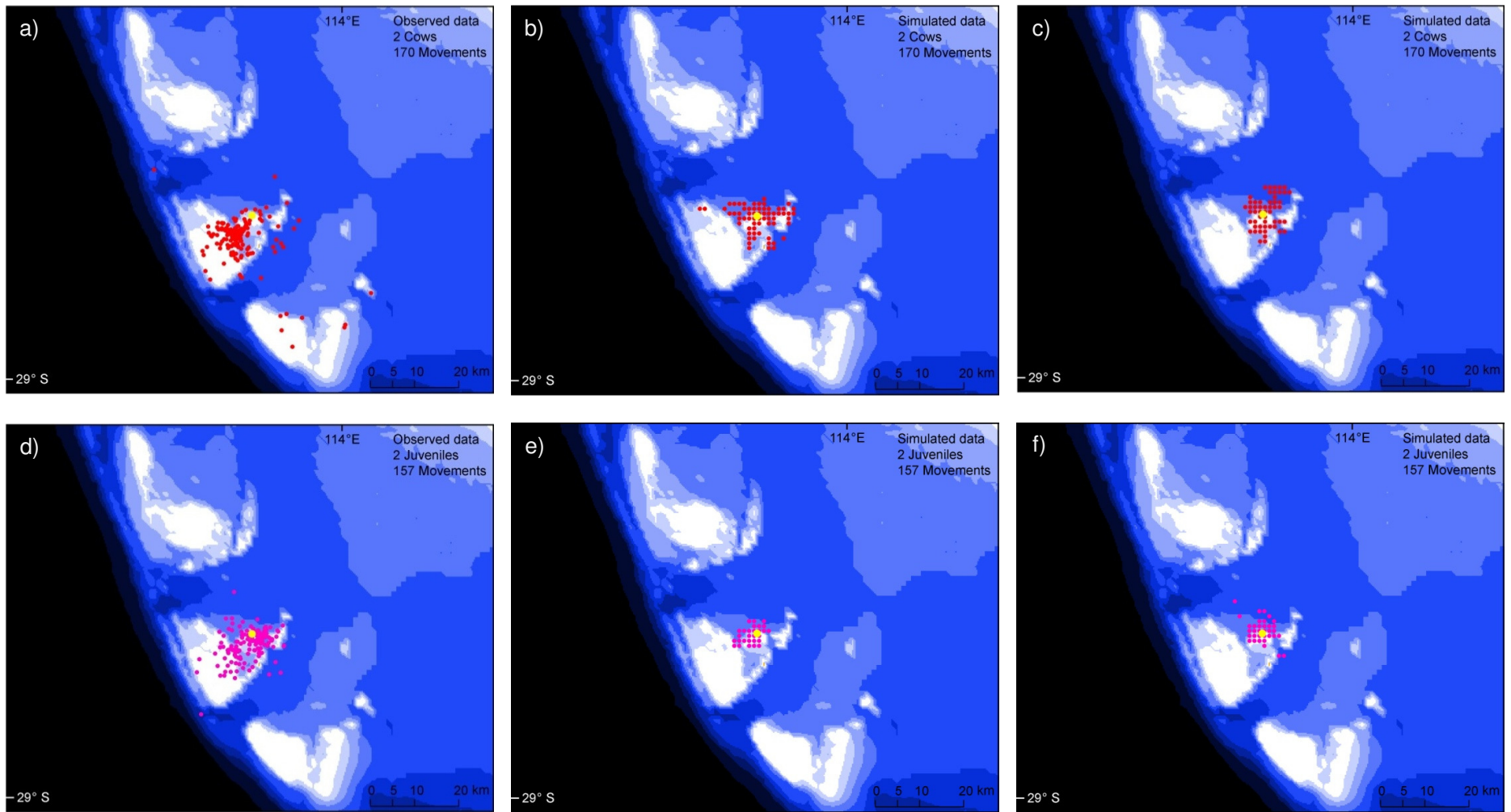


Figure 6: Observed and simulated location data for Australian sea lions at the Abrolhos Islands. Two sets of simulated data were extracted from model outputs, representing the same number of observations from the same number of individuals as in the observed satellite tracking data. a & d) observed locations for cows and juveniles, respectively, b & c) simulated data sets for cows, e & f) simulated data sets for juveniles.

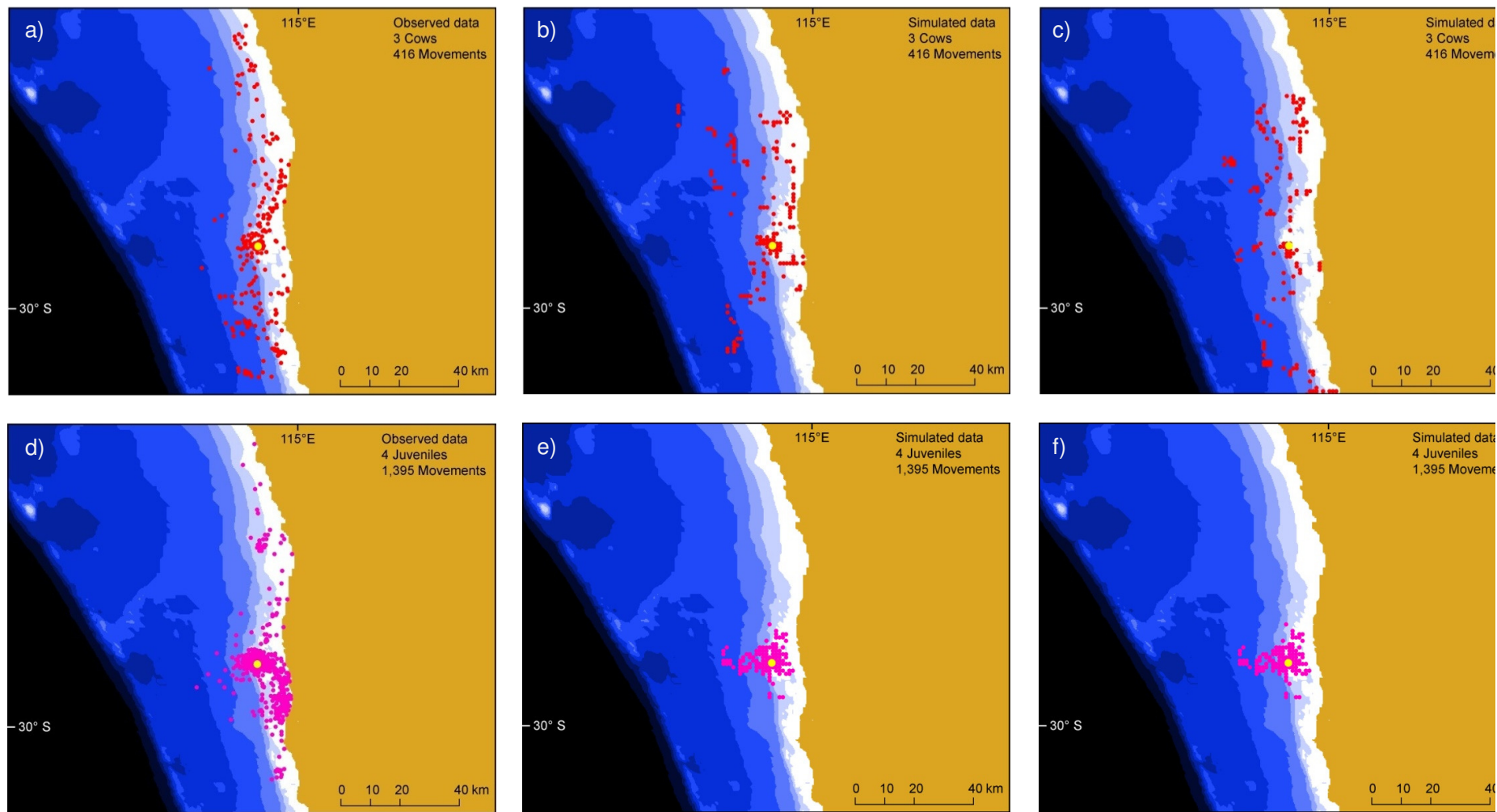


Figure 7: Observed and simulated location data for Australian sea lions at the Beagle Island near Jurien Bay. Two sets of simulated data were extracted from model outputs, representing the same number of observations from the same number of individuals as in the observed satellite tracking data. a & d observed locations for cows and juveniles, respectively, b & c) simulated data sets for cows, e & f) simulated data sets for juveniles.

At Investigator Island, on the south coast, there was again a degree of similarity between the observed and simulated geo-locations of cows, with the majority of observations occurring near the colony and with some others lying near the shelf-edge and the coast (Figs 8a-c). The observed locations for juveniles, in particular, at Investigator Island show two distinct clusters of points, one at the colony and another on the coast (a “haulout” location). The locations predicted by the model, as shown by the two simulated data subsets extracted for the comparison, mostly fell in relatively close proximity to the colony site (Figs 8e-f).

Observed vs simulated distributions for speed, depth, distance and forage time

The observed and simulated distributions for travel speed (km/h) and forage time (hrs) for cows at the Abrolhos Islands, were very similar, and the same was true for juveniles (Fig. 9a). Travel speeds were typically ≤ 2 km/h for cows, and ≤ 1 km/h for juveniles. Forage times typically did not exceed four days. The observed data show that cows at the Abrolhos Islands occurred at depths ranging down to ~ 50 m, with the proportion of observations decreasing progressively with increasing water depth. Although the locations of cows predicted by the model occurred within a similar depth range, there was a “spike” in the relative frequency of observations at depths of 35-39 m. The distances travelled by cows from the colony site tended to be underestimated by the model (Fig. 9a), possibly due to the Zeewijk Channel acting as a “barrier” to movements by simulated ASLs (*i.e.* because of the greater water depths in the channel than in the surrounding waters). Unlike the situation with cows, the observed and simulated depth distributions for juveniles at the Abrolhos Islands matched closely throughout the full range of depths, and both exhibited a distinct peak at 35-39 m. However, as with cows, the model sometimes underestimated the distances travelled by juveniles from the colony (Fig. 9b). Comparisons of the observed vs simulated distributions for travel speed, depth, distance and forage time, for cows at Beagle Island show that, in each case, they matched closely, and that the same was true for juveniles (Fig 9c-d).

