National Environmental Science Program

RESEARCH REPORT

Project 3.15 – Informing southern right whale management through continued monitoring, determination of aggregation areas and development of approaches to increase data flow efficiencies and utility

March 2026

Movements, connectivity, and population identity of southern right whales at the boundary of the eastern and western populations

Luciana M. Möller & Claire E. Wouters

CEBEL

Cetacean Ecology, Behaviour And Evolution Lab

Milestone number: 7
Research Plan number: RP2023

Please address inquiries to: Luciana Moller, luciana.moller@flinders.edu.au

Preferred citation

Möller, L.M. & Wouters, C.E. (2025) Project 3.15 – Informing southern right whale management through continued monitoring, determination of aggregation areas and development of approaches to increase data flow efficiencies and utility: Movements, connectivity, and population identity of southern right whales at the boundary of the eastern and western populations. Report to the National Environmental Science Program.

Flinders University

Copyright

Acknowledgement

This work was undertaken for the Marine and Coastal Hub, a collaborative partnership supported through funding from the Australian Government's National Environmental Science Program (NESP).

NESP Marine and Coastal Hub partners

The Australian Institute of Marine Science, Bioplatforms Australia, Bureau of Meteorology, Charles Darwin University, Central Queensland University, CSIRO, Deakin University, Edith Cowan University, Flinders University, Geoscience Australia, Griffith University, Integrated Marine Observing System, James Cook University, Macquarie University, Murdoch University, Museums Victoria, NSW Department of Planning and Environment (Environment, Energy and Science Group), NSW Department of Primary Industries, South Australian Research and Development Institute, The University of Adelaide, University of Melbourne, The University of Queensland, University of New South Wales, University of Tasmania, University of Technology Sydney, The University of Sydney, University of Western Australia, The University of Wollongong

Disclaimer

Cover images: (SA Department for the Environment and Water)

This report is available on the NESP Marine and Coastal Hub website:
www.nespmarinecoastal.edu.au

Contents

Executive summary ... **1**
1. Introduction ... **3**
2. Methods ... **5**
2.1 Data collection ... 5
2.2 Data processing ... 5
2.3 Statistical analysis ... 6
3. Results ... **7**
3.1 Movement behaviour ... 7
3.2 Dive behaviour ... 10
3.3 Risk exposure assessment ... 13
3.4 Photo-identification and biopsy sampling ... 15
4. Indigenous engagement ... **18**
5. Recommendations ... **21**
5.1 Research ... 21
5.2 Management ... 21
6. Conclusions ... **23**
7. References ... **24**
8. Appendices ... **27**
8.1 Appendix A. Hidden Markov model selection and results ... 27
8.2 Appendix B. Anthropogenic threat layers ... 30

List of figures

Figure 1. Interpolated movements of southern right whales (*Eubalaena australis*) with behaviour states determined by hidden Markov models based on satellite tag data from southern Australia. ARS: area-restricted search. 11

Figure 2. Dive metrics for satellite tagged southern right whale (*Eubalaena australis*) cows and unaccompanied adults (UAs) in southern Australia, including (a) Dive duration, (B) maximum dive depth and (C) post dive surface interval (PDSI). 12

Figure 3. Proportion of dive shapes conducted by cows with a calf and unaccompanied adults (UA) southern right whales (*Eubalaena australis*) satellite tagged in southern Australia. 13

Figure 4. Risk exposure of southern right whales (*Eubalaena australis*) in southern Australia to (A) pollution, (B) entanglement, (C) ship strike, (D) chronic underwater noise, (E) climate change, and (F) cumulative threats. Risk exposure is characterised as the density of the threat layer multiplied by the number of whales occurring within the grid cell and is normalised between 0 (none) and 1 (maximum). Dashed contour indicates the Australian Exclusive Economic Zone........ 14

Figure 5. Photo-identification of four satellite tagged southern right whale (*Eubalaena australis*) cows and unaccompanied adults (UAs) in Encounter Bay, South Australia......... 16

Figure 6. Photo identification images of four additional southern right whales not satellite tagged. 17

Figure 7. Poster of the *Kondoli* Dreamtime Story Lantern Workshops and Parade for the 2025 Winter Whale Fest, Victor Harbor, South Australia........ 19

Figure 8. Composite photo of workshop activities as part of the *Kondoli* Dreamtime Story, 2025 Whale Fest, Victor Harbor, South Australia 20

Figure 9. Hidden Markov model (HMM) histograms and decoded states (Viterbi) for area restricted search (ARS; green), intermediate (light blue), and transit (dark blue) behaviour in respect to the HMM data streams: (a) turning angle, (b) step length (*Sl*), (c) mean maximum dive depth (*Md*), and post-dive surface interval (*PDSI*). Covariate effects on the emission probabilities included Julian date on *Sl* and *PDSI*, bathymetry on *Md* and *PDSI*, and whale type (UA or mother) on *Sl*, *Md*, and *PDSI*. Covariate effects are numbered by Roman numerals and correspond to the histogram on the same row; all assume a fixed mean bathymetry of 2,700 m and a day of 245. The *PDSI* histogram only displays values up to 60 min for the sake of visibility, but maximum values reached nearly 600 min......... 28

Figure 10. Stationary state probabilities of area restricted search (ARS; green), intermediate (light blue), and transit (dark blue) behaviours as functions of covariates (a) Julian date, (b) distance to shore, (c) distance to seamount extent, and (d) chlorophyll-a concentration........ 29