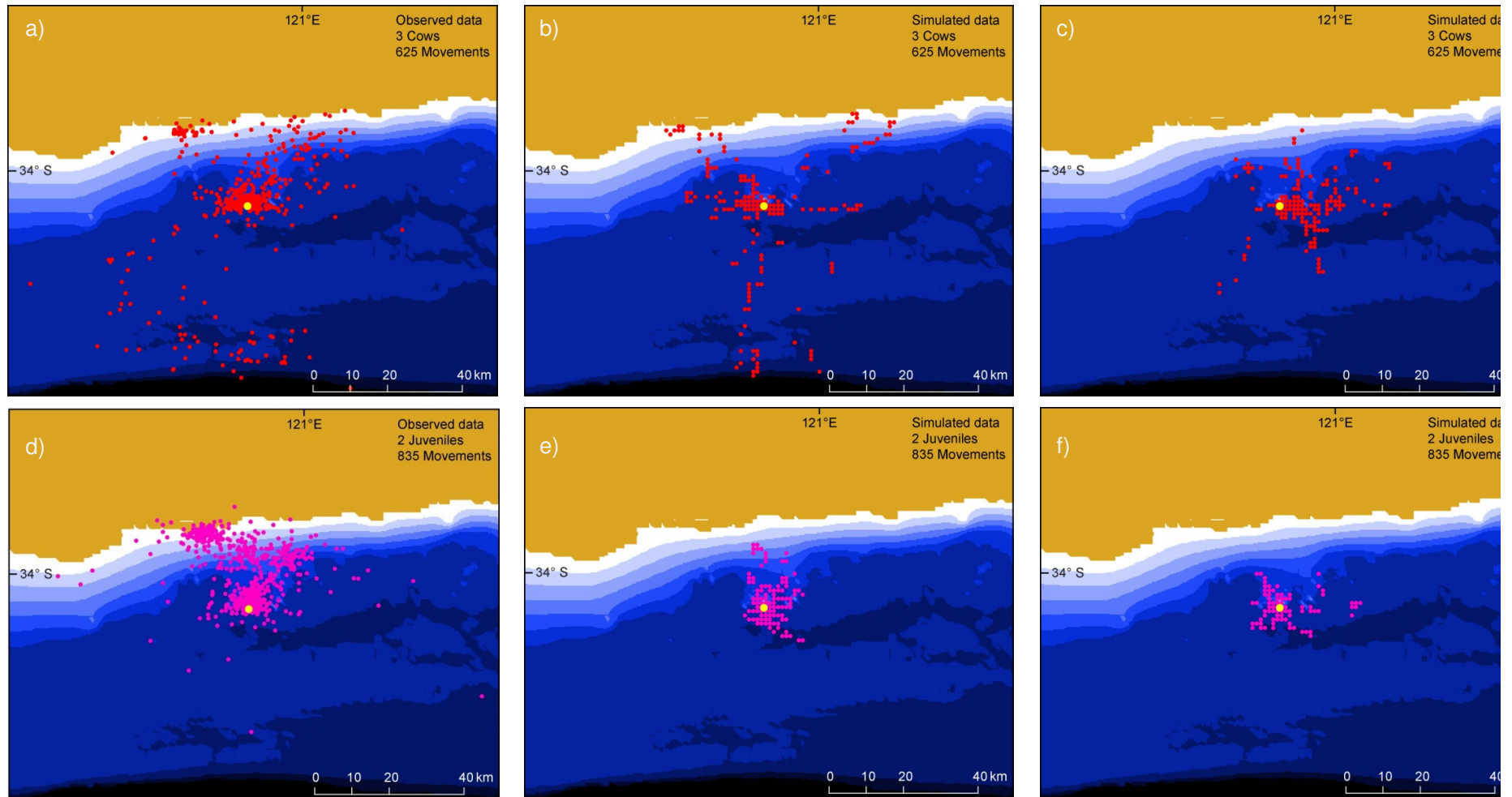


Figure 8: Observed and simulated location data for Australian sea lions at Investigator Island, near Esperance. Two sets of simulated data were extracted from model outputs, representing the same number of observations from the same number of individuals as in the observed satellite tracking data. a & d) observed locations for cows and juveniles, respectively, b & c) simulated data sets for cows, e & f) simulated data sets for juveniles.

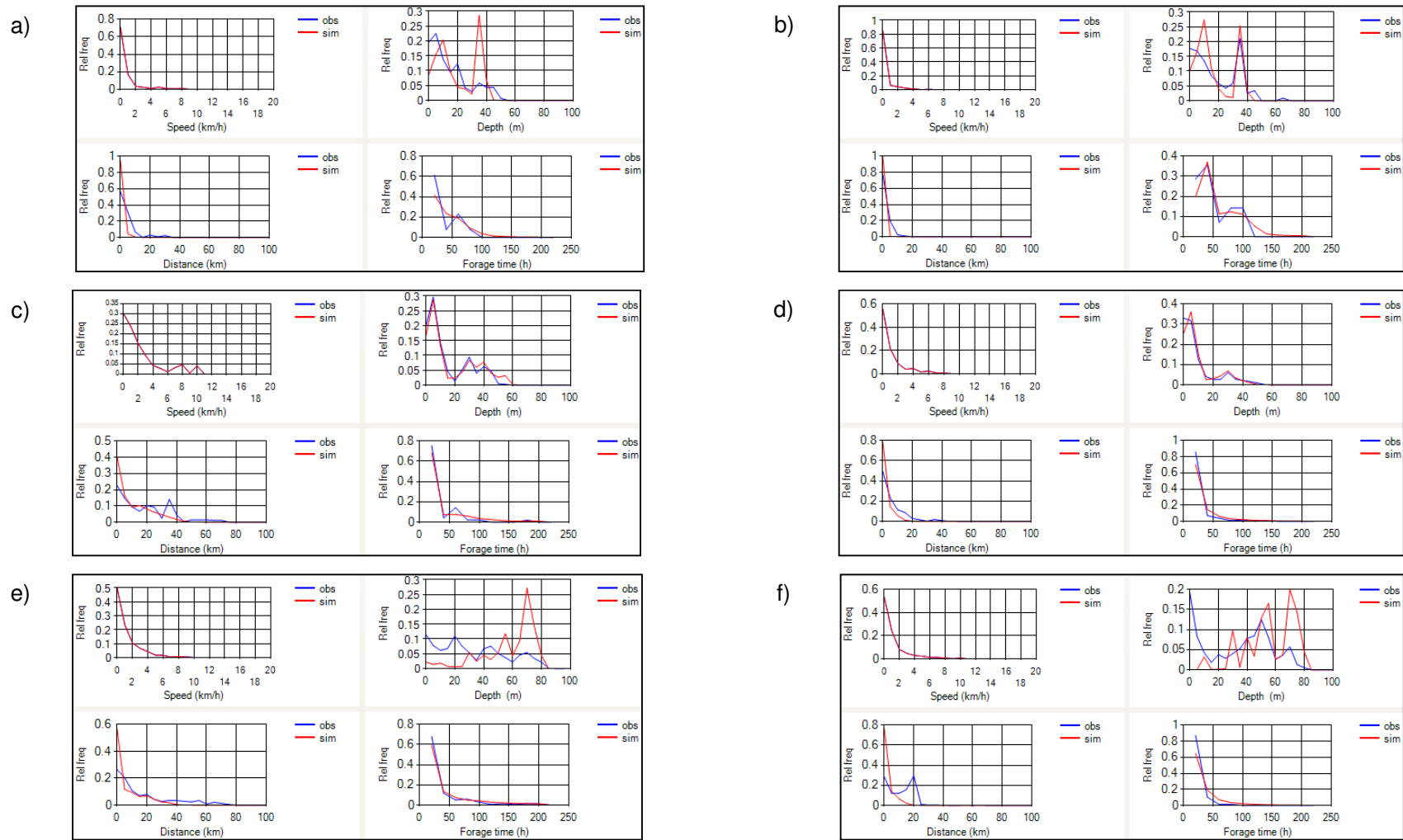


Figure 9: Simulated vs observed distributions for travel speed, water depth, distance from colony and forage time for Australian sea lions at three colonies. a & b) cows and juveniles, respectively, at the Abrolhos Islands, c & d) cows and juveniles, respectively, at Beagle Island near Jurien Bay, e & f, cows and juveniles, respectively, at Investigator Island near Esperance. The statistics shown are based on simulations for 200 individuals, and have been calculated at day 50 (*i.e.* end of model “burn in” period), during model runs.

For juveniles and cows at Investigator Island on the south coast, the distributions for travel speed and forage time were virtually the same (Fig 9e-f). However, the observed vs simulated depth distributions differed conspicuously, with the depths of locations predicted by the model tending to be greater than those recorded in the satellite data (note that this was not the case for many other south coast colonies – data not shown). The distances travelled by cows from the colony were occasionally greater than those predicted by the model, and frequently greater, in the case of juveniles.

Broad spatial patterns of simulated ASL movements

In broad terms, the spatial pattern of distribution of simulated movements for Australian sea lion cows is as would be expected, given the locations of the various WA ASL colonies, and previously available data about the distances that individuals of this species typically travel from various colony locations. Thus, the model predicts that, at the Abrolhos Islands on the west coast, individuals stay within very close range of those islands, whereas for colonies near Jurien Bay, individuals' movements sometimes extended northwards to waters near Leeman, and southwards to near Cervantes (Fig 10a). On the south coast, ASLs are found in waters ranging from about 100 km east of Albany to about 100 km east of Cape Arid, and in a restricted area of water well to the east of Cape Arid (*i.e.* Twilight Cove, see Fig. 1). The areas in which juveniles along the lower west and south coasts of Western Australia are estimated to forage are more restricted than is the case for cows (Fig. 10b).