List of tables

Table 1. SPLASH satellite tag and whale identification details for all four tagged southern right whales (*Eubalaena australis*) in Encounter Bay, South Australia. Type of whale refers to reproductive status and sex, including cow (seen with accompanying calf) and unaccompanied adults (UA).... 7

Table 2. Behavioural state details of southern right whales (*Eubalaena australis*) from all combined SPLASH satellite tag data deployed in Encounter Bay, South Australia, including the number of locations that were designated each state, step length, turning angle, average maximum dive depth (m), post-dive surface interval (PDSI), and the percent of time the behaviour was observed in inner shelf habitat (<100 m depth). ARS: area-restricted search........ 8

Table 3. Hidden Markov Model (HMM) selection of southern right whale movement behaviour, ranked by Akaike Information Criteria (AIC) scores. Transition covariates include Julian date, distance to shore, distance to seamount extent, and chlorophyll-a concentration. The final model chosen is shown in bold......... 27

Table 4. Spatial layers used to map anthropogenic threat sources and the relevant ecological pressure on southern right whales, modified from Ferreira et al. (2025)........ 30

Executive summary

Right whales (genus *Eubalaena*), once severely depleted by commercial whaling, continue to face major anthropogenic threats, including entanglement in fishing gear and vessel strikes, that impede their recovery. In Australia, southern right whales (*Eubalaena australis*) remain endangered and comprise two partially differentiated groups: a smaller eastern population and a larger western population. The degree of mixing between these groups is uncertain, such as in Encounter Bay, South Australia, a re-emerging calving ground where increasing sightings and bidirectional movements raise questions about its population identity.

Although long-term coastal surveys in southern Australia have documented trends in abundance and distribution, especially for the western population, knowledge of coastal and offshore movements remains limited. Satellite tracking studies from New Zealand and Western Australia indicate diverse migratory strategies, with relatively few whales recorded travelling on an eastward direction. Understanding fine-scale movements, identifying emerging calving and foraging areas, and assessing spatial overlap with anthropogenic threats are critical for effective management and conservation of these populations.

This study used satellite tracking data from whales tagged in Encounter Bay to map coastal and offshore movements, infer behavioural states, and quantify exposure to anthropogenic risks. It also reports on photo-identified and biopsy sampled individuals and documents a collaboration supporting Ngarrindjeri-led cultural activities during the 2025 Winter Whale Fest in Victor Harbor, South Australia.

Four whales were satellite tagged in June 2024, two unaccompanied adults (UAs) and two individuals that later gave birth, with tags transmitting for up to 198 days and recording individual movements exceeding 11,000 km. All individuals displayed transit, intermediate, and area-restricted search behaviours, generally travelling west or southwest and ranging between 31°–47°S and 96°–138°E. The two mothers spent prolonged periods of time in known reproductive areas in South Australia and Western Australia, as well as at previously undocumented nursery areas along the South Australian coast.

More than 19,700 dive events of the satellited tagged whales were recorded, revealing behavioural differences between mothers and UAs: mothers exhibited shallower dives and spent more time at the surface, although dive duration did not differ significantly between the two groups. The satellite tracks also showed substantial overlap with multiple marine industries, identifying areas of heightened risk for this recovering species, including nearshore regions of the Fleurieu, Yorke, and Eyre Peninsulas in South Australia, and offshore areas near Bremer Bay and Albany in southern Western Australia.

Nine southern right whales, including the four satellite tagged individuals, were photo-identified, all of which were assumed subadults or adults, with no calves at time of identification and none matching individuals from the existing Encounter Bay Southern Right Whale Photo-identification catalogue. Only one of the tagged whales was successfully biopsy sampled, preventing population genetic analysis, although movement patterns suggested all four tagged whales likely belong to the western population.

As part of this project, the Flinders University team also partnered with Ngarrindjeri Elders and the City of Victor Harbor to deliver the *Kondoli* Dreamtime Story Lantern Workshops for

the 2025 Winter Whale Fest, using art and storytelling to connect community, culture, and marine awareness. Across a week of workshops, First Nations artists, local schools, families, and community members created lanterns inspired by *Kondoli* (the whale man) story, culminating in a large public celebration attended by approximately 150 people. The project promoted cultural education, creative collaboration, community engagement, and skill development for both First Nations artists and local youth.

1. Introduction

Several whale species have been severely depleted due to the extensive practice of commercial whaling, which caused dramatic declines in their populations over the 19th and 20th centuries. Although widespread commercial whaling has ceased in the last four decades, anthropogenic sources of risk are a problem for the recovery of populations. For right whales (genus *Eubalaena*), entanglement and ship strike are some of the leading causes of injury and mortality for populations worldwide (IWC, 2010; Peel et al., 2018). Southern right whale (*Eubalaena australis*) populations in Australia are recovering (Grundlehner et al., 2025), however, they remain endangered despite inhabiting relatively remote calving areas (Pirzl, 2008) and offshore feeding grounds (Riekkola et al., 2025). The species is listed as endangered under the Environment Protection and Biodiversity Conservation Act 1999, and a National Recovery Plan came into effect in July 2024 (DCCEEW, 2024) to aid species recovery in Australian waters. Anthropogenic threats in both inshore and offshore waters pose ongoing risks to the populations and understanding fine-scale movement and behaviour is essential for effective management and mitigation.

Southern right whales that migrate seasonally to calving areas along the Australian coastline belong to either the smaller, slow recovering eastern population or the larger western population (Pirzl, 2008; Smith et al., 2022; Stamation et al., 2020). Genetic differentiation at the mitochondrial has been found between whales sampled in different calving grounds, suggesting a degree of isolation between the two populations, but genetic studies were conducted based on samples collected more than a decade ago (Carroll et al. 2011; Carroll et al., 2015). Encounter Bay, South Australia, is a re-emerging calving ground that geographically lies at a midway point between the two populations, but the area is considered part of the South-East Marine Region in the Marine Bioregional Plans. There has been a proportionally higher number of non-calving migratory adults, as well as cow-calf pairs in this area since the mid-2000s (Kemper et al., 2022), and photo identification of individuals sighted there have been documented as heading in both on a westerly and easterly direction (Gilmore, 2022). These leave questions about the population identity of whales sighted in Encounter Bay and their movements thereafter.

Long-term aerial (Bannister, 1990, Bannister, 2001, Evans et al., 2021, Smith et al., 2022) and land-based (Burnell, 2001, Charlton et al., 2022, Gilmore, 2022, Kemper et al., 2022) surveys have been instrumental in monitoring southern right whale occurrence and population trends in southern Australia. However, little is known about southern right whale migratory movements in unpopulated and offshore areas, or outside the short period that the aerial surveys are conducted along the coast. In addition, limited satellite tracking data from individuals tagged in southern Western Australia have revealed multiple migratory strategies, but with limited movement in an eastern direction (Sprogis et al., 2024). Satellite tracking also allows the estimation of behaviour state sequences (Langrock et al., 2012) and can collect dive data to add vertical context to the horizontal behaviour. As part of this, identifying novel calving and foraging grounds is crucial, as breeding and foraging success are of great significance for population recovery (Beltran et al., 2023; Jenouvrier et al., 2009; White, 2008). Additionally, satellite tagging studies can provide validation of reproductive and migratory biologically important areas (BIAs), including habitat critical to the survival of the species (reproduction BIA), both referenced in the National Recovery Plan (DCCEEW, 2024)

Tracking whale migratory movements also allows quantification of risks to anthropogenic threats. Spatial overlap between southern right whales and threats such as vessel strikes, entanglement, offshore infrastructure, and climate change anomalies remain poorly characterized in Australia yet remain essential to the survival and growth of these populations. The National Recovery Plan for the Southern Right Whale identifies as priority objectives monitoring the coastal movements and residency of individuals, managing anthropogenic threats to facilitate recovery of the species, and characterisation of its population structure in Australian waters.

Here, we aim to (1) identify southern right whale migratory corridors and distribution of behavioural states, (2) investigate whether whales from Encounter Bay are part of the western or eastern population based on their spatial movements, and (3) quantify exposure to anthropogenic risk based on the tagged whale movements. We also report on the whales photo-identified during the boat-based fieldwork in Encounter Bay, and the Ngarrindjeri activities as part of the Winter Whale Fest 2025 in Victor Harbour, South Australia.

2. Methods

2.1 Data collection

Four non-retrievable Type-C (consolidated) SPLASH10-TDR10 tags (Wildlife Computers Ltd, Remond, Washington, USA) were deployed on southern right whales in Encounter Bay, South Australia, in June 2024. All tag deployments were in nearshore waters between Goolwa Beach (easternmost end 138°52'8.51"E) and Parsons Beach (westernmost end 138°27'45.64"E). Tagging occurred in June 2024 from a 6.3 m rigid-hulled inflatable vessel in conditions comprised of <20 knots of wind, >2 km visibility, and in variable sea states (Beaufort 2-3). An experienced whale tagger was located on the raised bow sprit of the vessel, providing approximately 1.5 m of elevation to assist with the dorsal implantation of the tags. Whales were first confirmed as having good body condition then photographed and checked against a local catalogue of known calving females. Once deemed an unknown individual and estimated to be smaller than the typical length of reproductively mature females in the western Australian population (range = 13-16 m, mean 14 ± 0.7 m; Nielsen et al. 2019), the whales were approached to within 5 m, and tags were deployed to a few dozen centimetres behind the blowholes in the fatty neck tissue area using a custom-modified pneumatic line thrower (Air Rocket Transmitter System; Heide-Jorgenson et al 2001) set at 14-15 bars pressure. Biopsy samples were also successfully collected from one of the tagged whales immediately after deploying the tag to assist in sexing the animal, and visual observations were minimally maintained after tag deployment to ensure minimal disturbance.

All fieldwork was conducted under animal ethics approval from the Flinders University Animal Welfare Committee (Approval Number AEC BIOL7196-7), and a research permit from the South Australian Department for the Environment and Water (Permit Number A27430-1).

2.2 Data processing

To analyse spatial movements and behaviour, raw Argos location data was first manually filtered to remove invalid location codes (“Z”), duplicate time stamps, and implausibly high swim speeds (defined as >6 m s^{-1}). Further preprocessing included removing outlier points using a context-based filter adapted from Weir et al. (2024), where locations were removed if the latitude or longitude was more than four standard deviations from the local mean, calculated as the mean value of locations within two days before and after each point. This approach eliminated anomalous locations that may not have been detected by the Argos location class code filter, while keeping genuine locations indicative of large-scale movements. Argos location data was not collected over equally spaced temporal periods, and large multi-day transmission gaps happened in all tags from unknown factors. To account for the irregular nature of the telemetry data, tracks were segmented into continuous transmission periods, with transmission gaps >24 hr treated as a segment break in the track, and segments with <10 locations removed to prevent future unrealistic interpolation of the data. The remaining tag locations (n = 6,715 combined) comprised the filtered dataset. A state-space model (SSM) was applied to the filtered dataset to predict whale locations at 6 h intervals, resulting in modelled tracks with a combined 1,792 locations.