Broad spatial patterns of fishing effort

The fishing effort data for 2006/07 show that this fishery operated throughout much of the inner shelf waters along the south and west coasts, southwards of Shark Bay,

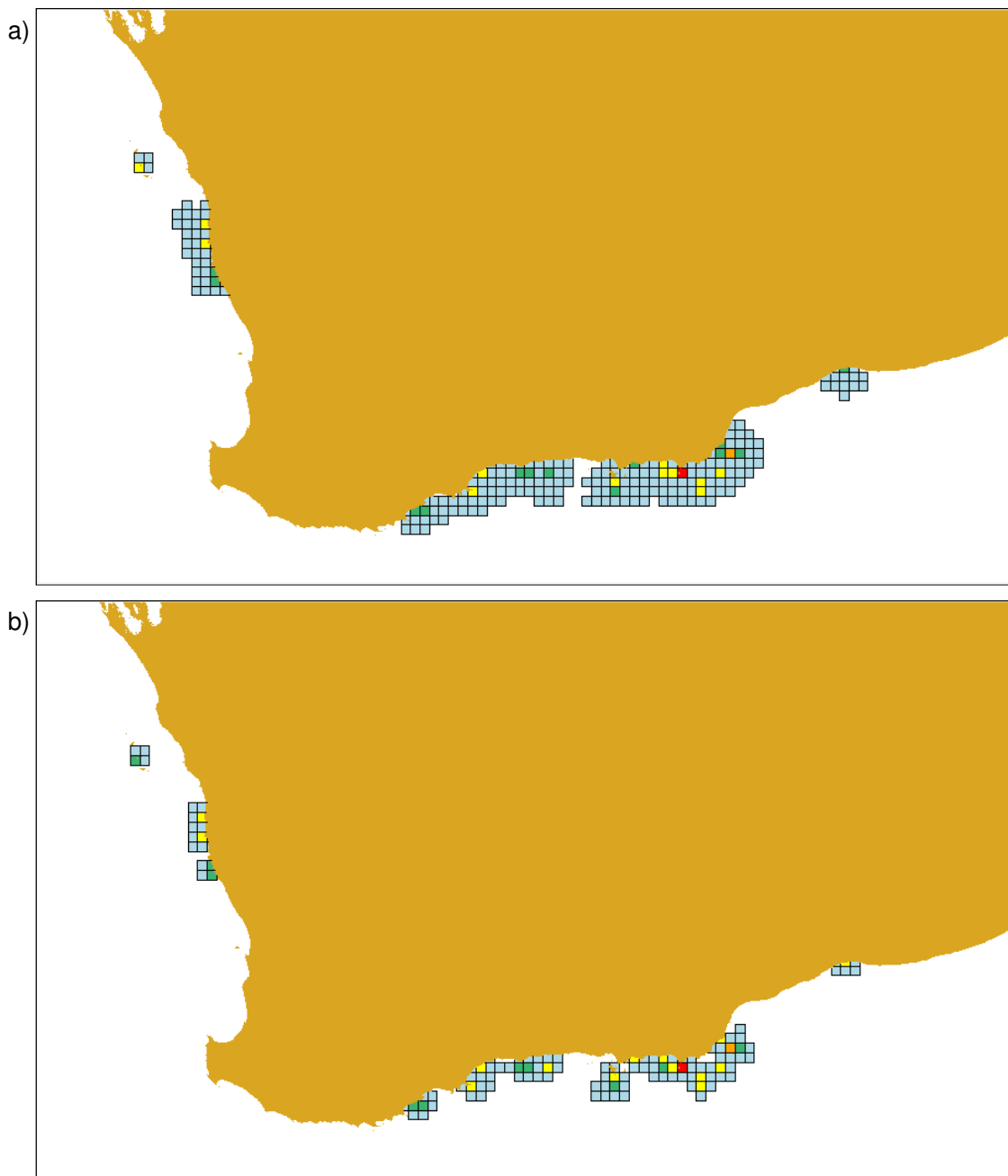
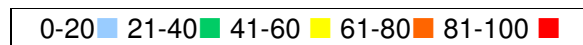


Figure 10. Spatial distribution of simulated locations of Australian sea lion a) cows and b) juveniles across all 24 surveyed breeding colonies in southern Western Australia. For each colony, data were simulated for 200 (computer-generated) cows and 200 juveniles. Square blocks denote 10x10 nm grids. Colours denote intensity of movements in each block.



and eastwards to almost the border of SA (Fig. 11a). In November 2007, most commercial fishing (including demersal gillnetting) was prohibited off the west coast between 31° 00' S and 33° 00' S latitudes, resulting in far less gillnet fishing between Lancelin and Mandurah during 2007/08 and none in waters less than 250 m deep in 2008/09 (Fig. 11b,c). During 2008, a Voluntary Fishery Adjustment Scheme removed ~35% of demersal gillnet/longline fishing effort units in the WCDGDLF, which contributed to a nearly 50% reduction in that fishery's effort in 2008/09.

In 2006/07, fishing effort was most concentrated in fishery blocks in certain inshore waters (< 40 km from shore) off the south coast. These blocks were located in areas near Cape Leeuwin, just east of Bremer Bay, between Esperance and Cape Arid, and a few areas to the east of Cape Arid (Fig. 11b). In the following two years, fishing effort was largely restricted to the above described areas along the south coast, although, in 2007/08, substantial levels of fishing were also recorded along the west coast in inshore waters near Jurien Bay (Fig. 11b,c).

Broad spatial patterns of estimated potential encounters of ASLs with gillnets

For the west coast, the model simulations indicate that in 2006/07, neither cows nor juveniles at the Abrolhos Islands would have encountered a gillnet and that those belonging to colonies near Jurien Bay had only occasional potential encounters (PEs) with gillnets (Figs 12a, 13a). Simulations predicted that PEs occurred at a range of locations throughout the distribution for ASLs along the south coast. The highest PE rates in that year were recorded for fishery blocks just east of Albany and Bremer Bay and near Cape Arid. As would be expected for the distribution of fishing effort described above, high rates of PEs (relative to other fishery blocks throughout WA) were more commonly recorded in inshore fishery blocks (< ~40 km from the coast). In 2007/08, the model indicates that there was a marked increase in PE rates off the west coast near Jurien Bay, and the same was true for the following year. The spatial patterns of PEs off the south coast were broadly similar across the three financial years (Figs 12a-c, 13a-c).

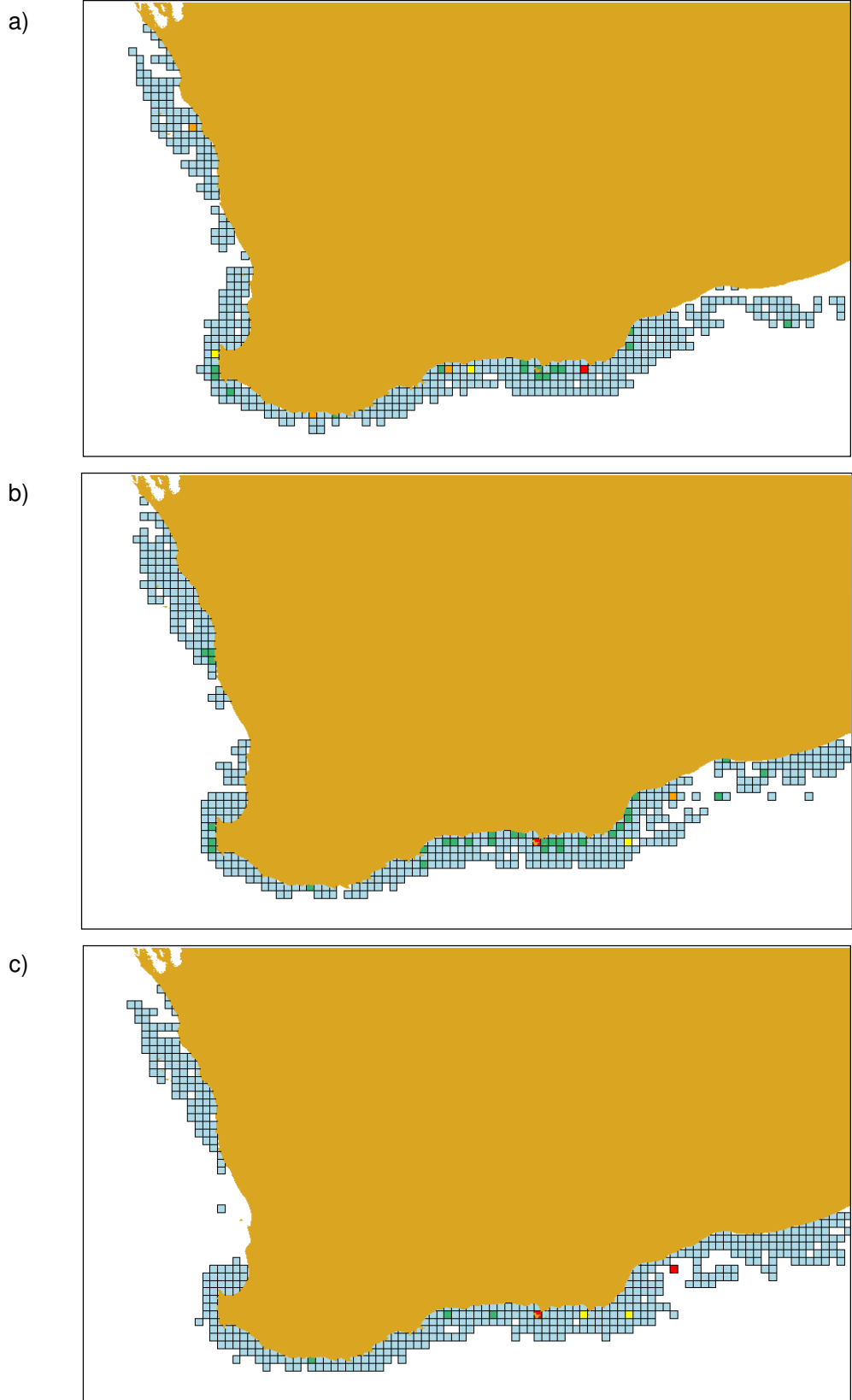
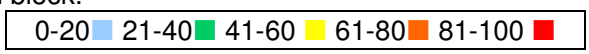


Figure 11. Spatial distribution of fishing effort in southern Western Australia in a) 2006/07, b) 2007/08 and c) 2008/09. Square blocks denote 10x10 nm grids. Colours denote level of fishing intensity in each block.