Dive events were classified as a submergence to a depth of at least 5m and for longer than 15 sec in duration. Tags automatically recorded dive start and end times, maximum dive depth, dive duration, dive shape (based on the proportion of the dive spent at the maximum depth), and post-dive surface interval. Dive data was visually checked for outliers, then aggregated by dive start time into 6 hr bins representing the three hours before and after each modelled location, resulting in 19,732 dives (96.57%) with corresponding location data. Maximum dive depth, dive duration, and post-dive surface interval were averaged in each bin, and the proportion of V-shaped dives within the 6 h bin was calculated. V-shaped dives, which are characterised by a whale spending less than 25% of the dive time at the bottom of the dive, are indicative of transitory behaviour in southern right whales (Fortune et al., 2020; Nowacek et al., 2001).

2.3 Statistical analysis

A multivariate hidden Markov model (HMM) was developed in a step wise fashion to investigate latent behavioural states using the R package ‘momentuHMM’ (version 1.5.5; McClintock & Michelot, 2018), and the Viterbi algorithm was used to determine the likely sequence of behavioural states for each track (McClintock & Michelot, 2018; Zucchini et al., 2016). The HMM included three states: area-restricted search (ARS), directed travel, and a third intermediate or transitional state. The state transition probabilities were modelled using a multinomial logit formula, allowing the probability of switching between behavioural states to vary by distance to the nearest seamount extent, Julian date, distance to shore, and chlorophyll-a concentration (as a proxy for marine productivity). The final model was decided based on lowest AIC score.

The exposure of tagged southern right whales to anthropogenic threats (Appendix, Table 1) was quantified using threat layers compiled in Ferreira et al. (2025), including ship strike, underwater noise, chronic pollution, entanglement, and climate change. These were mapped in 10 x 10 km grid cells and normalised between 0 (no threat) and 1 (maximum intensity). Exposure was then calculated as the proportion of total individual whales (n = 4) present multiplied by the threat intensity within each grid cell. Cumulative exposure was calculated by summing all individual threats and normalising the data.

Diving behaviour analysis was used to complement risk exposure, especially to ship strike risk. Separate linear mixed-effects models were used to investigate how dive depth and duration varied with the reproductive state of the individual and the time of day. Whether a dive was in inner shelf (< 100 m) habitat or not was included as an additional fixed effect. Response variables were log-transformed and applied as fixed effects, and individual tag ID was included as a random intercept.

3. Results

Satellite tags deployed on four southern right whales in Encounter Bay, South Australia, transmitted for 132-198 days (Table 1) between June 2024 and January 2025. Photo identification did not match any of the tagged whales to individuals seen in the local Encounter Bay catalogue or the national Australian Right Whale Photo Identification Catalogue (ARWPIC). Two whales (*Tari* and *Marti*) were later confirmed as pregnant at the time of tagging and to have given birth to their calves in subsequent weeks. At the time of tagging, *Tari* was estimated as approximately 10.4 m in body length, while *Marti* was estimated at < 11.3 m. A third whale (*Muralapi*) was identified as female through genetic analysis of the skin biopsy, and estimated at < 10 m. All four whales moved in a westerly or south-westerly direction, with varying directional persistence and destinations (Figure 1).

Table 1. SPLASH satellite tag and whale identification details for all four tagged southern right whales (*Eubalaena australis*) in Encounter Bay, South Australia. Type of whale refers to reproductive status and sex, including cow (seen with accompanying calf) and unaccompanied adults (UA).

Tag ID	**Name** (Ngarrindjeri language)	**Type (sex)**	**Date deployed**	**Tag duration**	**Minimum dist. travelled**
261252	*Muralapi*	UA (F)	17-06-2024	185 d	9,938 km
261253	*Plonggi*	UA (Unk.)	17-06-2024	198 d	11,626 km
261255	*Tari*	Cow (F)	19-06-2024	150 d	4,089 km
261256	*Marti*	Cow (F)	22-06-2024	132 d	6,014 km

3.1 Movement behaviour

The final behavioural Hidden Markov Model included step length, turning angle, mean maximum dive depth, and average post-dive surface interval. Whale type (UA or cow), Julian date, and seafloor depth were included as covariates on emissions, and distance to seamount extent, Julian date, distance to shore, and chlorophyll-a were covariate effects on transitions. The model characterized three behavioural states, indicating area-restricted search (ARS), transit, and a third intermediate or transitional state.

Based on state-specific parameter estimates (Table 2), the ARS state consisted of short step lengths (3.80 ± 2.78 km per 6 h), tortuous movements (0.063 ± 1.78) with shallow dives (26.09 ± 31.32 m) and very long surface intervals (18.67 ± 57.1 min) (Fig 8). A large portion of ARS behaviour (57.6%) was conducted in inner shelf (<100 m depth) habitat, as expected for cows resting and nursing young calves in shallow waters. However, the nearly equally large proportion of off-shelf ARS behaviour implies that the modelled ARS state may include other behaviours when whales are offshore, possibly including intensive and shallow feeding bouts, that the model cannot differentiate between.

The transit state, as expected, consisted of longer steps (25.04 ± 9.26 km per 6 h) and directed movement (-0.019 ± 0.34) with deeper dives (45.52 ± 37.34 m). The intermediate state had similar step lengths (9.78 ± 6.34 km) to ARS behaviour, but with moderate dive depths (34.42 ± 30.42 m) and the smallest average surface interval (1.54 ± 1.37) (Fig 8). Bouts of Intermediate state behaviour were often interspersed with transitory behaviour, and together with the state parameters indicate that this state also includes multiple behaviours depending on the context, but all seem to be related to exploratory or investigative movements. These likely include foraging, changing habitats along the coast, social behaviour, or adjusting course. Over a third (35.6%) of Intermediate state locations were in inner-shelf habitat, and since foraging is not considered to occur in nearshore waters for this species, behaviour being exhibited may be context dependent. Cows with calves conducted slightly shorter step lengths and remained on the surface longer in ARS and Transit states than unaccompanied adults (Fig 8b(iii), d(iii)), which is expected given calves have lower migratory ability due to their smaller size and lower available body energy. Post-dive surface intervals shortened as the year progressed (Fig 8d(iv-v)), which is likely related to a shift from resting in coastal areas into offshore movements.

The stationary state probabilities were determined to allow the order of behavioural states along a track to be influenced by distance to the nearest seamount extent, Julian date, distance to shore, and chlorophyll a concentration (Fig 9). Behavioural states were more stable as whales moved further from shore, whales were less likely to change from ARS to Transit or vice versa, instead shifting into Intermediate behaviour first. Intermediate behaviour was also more often followed by ARS behaviour later in the year, potentially indicating rest periods after some foraging effort. Whales in waters with higher chlorophyll concentration were more likely to transition from transiting behaviour into the Intermediate state, and to stay longer in the Intermediate state, while the likelihood of ARS increased (Fig 9d). This further supports that both the Intermediate and ARS states likely include foraging and feeding behaviour. Proximity to seamount habitats resulted in more direct shifting from Transit to ARS states (Fig 9c), and a very weak influence on the probability of transitioning from Transit to Intermediate. This could indicate that more spatially intensive, tortuous, and shallower feeding bouts are occurring in these types of habitats, and that seamount areas could be used for navigational markers or socialising, as suggested for humpback whales (Derville et al., 2020).

Table 2. Behavioural state details of southern right whales (*Eubalaena australis*) from all combined SPLASH satellite tag data deployed in Encounter Bay, South Australia, including the number of locations that were designated each state, step length, turning angle, average maximum dive depth (m), post-dive surface interval (PDSI), and the percent of time the behaviour was observed in inner shelf habitat (<100 m depth). ARS: area-restricted search.

State	**Count**	**Step length (km)**	**Turning angle**	**Max. dive depth (m)**	**PDSI (min)**	**% State over inner shelf**
ARS	616	3.80±2.78	0.063±1.78	26.09±31.32	18.67±57.1	57.6
Intermediate	792	9.78±6.34	0.008±1.39	34.42±30.42	1.54±1.37	35.6
Transit	399	25.04±9.26	-0.019±0.34	45.52±37.34	2.40±3.35	33.8

Both pregnant females spent a considerable amount of time in shallow coastal waters while pregnant and after giving birth. 261255 *'Tari'* (Fig. 1e) was tagged on 19 June 2024 and spent two more days in the Encounter Bay area before moving west through Backstairs Passage (north of Kangaroo Island) and across the Gulf St Vincent then Spencer Gulf showcasing a mix of all three behavioural states. Following a brief loop offshore in transitory behaviour, *Tari* came back to the coastline and alternated between ARS and Intermediate states along a 250 km stretch of coastline, spending some time close to Streaky Bay, the western side of St. Peter Island, and around Point Bell (Fig. 1g). Each of these stop overs were characterised by ARS behaviour over multiple days in shallow, sandy and southeast-facing bays, suggesting that this whale may have given birth either in the offshore trip or shortly after returning to shallower waters, around the first week of July. *Tari* was subsequently documented in Fowlers Bay with a calf on 25 July (Current Environmental pers. comm.) and remained there until 16 August. The tag stopped transmitting the next day and until 11 of September, when it re-started transmitting, revealing that *Tari* had moved over 1,000km south toward the Subtropical convergence. There was one sighting during this transmission gap by survey team at Head of Bight on 30 August (Current Environmental pers comm.), showing *Tari* was between Fowlers Bay and Head of Bight for another two weeks after the tag stopped transmitting and before transmissions resumed while offshore.

The second pregnant female, ID 261256 '*Marti'*, also used coastal areas extensively (Fig. 1f), and did not remain in Encounter Bay after tagging. Instead, it transited west across Gulf St Vincent then Spencer Gulf (Fig. 1h), exhibiting alternating Transit and Intermediate behaviour for one week before undertaking a rapid westward transit along the Great Australian Bight to Israelite Bay, southern Western Australia (WA), arriving there on 11 of July. Marti stayed in Israelite Bay for 80 days until late September and was spotted with a calf by the Southern Right Whale aerial survey team on 21 of August (West Australian Museum pers. comm.). The high concentration of ARS behaviour in Israelite Bay immediately upon arrival and throughout the stopover suggests birth of the calf may have been soon after arriving, around mid-July. After leaving Israelite Bay, *Marti* moved directly offshore and into the Southern Ocean, first turning southeast to around 500 km east of the Bremer Canyon system before conducting clusters of Intermediate behaviour separated by transit for the next month, at which point the tag ceased transmitting.