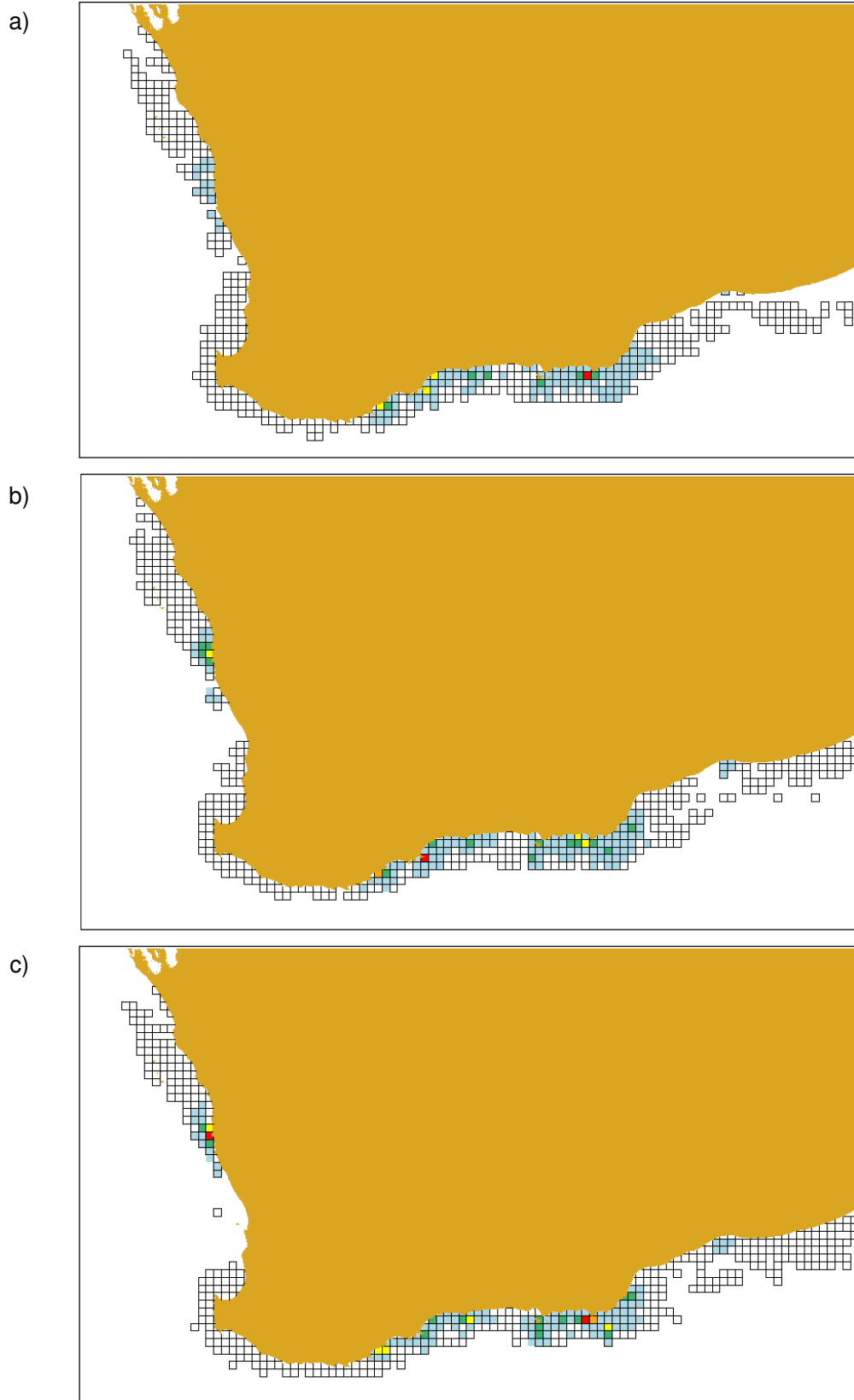
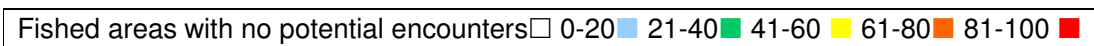


Figure 12. Spatial distribution of estimated potential encounters of Australian sea lion cows with commercial gillnets in southern Western Australia in a) 2006/07, b) 2007/08 and c) 2008/09. Square blocks denote 10x10 nm grids. Colours denote intensity of encounters in each block.



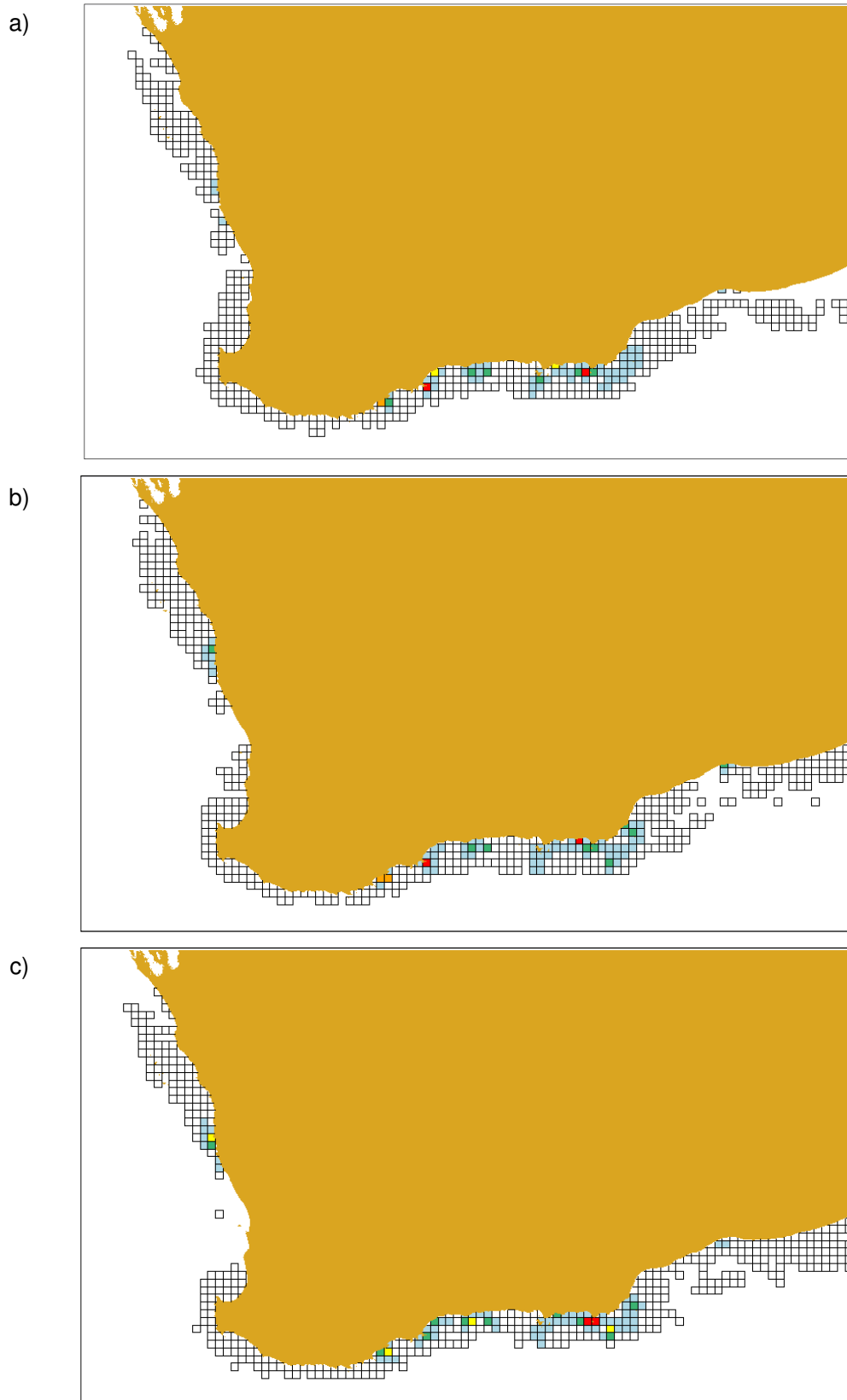
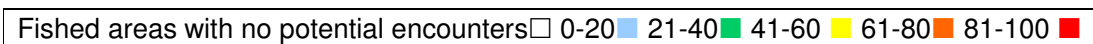


Figure 13. Spatial distribution of estimated potential encounters of Australian sea lion juveniles with commercial gillnets in southern Western Australia in a) 2006/07, b) 2007/08 and c) 2008/09. Square blocks denote 10x10 nm grids. Colours denote intensity of encounters in each block.



Estimated numbers and annual rates of potential encounters

To increase the robustness of analyses, movements were simulated for a relatively large number of cows (200) and juveniles (200), for each colony. The numbers of “real” cows and juveniles belonging to the various ASL colonies in WA vary from colony to colony and in some cases, the total number of ASLs (including pups and males) has been estimated to be as low as 20. This is taken into account in some of the statistics reported later in this section.