The two non-calving adults conducted different migration strategies and timing. ID 261253 '*Plonggi'* spent significant time in both inshore and offshore areas (Fig. 1d). After being tagged on 17 June, *Plonggi* remained in the Encounter Bay area for four days before travelling west along the coastline. Like 261255 *'Tari'* and 261256 '*Marti*', *Plonggi* did not enter the Gulf St. Vincent or Spencer Gulf, instead transiting across them and conducting Intermediate behaviour on the western edges before continuing west. *Plonggi* followed an acutely similar migratory track as *Marti* but will much lower travel efficiency. Over a three-week period between late June and mid-July, it progressed westward with multiple stop overs and repeated segments of Intermediate behaviour. These stopovers included established and emerging calving areas such as Head of Bight, where *Plonggi* stayed for five days and displayed extended ARS behaviour, and Twilight Cove and Israelite Bay, where it again stayed for multiple days conducting ARS behaviour. Although the sex has not been confirmed for this individual, this behaviour likely reflects socialising behaviour and, if female, could indicate scoping for future calf rearing areas. *Plonggi* then transited south to the Subtropical Convergence, where it conducted alternating Transit and Intermediate behaviour in an easterly direction before looping back to an area between 100 km east and 250 km south of the Bremer Canyon system that lies north of a cluster of underwater seamounts (Fig. 1b). Here it conducted alternating Intermediate and ARS behaviour during October, at which point the tag ceased transmitting briefly. In another southern right whale study, the offshore area near Bremer Canyon system was also visited by individuals tagged in WA and New Zealand (Riekkola et al., 2025), and some ARS behaviour was recorded there, suggesting this area as ecologically valuable to this species.

When *Plonggi*'s tag resumed seven weeks later, it had moved to the subtropical convergence, west of WA. There it continued clusters of Intermediate and ARS behaviour split by periods of transit for the next two weeks until the tag ceased transmitting in early January 2025.

While *Plonggi* conducted mixed inshore and offshore movements after tagging, ID 261252 '*Muralapi*' (Fig. 1c) remained in Encounter Bay area for two days post-tagging and shortly after the tag ceased transmitting for 21 days. When it resumed transmissions in late July, *Muralapi* had travelled far offshore to the Subtropical Front and was moving in a westerly direction. It then looped north and conducted ARS and Intermediate behaviour around a cluster of seamounts near the Bremer Canyon system in October (Fig. 1a), which mirrors *Plonggi*'s movements and timing. It then travelled west within the Diamantina Fracture Zone between 20 October and 18 December, engaging mostly in transitory behaviour, with periods of Intermediate behaviour and occasional ARS.

3.2 Dive behaviour

Dive behaviour was strongly influenced by whale type, either cow with a calf or unaccompanied adult (UA) (Fig 2). UAs dove considerably deeper and with more variability across all timeframes (day: mean = 18.83 m, median = 11.0 m; night: 16.64 m, 10.5 m) than cows (day: mean = 8.74 m, median = 6.5 m; night: 8.61 m, 6.5 m) ($\beta = 0.553$, SE = 0.125, $t = 4.43$), a difference that was reduced slightly at night ($\beta = -0.059$, SE = 0.020, $t = -2.98$). Dives conducted outside the inner shelf were over 35% deeper than those inside ($\beta = 0.31 \pm 0.01$, $t = 21.50$). There was no diel effect on dive depth ($\beta = -0.006$, SE = 0.016, $t = -0.39$), and the linear mixed-effects model indicated no significant overall differences in dive durations between cows and UAs ($\beta = 0.0167$, SE = 0.127, $t = 0.13$). However, cows conducted significantly shorter dives at night than during the day ($\beta = -0.0916$, SE = 0.0237, $t = -3.86$). Random intercept variance was small (SD = 0.125), indicating no significant difference in dive behaviour between individual whales.

There was little overall difference in dive duration between cows and UAs ($\beta = -0.06 \pm 0.14$, $t = -0.43$), but dives conducted in offshore waters were around 11% longer than those in the inner shelf ($\beta = 0.10 \pm 0.02$, $t = 4.83$). Dives were also significantly shorter at night than during the day ($\beta = -0.09 \pm 0.02$, $t = -3.76$), and cows reduced their dive duration more at night compared to UAs ($\beta = 0.12 \pm 0.03$, $t = 4.21$).

Post-dive surface intervals varied strongly between unaccompanied adults and cows with calves; cows conducted significantly longer ($\beta = -0.598 \pm 0.075$, $t = -8.01$) and more variable time at the surface (mean 6.9 min, median 1.22 min, range 0.05–864.5 min) than unaccompanied adults (mean 1.71 min, median 1.02 min, range 0.05–140.45 min). Dive duration was a strong positive predictor of post-dive surface interval ($\beta = 0.109 \pm 0.003$, $t = 36.17$), indicating resting, and dive depth had a small but significant negative effect on post-dive surface interval (β = −0.0017 ± 0.00075, t = −2.23). Longer surface intervals were conducted more in inshore (inner shelf) habitats than in offshore (β = -0.15 ± 0.04, t = -3.61).

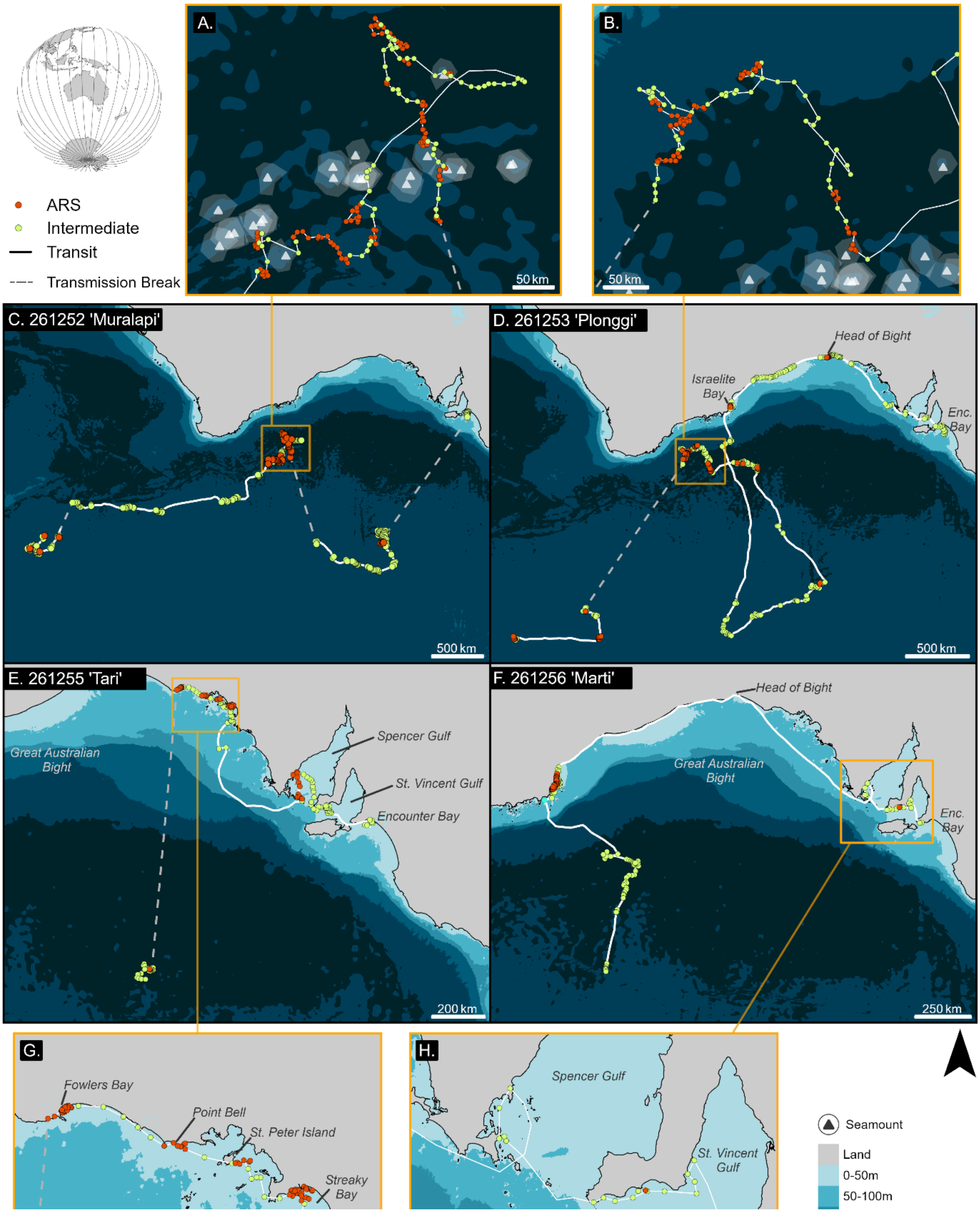

Figure 1. Interpolated movements of southern right whales (*Eubalaena australis*) with behaviour states determined by hidden Markov models based on satellite tag data from southern Australia. ARS: area-restricted search.

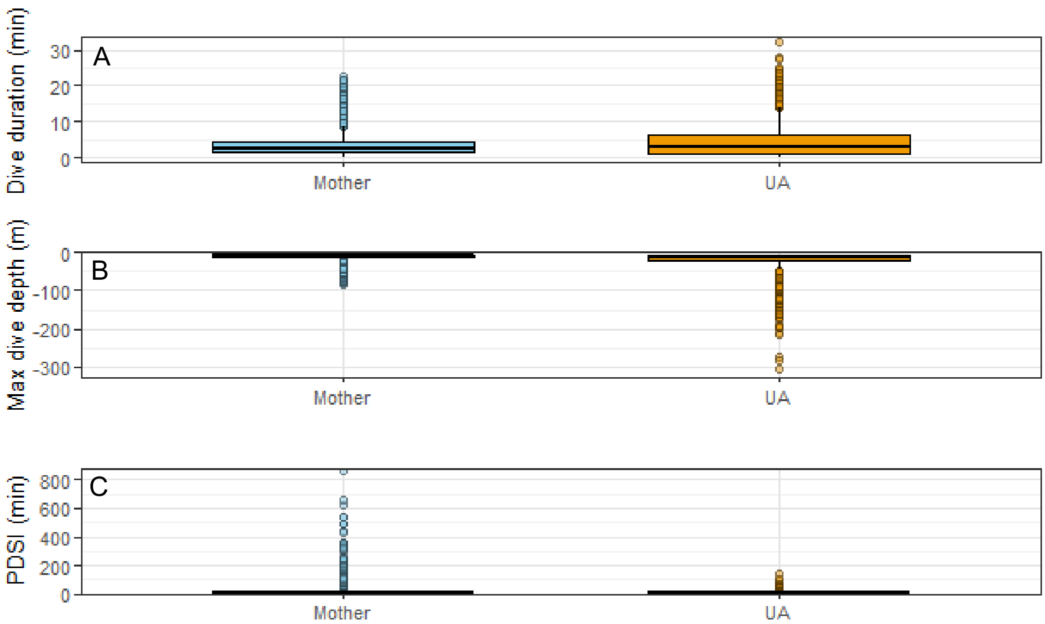

Figure 2. Dive metrics for satellite tagged southern right whale (*Eubalaena australis*) cows and unaccompanied adults (UAs) in southern Australia, including (a) Dive duration, (B) maximum dive depth and (C) post dive surface interval (PDSI).