Over the three financial years for which model simulations were run (assuming 200 cows and 200 juveniles per colony), the number of estimated PEs between cows and gillnets, in any year, ranged between 0 for the Abrolhos Islands colony and 252 for Beagle Island, near Jurien Bay on the west coast (Table 3). For a number of colonies, the estimated numbers of PEs differed substantially between years. For example, the number of PEs estimated for cows at Beagle Island, North Fisherman Island and Doubtful Island, all ranged widely, *i.e.* from 17 to 252, 9 to 197 and 98 to 231, respectively. Although the number of PEs for juveniles was often less than for cows, the overall trends among colonies were similar. Thus, as with cows, no simulated encounters were recorded for the Abrolhos Islands colony in any year (Table 4). Estimates of PEs were likewise variable between years for Beagle Island (1-149), North Fisherman Island (1-121) and Doubtful Island (63-209).

Taking into account the estimated numbers of cows and juveniles in each of the 24 WA ASL colonies, the model estimated that, on average, between 0 (Abrolhos Islands) and 77 (Beagle Island) cows potentially encountered a gillnet each year between 2006/07 and 2008/09, inclusive (Table 3). The number of estimated PEs was substantially lower for juveniles, ranging upwards to only 35 (Hauloff Rock) (Table 4). The model outputs indicate that, across all colonies, the average annual number of PEs for cows (409) is about twice that for juveniles (215), *i.e.* if assuming a proximity-to-net distance of 500 m.

The average proportion of cows estimated to have potentially encountered a gillnet at least once in each of the three financial years ranged between 0 (Abrolhos

Table 3: Statistics on simulated potential encounters (PEs) for Australian sea lion cows with commercial gillnets, including the number estimated (actual) cows in each colony, the estimated numbers of PEs for 200 simulated cows in each of three successive years and associated averages and 95% confidence limits across years, the estimated numbers of PEs adjusted for colony demographics, the estimated proportion of cows in each colony that potentially encountered a net at least once per year, the per capita rates of PE for each colony, and colony rankings, determined according to per PE capita rates.

Colony	Cows	PEs 2006/07	PEs 2007/08	PEs 2008/09	Average	± 95% CLs	PEs / colony / yr	± 95% CLs	Prop. cows ≥1 PE / yr	Annual per capita PE rate	Rank
Abrolhos Is.	29	0	0	0	0	0	0	0	0.00	0.00	24
Beagle Is.	114	17	252	134	134	292	77	166	0.42	0.67	3
N. Fisherman Is.	91	9	126	197	111	235	50	107	0.38	0.55	5
Buller Is.	56	7	19	7	11	17	3	5	0.05	0.06	23
Hauloff Rock	51	154	220	176	183	83	47	21	0.60	0.92	1
Doubtful Is.	29	143	231	98	157	168	23	24	0.52	0.79	2
Red Islet	58	145	86	87	106	84	31	24	0.37	0.53	6
West Is.	36	87	76	144	102	91	18	16	0.38	0.51	7
Investigator Is.	36	67	52	44	54	29	10	5	0.23	0.27	14
Termination Is.	14	22	63	58	48	56	3	4	0.20	0.24	16
McKenzie Is.	14	77	85	108	90	40	6	3	0.34	0.45	8
Kimberley Is.	72	42	66	87	65	56	23	20	0.27	0.33	12
Kermadec Is.	7	61	77	63	67	22	2	1	0.29	0.34	11
Taylor Is.	14	46	145	45	79	143	6	10	0.32	0.39	9
Glennie Is.	43	170	83	134	129	109	28	23	0.47	0.65	4
George Is.	7	43	31	55	43	30	2	1	0.20	0.22	18-20
Wickham Is.	29	52	36	83	57	59	8	9	0.25	0.29	13
Salisbury Is.	36	18	53	60	44	56	8	10	0.2	0.22	18-20
Cooper Is.	7	24	42	83	50	75	2	3	0.22	0.25	15
Round Is.	36	28	56	51	45	37	8	7	0.21	0.23	17
Six Mile Is.	72	42	96	77	72	68	26	24	0.30	0.36	10
Ford Is.	43	29	57	34	40	37	9	8	0.19	0.20	21
Spindle Is.	87	45	53	34	44	24	19	10	0.20	0.22	18-20
Twilight Cove	7	6	49	12	22	58	1	2	0.11	0.11	22
Total							409				

Table 4: Statistics on simulated potential encounters (PEs) for Australian sea lion juveniles with commercial gillnets, including the number estimated (actual) juveniles in each colony, the estimated numbers of PEs for 200 simulated juveniles in each of three successive years and associated averages and 95% confidence limits across years, the estimated numbers of PEs adjusted for colony demographics, the estimated proportion of juveniles in each colony that potentially encountered a net at least once per year, the per capita rates of PE for each colony, and colony rankings, determined according to per capita PE rates.

Colony	Juv.	PEs 2006/07	PEs 2007/08	PEs 2008/09	Average	± 95% CLs	PEs / colony / yr	± 95% CLs	Prop. juv. ≥1 PE / yr	Annual per capita PE rate	Rank
Abrolhos Is	23	0	0	0	0.0	0	0	0	0.00	0.00	24
Beagle Is.	92	1	149	22	57	199	26	92	0.20	0.29	6-7
N. Fisherman Is.	73	1	49	121	57	150	21	55	0.22	0.29	6-7
Buller Is.	45	3	0	12	5	16	1	3	0.02	0.03	23
Hauloff Rock	41	126	256	129	170	184	35	38	0.54	0.85	1
Doubtful Is.	23	138	209	63	137	181	16	21	0.46	0.68	2
Red Islet	46	83	21	42	49	78	11	18	0.19	0.24	11-13
West Is.	29	48	67	130	82	107	12	15	0.31	0.41	4
Investigator Is.	29	50	46	42	46	10	7	1	0.18	0.23	14
Termination Is.	12	19	35	29	28	20	2	1	0.12	0.14	20
McKenzie Is.	12	54	25	39	39	36	2	2	0.16	0.20	15-16
Kimberley Is.	58	68	41	61	57	35	16	10	0.22	0.28	9
Kermadec Is.	6	52	45	49	49	9	1	0	0.20	0.24	11-13
Taylor Is.	12	15	174	27	72	220	4	13	0.24	0.36	5
Glennie Is.	35	121	59	134	105	100	18	17	0.39	0.52	3
George Is.	6	39	29	82	50	70	2	2	0.21	0.25	10
Wickham Is.	23	15	19	74	36	82	4	9	0.15	0.18	17
Salisbury Is.	29	8	49	41	33	54	5	8	0.14	0.16	19
Cooper Is.	6	10	24	84	39	98	1	3	0.17	0.20	15-16
Round Is.	29	8	28	30	22	30	3	4	0.10	0.11	21
Six Mile Is.	58	26	64	52	47	48	14	14	0.21	0.24	11-13
Ford Is.	35	27	50	27	35	33	6	6	0.16	0.17	18
Spindle Is.	70	14	29	16	20	20	7	7	0.09	0.10	22-23
Twilight Cove	6	4	51	7	21	65	1	2	0.10	0.10	22-23
Total							215				

Islands) and 0.60 (Hauloff Rock) (Table 3). For juveniles, this statistic ranged upwards to 0.54 (Table 4). Estimates of the per capita rate of PEs for cows (= number of estimated PEs for a colony divided by the number of cows in that colony) ranged between 0 (Abrolhos Islands) and 0.92 (Hauloff Rock) (Table 3). The range was similar for juveniles, with the highest estimate (0.85) also being recorded for Hauloff Rock (Table 4). In descending order, the colonies with the 5 highest per capita annual PE rates for cows were Hauloff Rock and Doubtful Island, Beagle Island, Glennie Island and North Fisherman Island (Table 3). For juveniles, the colonies with the 5 highest per capita annual PE rates were Hauloff Rock and Doubtful Island, Glennie Island, West Island and Taylor Island (Table 4).

Effect of different proximity-to-net distance values on potential encounters

The values reported above for numbers of PEs are likely to be highly dependent on the proximity-to-net distance used to represent the risk of a sea lion encountering the net. Exploration of the effect of using different values of that variable for cows at one colony, Beagle Island in 2007/08, indicates that the number of PEs, at least in that situation, was approximately proportional (*i.e.* linearly-related) to the specified distance, within the range of 0 to 10,000 m (Fig. 14).

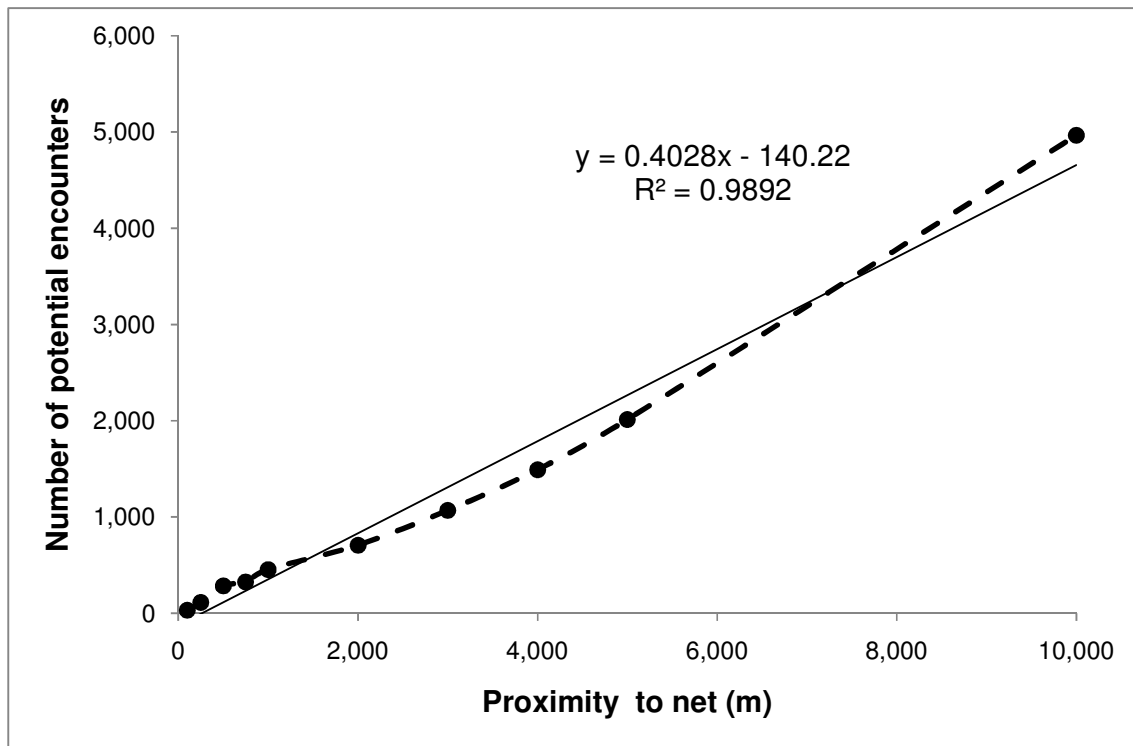


Figure 14: Effect of modifying the proximity-to-net distance used to define the number of potential encounters of ASLs with gillnets. Analysis is based on model simulations undertaken for the Beagle Island colony during 2007/08.

DISCUSSION

Model simulations of Australian sea lion movements

Model development and data analysis

A major component of this study was to develop a model for simulating movements of Australian sea lions (ASLs). To provide reliable information relating to interactions of ASLs with gillnets (through estimating *potential encounter* rates), it was particularly important that the movement model simulated movements of ASLs that matched, as closely as possible, the movements of “real” individuals. Before examining the extent to which this goal was achieved, attributes of the model and analyses of movement data are first discussed.

As described in the background, an agent-based model has been developed which employs a “biased random walk” approach for simulating ASL movements (see Codling *et al.*, 2008). One of the benefits of this approach was that it readily enabled movement directions in the model to be modified according to our knowledge of ASL biology. It is known, for example, that this species is a benthic forager, and that it dives continuously throughout foraging trips (Richardson & Gales, 1987; Costa *et al.*, 1989; Costa & Gales, 2003). As a consequence of this feeding behaviour, younger individuals that have a lesser diving capacity than mature animals, and tend to feed at shallower depths and within a closer range of their colony (Fowler *et al.*, 2006). Juveniles also tend to have shorter foraging trip times and move more slowly through the sea (Fowler *et al.*, 2007). These ontogenetic differences in foraging behaviour were captured well in the simulations.

An important consideration in our modelling of ASL movements was the fact that, for a given demographic (*e.g.* juveniles or mature females), movements can differ substantially among individuals belonging to different colonies (Fowler *et al.*, 2007; Campbell, 2008). For this reason, it would have been ideal to model ASL movements based on representative satellite tracking data for individuals from each colony. However, the paucity of available satellite tracking data for ASLs in WA (data were available for 20 cows and 21 juveniles from 8 of the 24 colonies) meant that it was necessary to “borrow” information from colonies for which there were data to

infer, through simulation, movements for other colonies. Furthermore, to derive sound statistical distributions for key variables that influence ASL movement patterns (depth, distance from colony, forage time, rest time and travel speed), it was often considered necessary to pool data for individuals from several colonies (see Table 2). Therefore, it was important that the data were organised in such a manner that the most important differences in foraging behaviour among colonies in WA would be maintained in the simulated movement data.

The decision to isolate data for the Abrolhos Islands from other colonies was made on the basis of Campbell's (2008) finding that satellite-tracked individuals at this location tended to forage in shallower waters and far nearer to the colony site than ASLs from other WA colonies. The data for colonies on the west and south coasts were grouped separately on the basis that satellite-tracked individuals off the west coast often tended to forage in shallower waters, as shown by observed satellite PTT locations. Because the movement data were also split between juveniles and adult females, a decision was made to not divide the data any further. It should also be noted that, as the modelled movement patterns for 18 of the WA colonies are based on entirely on data for ASLs from other colonies, the results for those colonies are less reliable than those for those colonies from which the empirical data were collected.

Extent of matching between simulated and observed ASL location data

Visual plots, showing locations of ASLs at the Abrolhos Islands, and Beagle Island and Investigator Island (*i.e.* one colony for each data grouping) demonstrate the model's ability to produce simulated movement data for ASLs that broadly approximate the locations recorded by ARGOS satellite tracking of individuals from those colonies. In support of this view is that the simulated and observed location data show similar patterns of differences between colonies. For example, both observed and simulated movements of ASLs at the Abrolhos Islands clearly show that movement patterns are more restricted than those at both Beagle Island and Investigator Island. Moreover, the observed vs simulated distributions for depth,

distance from colony, forage time and travel speed show close matches between these parameters in most circumstances.

Although the model did produce simulated location data that broadly matched observations from satellite tracking, some limitations in the extent to which the model was able to describe various aspects of ASL movements are apparent. For example, the observed location data for juveniles at Investigator Island clearly show two clusters of points, one of which is for individuals that were at a known haul out location (see Fig. 8). Due to data limitations, in particular, the influence of haul out locations on ASL movements has not been modelled in this study. If sufficient data were available, the use of haul out points by ASLs could potentially be accounted for in our model by having multiple focal points of attraction, *i.e.* corresponding to the haul out points, rather than just the breeding colony.

Comparisons between the simulated vs observed distributions for depth at Investigator Island on the south coast, in particular, showed that the model was not always able to match the observed data for this variable. The presence of a conspicuous spike in the relative frequency of occurrence of simulated ASLs towards the edge of their depth range suggests that individuals sometimes tended to become “stuck” in deep water, even though the likelihood of them remaining there (based on the depth probability distributions) would be expected to be low. As the directions of ASL movements in the model were driven by “distance from colony” as well as “depth”, it would appear that individuals frequented certain deep water locations more often than expected because they were well within the home range for individuals of that colony. This suggests that the movement algorithm was not always adequate for finding combinations of locations within the landscape map that were of the same depths and distances from colony as recorded in the observed data. It thus appears that further refinement of the movement model will lead to improvements in its reliability. A range of strategies for refining the movement model are discussed under the heading *Further Development*.

Spatial patterns of ASL movements

The results of the simulations of ASL movements indicate that individuals at the Abrolhos Islands always remain in close proximity to the breeding colony, whereas those near Jurien Bay, also off the west coast, move far greater distances away from their colony sites, particularly in alongshore directions. As indicated above, this pattern matches the observed satellite tracking data for ASLs in these two regions. On the south coast, ASLs are predicted to move throughout a substantial proportion of the shelf waters along that coast, as would be expected given the wide spatial distribution of colonies in the region. At a broad level, there is considerable similarity between the predicted ASL movement patterns from this study and those from previous modelling by Campbell (2008). There were some conspicuous differences, however. In particular, this study suggests a higher concentration of ASL movements in some offshore areas along the south coast than estimated by the previous study.

Differences between the predictions of these two studies most likely reflect the very different methodologies and data sources used in the two studies. In the former study of Campbell (2008), movements were predicted assuming that the distances to which ASLs travel around their colonies conform to a normal distribution. The movements were estimated for each demographic category of ASLs at each colony employing a common mean and standard deviation value for distance travelled, for all colonies. The mean and standard deviation values used were derived from Goldsworthy & Page's (2007) study on ASLs in South Australia. In this study, in contrast, movements of ASLs were estimated employing a biased random walk model. Movement directions were estimated based on distributions for a range of parameters, including depth, distance from colony, travel speed, forage trip time and rest time, for juveniles and adult females. These distributions were based on available satellite-tracking data for ASLs in WA. The estimated spatial patterns of movements produced by the current model are thus more refined than those of the previous study.

Spatial patterns in fishing effort

The commercial fishing effort data show that WA's temperate demersal gillnet fisheries operate throughout much of the continental shelf waters of the lower west and south coasts of the state. With certain exceptions (*e.g.* close to the Abrolhos Islands and, since 2007, in continental shelf waters between Lancelin and Mandurah), there is no restriction on where fishers are permitted to deploy demersal gillnets within each management zone. The data used in this study do show, however, that as might be expected (Fig. 11), fishing tends to be most concentrated in inshore waters, *i.e.* within ~40 km from shore. During the three years considered in this study, fishing intensity tended to be relatively low in all reporting blocks off the west coast, except inshore of the Abrolhos Islands in 2006/07 and near Jurien Bay in 2007/08. The higher intensity of fishing near Jurien Bay in 2007/08 may be explained by a re-distribution of fishing effort resulting from the introduction of a prohibition on commercial fishing in the "Metropolitan Region" (*i.e.* between Lancelin and Mandurah, south of Jurien Bay) in November 2007. However, the impacts of northwards displacement of WCDGDLF fishing effort on target (shark) stocks was mitigated by a Government "buy-out" of 35% of fishing effort entitlements (equivalent to the proportion of the WCDGDLF that was closed) and a subsequent 50% decline in active WCDGDLF effort in 2008/09. The implications of this shift in effort are discussed later. In broad terms, fishing intensity on the south coast during the three financial years tended to be most concentrated in the middle section of that coastline (*e.g.* between Bremer Bay and Cape Arid), where most ASLs colonies are found.

Since the beginning of 2006/07, TDGDLF fishers have reported daily catch and effort fishing returns according to 10 x 10 minute blocks (approximately 10 x 10 nautical miles). Thus, the fishing effort data analysed for this study are at much finer temporal and spatial scales than were previously available. About one third of the fishing effort data used in this study were reported by blocks. The remainder were reported as GPS positions and were thus more precise than the block-reported data. For the block-reported data, a random search of locations within that block was

undertaken (using the bathymetry grid) to find a location with a depth that matched the depth reported by the fisher for the corresponding fishing session. In other words, the depths of the fishing locations used in the model always approximately corresponded to the same depths as reported in the daily log book data.

The new higher resolution data on commercial fishing effort are very valuable for this type of assessment for a number of reasons. As noted by Campbell (2008), because the previous data were at a coarse scale, researchers could not determine whether there was any tendency for fishing effort to be more concentrated in either inshore or offshore waters. The data presented here answers this question. The higher resolution data are also important for estimating potential encounter rates of ASLs with fishing nets. As pointed out in previous studies, Australia's temperate gillnet fisheries tend to target different species (primarily sharks) than ASL prey species. Therefore, at a fine geographic scale, there may be some degree of spatial separation between ASL foraging areas and gillnet fishing locations (McKenzie *et al.*, 2005; Campbell 2008). Furthermore, fishers prefer to avoid interacting with ASLs, due to the species' vulnerable and protected status and their tendency to depredate fish caught in nets (R. McAuley, as cited by Campbell, 2008). However, as ASLs are attracted to scatefish and sharks caught in gillnets (Shaughnessy *et al.*, 2003), this behavioural attribute of ASLs potentially leads to increased interaction rates. The above arguments and counter-arguments regarding the extent of micro-scale spatial overlap between ASLs foraging areas and gillnetting areas highlight the importance of acquiring fine scale data on fishing effort and ASL movements. The agent-based model simulations produced by this study have yielded statistics on potential encounter rates of ASLs with gillnets, using newly-available, high resolution data for commercial gillnet fishing effort and ASL movement patterns.

Statistics on potential encounters of ASLs with gillnets

When interpreting the results of this study, the following issues need to be borne in mind. The model simulations have enabled estimation of the annual rate at which, on

average, an ASL from a given WA colony is likely to have occurred at least once within a specified distance of a commercial gillnet. However, it is important to note that the 95% confidence intervals associated with potential encounter rate estimates for some colonies are larger than their corresponding mean annual rates (Table 3, 4). This uncertainty probably reflects inter-annual fluctuations in the distribution of gillnet fishing effort more than the paucity of satellite-tracking data used to model ASL foraging movements. Nevertheless, as discussed below, additional tagging data, particularly for animals from those colonies for which data are currently unavailable, would be very beneficial to better inform the model on the full extent of ASL movements. As further illustrated by the increase in PE rates in the WCDGDLF between 2006/07 and subsequent years, redistribution of fishing effort can have a marked influence on the fisheries' potential encounter rates with ASLs.

The term *potential encounter* has been used throughout this report as a surrogate for *interaction* for a number of reasons. First, the actual distance over which a sea lion is at risk of interacting with a demersal gillnet is unknown and may vary considerably according to environmental conditions and sea lion behaviour. Furthermore, as illustrated in Fig. 14, the proximity-to-net value that is used to describe potential encounters has a dramatic influence on results. Given that a proximity-to-net value is needed to run model simulations, a value of 500 m was subjectively chosen, *i.e.* as it was considered plausible that a sea lion is possibly at risk of interacting with a net if it occurs within that proximity. Finally, the relationships between sea lions "encountering" gillnets, physically interacting with them (*e.g.* coming into contact with or feeding on fish caught by them), becoming entangled and then dying as a result of entanglement, are completely unknown and likely to vary according to individual circumstances. Thus, a potential encounter cannot be taken to mean that a sea lion has come in to physical contact with or has been harmed by a net.

For the Abrolhos Islands, the results of the model simulations suggest that no ASLs encountered gillnets between 2006/07 and 2008/09. This result largely reflects the limited distribution of movements of ASLs at the Abrolhos Islands, and demersal

gillnet fishing being restricted to areas more than 3 nm from the islands. Although comparisons between the simulated and observed movements of ASLs at the Abrolhos Islands indicated that the extent of movements is likely to have been slightly underestimated, inspection of the actual locations of nets over the grid around the Abrolhos Islands (data not shown) indicated that there were very few nets close enough to the colony to have been likely to result in any encounters.

At Jurien Bay, the numbers of potential encounters (recorded in simulations for 200 cows and 200 juveniles) at two of the three colonies (Beagle Island and North Fisherman Island) were very low (*e.g.* 17 and 9, respectively, for cows) in 2006/07. However, in the following two years, they were far higher (*e.g.* to 252 and 126 in 2007/08, respectively, and 134 and 197 in 2008/09, respectively, for cows). The plots of fishing effort show a marked shift in the distribution of fishing effort along the west coast between the first and latter two years, coinciding with the introduction of a commercial fishing closure along the stretch of coast just south of Jurien Bay, between Lancelin and Mandurah. Notably, fishing intensity apparently increased around the Jurien Bay area in 2007/08 and 2008/09, despite a nearly 50% overall reduction in WCDGDLF fishing activity. Although 35% of WCDGDLF fishing entitlements were bought out of the fishery in 2008 to mitigate potential impacts on target fish stocks of effort displacement caused by the metropolitan closure, the data available for this study suggest there was a concurrent increase in the risk of sea lion interactions with demersal gillnets.

The highest estimates for the annual number of potential encounters of cows with gillnets (column 7 of Table 3) were recorded for Beagle Island and North Fisherman Island. Similarly, for juveniles, the estimates for this statistic were higher at these two colonies than for all other colonies except Hauloff Rock. However, Beagle Island and North Fisherman Island have the largest numbers of both cows and juveniles of all colonies and thus the risk posed to the sustainability of those colonies by each potential encounter will be less than for many colonies on the south coast which have far fewer individuals. The three south coast colonies that ranked in the top five estimated per capita potential encounter rate for cows were Hauloff Rock

and Doubtful and Glennie Islands. With respect to juveniles, the top five colonies were all on the south coast and, in order, were Hauloff Rock and Doubtful, Glennie, West and Taylor Islands. The difference in the rankings for juveniles vs cows with respect to colonies on the west and south coasts may reflect the greater tendency for juveniles on the latter coast to forage in deeper (> 40 m) waters off the south coast (see Fig. 9), *i.e.* at depths where fishing activity is likely to be more concentrated on the west than south coast.

As the data presented in this study on ASL movements and spatial distribution of fishing effort in WA are of a far higher resolution than previously available, they provided the basis for producing absolute estimates of potential encounter rates of ASLs with gillnets at a much finer scale than was previously possible. Unlike the current agent-based modelling approach, previous methods have estimated the relative “interaction probabilities” for colonies by overlaying estimated spatial distributions of ASL movements and fishing effort. Because the model developed during this study can provide fine temporal and spatial scale information on potential encounter rates, it is potentially a powerful tool for assessing the appropriateness and design of any program to monitor ASL capture rates (a condition of the fisheries’ WTO accreditation under the EPBC Act) and analysing the effectiveness of any fishery management measures aimed at reducing the risk associated with sea lions encountering nets. In doing so though, it must be remembered that the relationships between potential encounter, interaction and ASL capture rates are unknown and that some, if not many, sub-surface encounters may not be detectable by observers.

It is relevant to note that McAuley and Simpfendorfer (2003) reported no ASL captures from observation of 23,096 km hours of WCDGDLF commercial gillnet fishing effort between 1994/95 and 1998/99. This level of observed fishing effort (over five years) equates to between 45% (2006/07 and 2007/08) and 85% (2008/09) of reported WCDGDLF effort during the present study. The model estimated an average of 130 and 48 potential encounters of cows and juveniles, respectively, in WCDGDLF gillnets per year between 2006/07 and 2008/09. A similar comparison of ‘observer’ data from Zone 2 of the JASDGLF (east of 116° 30’ E longitude) between

1994/95 and 1998/99, also suggests a very low ratio of potential encounters to observed capture. McAuley and Simpfendorfer (2003) reported a single ASL capture during 14,390 km hours of observed fishing effort in Zone 2 of the JASDGLDF (east of 116° 30' E longitude), while the model suggested approximately 280 and 167 potential encounters of cows and juveniles, respectively, per year for the same region. The observed level of effort in Zone 2 was equivalent to between 14% (in 2008/09) and 21% (in 2006/07) of the contemporary Zone 2 effort assessed during this study.

Several factors may have contributed to the very low detection rates of observed ASL captures in the WA demersal gillnet fisheries. These include, but may not be limited to, a very low proportion of encounters resulting in capture, fine scale differences in the distribution of 'observed' fishing effort between the two reported study periods, limited net observation time (*i.e.* during deployment and retrieval), high rates of cryptic interactions/captures, and restricted visibility of the nets to observers on some vessels. While the relative contributions of these factors to the extremely low observed ASL capture rates during the late 1990s cannot be determined, they would all need to be considered in assessing the appropriateness and design of any future observer program. A further consideration for such a program would be the cost of deploying observers across such a geographically large fishery, in which fishing effort is very sparsely distributed.

BENEFITS AND ADOPTION

This research was required by the WA Department of Fisheries to re-assess previous risk assessments of ASL interactions with WA's temperate gillnet fisheries. In particular, a more rigorous assessment of this risk was required to satisfy a condition of the Western Australian Temperate Demersal Gillnet and Demersal Longline ("Shark") Fisheries' Wildlife Trade Operation (WTO) accreditation under the EPBC Act. As this accreditation is required for all Australian export fisheries (in this case shark fin byproduct from these fisheries), there was a clear need for this research. Western Australia's demersal gillnet fisheries and their representative body (the

Western Australian Fishing Industry Council, WAFIC) will be the direct beneficiaries of meeting this WTO condition. As pointed out in the original application, the research may also be adopted by industry if it chooses to pursue full Marine Stewardship Council assessment, which could not only provide increased economic returns to industry members but also a clear demonstration of the fisheries' performance against ecological sustainability objectives.

Australian sea lions are a rare species of marine mammal that have reproductive characteristics that render them particularly susceptible to population decline from uncertain or unmanaged rates of fishery interaction. There is thus considerable concern within the community about the potential risks that fisheries pose to the sustainability of ASLs. The development and application of this model will provide benefits to fishery and conservation researchers and managers by demonstrating an approach to assess the implications of these low frequency, high risk interactions between this species and fishing activities. Improved understanding of these risks and development of management strategies to mitigate the consequences of these interactions will be of clear value to conservation advocacy groups and their stakeholders, as well as to the general community.

The modelling framework developed during this study provides a platform for exploring a range of research questions related to movements of ASLs, which may have equally beneficial application to other Threatened, Endangered and Protected species and other aquatic or terrestrial wildlife. The model is well suited to describing animal movement and habitat use patterns and for exploring implications of human-wildlife interactions, and the effectiveness of alternative strategies for mitigating any negative impacts caused by such interactions.

FURTHER DEVELOPMENT

The focus of this tactical FRDC research study was to rapidly produce a model to estimate the frequency with which Australian sea lions (ASLs) from different colonies potentially interact with gillnets used by the WA's demersal commercial gillnet fisheries. For this purpose, an agent based model was developed that applies a

biased-random walk (BRW) algorithm for describing movements of ASLs. Data from fishers' log books were also used in the model, to "replay" fishing activities over the three years. Like ours, most movement models are based on some form of random walk process. However, as outlined in the background section of this report, random walk models vary markedly in their degree of sophistication. In future, it would be useful to explore the extent to which enhancing the level of sophistication of the current movement model and/or employing alternative movement algorithms influences the reliability of results.

The realism of the model developed in this study could be enhanced by modifying the approach used for determining the directionality of ASL movements, *i.e.* rather than restricting movements of individuals to cardinal directions using a "lattice", it would be possible to allow ASLs to move in any direction, *e.g.* through the sampling of random angles from a circular distribution such as a von Mises, wrapped Cauchy or wrapped normal distribution (see Codling *et al.*, 2010). The realism of model results could also be improved by incorporating methods to evaluate proximities of individual ASLs to nets at a finer scale than currently considered by the model. While this development would better reflect the actual relationship between ASL movements and individual nets, it would substantially increase the number of model calculations undertaken during a simulation, and thus increase computation time. Increasing the sophistication of these components of the model would also require substantial structural and mathematical changes to the current model, but could lead to substantial gains in accuracy and/or realism.

It would be beneficial for future research related to the agent-based model developed in this study to be accompanied by more detailed statistical comparisons between simulated vs observed location data. Such comparisons should recognise that successive movements of ASLs are correlated, and thus, statistics need to take into account the influence on results of "repeated measures". Future analyses could involve randomly selecting values for several variables, *e.g.* distance from colony, depth *etc.* from the observed movement data, taking only one observation for each variable from each foraging trip. The random values for those variables could then be

compared against distributions for those corresponding variables derived from simulated data, to determine the frequency with which the observed values fall outside the distributions generated by the model.

In this study, simulations were repeated for three consecutive years of fishing effort data, each employing a large number of simulated individuals. The resultant estimates for potential encounter rates have been averaged across years and individuals, thereby taking into account variability in the movements of individual ASLs and variability in the spatial distribution of fishing effort between years. The estimates of precision for potential encounter estimates (Tables 3 and 4) reflect inter-annual variability in the spatial distribution of fishing. It would be valuable for future research to re-run simulations using different starting points (*i.e.* random number seed values), to explore the precision of the potential encounter estimates for a specified financial year (and colony and sex). It would also be useful to explore the extent to which increasing the number of specified ASLs in simulations influences the precision of potential encounter estimates. Note that such analyses would be very computer intensive and time consuming, and thus beyond the scope of the present project.

This study highlights that a major impediment to future research on ASLs in WA is likely to be the current paucity of satellite (or other) tracking data. Although the available satellite-tracking data are of good quality, there is a total absence of data for juveniles and adult females for about two thirds of all WA colonies and essentially no data for pups and adult males for any WA colony. In the current study, statistics relating to potential encounter rates were thus unable to be produced for pups or adult males and by necessity, results for two thirds of WA colonies are based on data for sea lions from other colonies. The acquisition of further satellite-tracking data for ASLs in WA is therefore of utmost importance for 1) improving the accuracy of any future modelling of ASL movements, *e.g.* by enabling individualistic ASL foraging behaviours and use of haul-out locations to be modelled and 2) improving the reliability of risk assessments relating to ASL/gillnet interactions. Note that the ABM produced in this study could be used to inform the design of future fieldwork

programs for research on ASLs. For example, the model could be used to examine the likely effectiveness (and cost) of future satellite tagging studies, *i.e.* as the model could be used (as an *operating model*) for conducting “power analyses”, to determine the level of sampling intensity required in a biological research program for providing informative results.

The ability to inform risk assessments of ASL/gillnet interactions would also be enhanced by collection of empirical data on the distances at which individuals of ASLs of different life stages can detect a net. It is envisaged that this could possibly be achieved by using accelerometers, fine scale GPS and/or acoustic tracking of ASL movements within the vicinity of gillnets, and statistical analyses of data on turning angles of individuals at different distances from the net. Such information would allow better estimation of a realistic value for the proximity-to-net parameter in the model which, in turn, would provide more accurate estimates of *interaction rates* (rather than their surrogate, *potential encounter rates*, as estimated in this study).

To our knowledge, this is the first study to produce an agent-based model for describing movements of pinnipeds in Australian waters. Around the world, use of this type of model in animal movement studies has increased in recent years, as evidenced by the number of papers emerging in the literature. The strength of this approach lies in its ability to model animal movement patterns on a fine scale through space and time at the level of the individual.

The model has considerable potential to address and inform the management of fishery-protected species interaction issues. Further refinement of the model so that discrete rates of potential encounter with respect to foraging effort, fishing effort and distance from colony can be readily estimated, would greatly benefit its application. Development of the model’s capacity to determine spatial relationships between probabilities of encounter rate per unit of fishing effort and relative levels of foraging effort would further facilitate understanding of levels of interaction between ASLs and temperate commercial gillnet fisheries. This capacity would allow investigation of the effects of various spatial exclusion scenarios or of spatial transfer of fishing effort on likely encounter rates. It would also allow researchers to

investigate relationships between expected encounter rate and empirical observer data, either from previous studies (*i.e.* McAuley & Simpfendorfer, 2003) or from future studies. With further development, the model could be applied to help identify mitigation measures that balance the operational requirements of fishers with maximum conservation benefit for sea lions.

PLANNED OUTCOMES

The simulation modelling undertaken in this study has led to the production of statistics relating to potential encounter rates between ASLs and gillnets used by WA's Temperate Demersal Gillnet and Demersal Longline Fisheries. Of particular value are the relative per capita estimates of potential encounters, which have been estimated independently for cows and juveniles for each of 24 ASL breeding colonies in WA. These estimates, which take into account both the total numbers of estimated encounters and colony size, will be considered by the Department of Fisheries, WA and the Commonwealth Department of Sustainability, Environment, Water, Population and Communities (SEWPaC), when re-assessing the risks posed to Western Australian sea lion colonies by demersal gillnet fishing. The completion of this research meets the requirement of a key component of the fisheries' Wildlife Trade Operation (WTO) approval to "undertake a study to estimate risk of interactions between (demersal gillnet) fishers and Australian sea lions".

CONCLUSION

In this tactical research study, a computer simulation tool was rapidly developed to estimate rates of *potential encounter* of Australian sea lions (ASLs) with gillnets deployed by commercial fishers in southern Western Australian waters.

During the project, available satellite-tracking data for ASLs in WA were analysed to produce statistical distributions for key biological variables known to influence ASL movements (*e.g.* water depth and distance from colony). A "random walk" approach was then used in the model to simulate ASL movements around

each WA colony. Comparisons between the simulated vs observed location data provided evidence that the approach for simulating ASL movements is sound. Additional satellite-tracking data for ASLs in WA and further exploration and refinement of the movement model are likely to improve the accuracy/precision of model outputs.

Data on commercial gillnet fishing effort in WA were extracted from fishers' log books. These data, which are at a much finer scale than available in the past, were used in the model to "replay" the activities of WA's temperate demersal gillnet fisheries over three consecutive financial years (2006/07 - 2008/09).

A range of statistics were produced by the model relating to potential encounters of ASLs with gillnets, which will assist in determining the implications of the recent distribution of commercial gillnet fishing for different ASL colonies (project objective # 1). These include estimates of the proportion of individuals (juvenile and adult female) in each colony that potentially encountered gillnets (at least once) in each of the three consecutive financial years investigated (project objective # 2).

An important parameter required by the model is one that describes the distance over which it is plausible that there may be risk of a sea lion interacting with a gillnet, which has been referred to as the "proximity-to-net" distance. As the true value of this parameter is not known and in reality, is likely to be variable and difficult to measure, a value of 500 m was subjectively chosen to enable development and testing of the model. Although this value was considered to represent a plausible distance over which there is a risk of a sea lion either accidentally or deliberately encountering a net, other values may be equally credible. Should more defensible, empirically derived estimates become available in the future, re-running the model with those estimates is recommended to provide a better assessment of actual risks to WA colonies.

At a broad scale, the contemporary fishery data confirm that the distribution of commercial gillnet fishing overlaps that of ASLs. Model results suggest that, for two ASL colonies near Jurien Bay, the rate at which individual sea lions encountered gillnets rose dramatically between 2006/07 and the following two years. This rise in

estimated encounter rates coincided with a redistribution of fishing effort in the West Coast Demersal Gillnet and Demersal Longline Fishery (WCDGDLF), following a prohibition on commercial fishing (including demersal gillnetting) south of that area. However, previous empirical observations of demersal gillnet fishing in the WCDGDLF did not detect any sea lion captures, despite observer coverage (over 5 years) being equivalent of 45% to 85% of the assessed annual fishing effort levels.

The data produced by this project will assist the Department of Fisheries WA in re-assessing the risks posed to ASL colonies by commercial gillnet fishing. As required by a condition of the fisheries' WTO accreditation under the EPBC Act, model outputs can be used to assess the appropriateness and design of an observer program for monitoring ASL interactions with gillnets. The information provided by this study is highly relevant to ASL conservation and management.

We consider that the modelling approach adopted in this study has excellent potential for assessing the relative merits of alternative management options relating to ASLs and gillnet fishing, if required. The modelling framework is also applicable to other situations where there are issues associated with wildlife/human interactions.

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APPENDIX 1: INTELLECTUAL PROPERTY

The information produced in this study is not suited to commercialisation.

APPENDIX 2: PROJECT STAFF

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