V-shaped dives, which are thought to reflect transit behaviour (Fortune et al., 2020; Nowacek et al., 2001), were 9.64% of the dives conducted by unaccompanied adults and 6.20% of the dives conducted by cows with calves (Fig 3). Cows made a proportionally greater number of square-shaped dives than UAs and smaller number of U-shaped dives. Consecutive U-shaped dives, which is a more energetically demanding dive type (Derville et al., 2020), is associated with feeding behaviour in humpback whales (Goldbogen et al., 2008; Goldbogen et al., 2017), but the two species show different feeding styles.

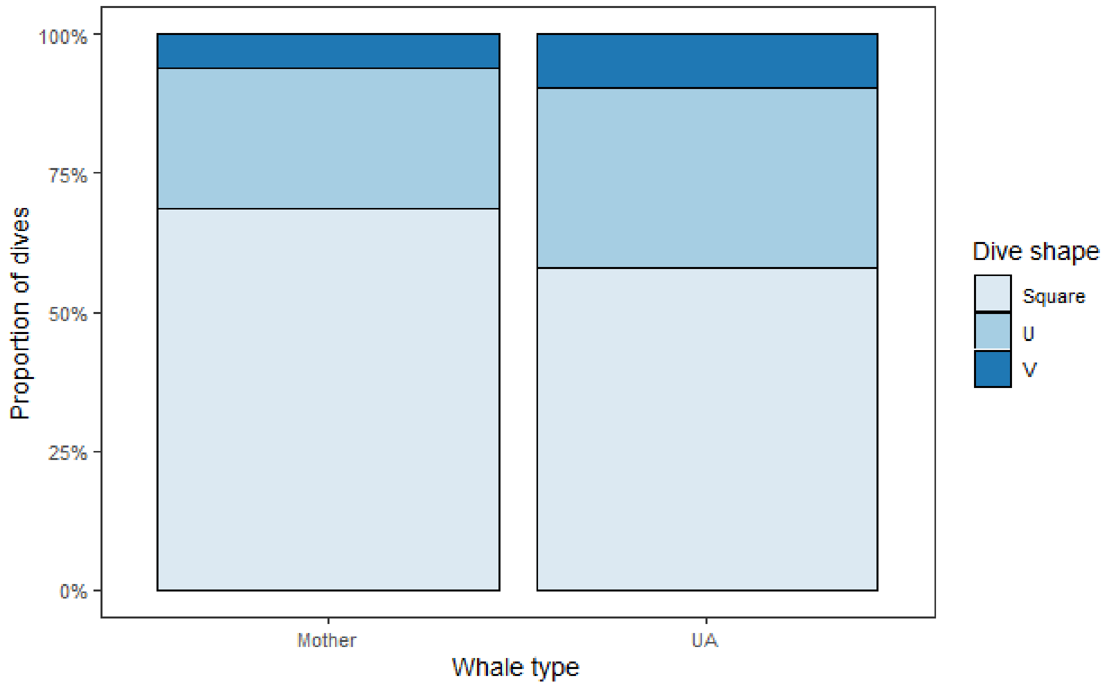

Figure 3. Proportion of dive shapes conducted by cows with a calf and unaccompanied adults (UA) southern right whales (*Eubalaena australis*) satellite tagged in southern Australia.

3.3 Risk exposure assessment

Spatial overlap of anthropogenic threats with tagged whales revealed where areas of concern to the larger Australian southern right whale population may occur. While the density of these threats is minimal (Fig. 4), the widespread nature and implications for the larger population are possibly considerable. Specifically, inshore areas around the Fleurieu, Yorke, and Eyre Peninsulas in South Australia were used by all tagged whales and were represented in threats we assessed. Normalised cumulative exposure values in these areas were some of the highest in the entire study area and are likely a consequence of the larger human population concentration in this region. Offshore (>50 km) waters from Bremer Bay and Albany in southern WA is another such area, where all threats, besides entanglement, were represented. Overlap with entanglement threat was only found around the three South Australian peninsulas, the lack of risk in other areas is likely a reflection of the entanglement layer only including commercial fisheries. For example, the habitat used by the tagged whales south of WA overlaps with two National Park Zones, where no commercial fishing is permitted, and a Multiple-Use Zone, which requires authorisation for commercial fisheries and bans long-lines, nets, bottom trawling, and trot lining. Similarly, there is commercial fishery presence in the Great Australian Bight, however it is focussed along the shelf edge around 180 km offshore, an area that was only possibly travelled by one of our whales (*Tari*) during a transmission break (Fig 1e). As presence within grid cells cannot be ascertained during transmission breaks, the area becomes unrepresented in the risk exposure assessment.

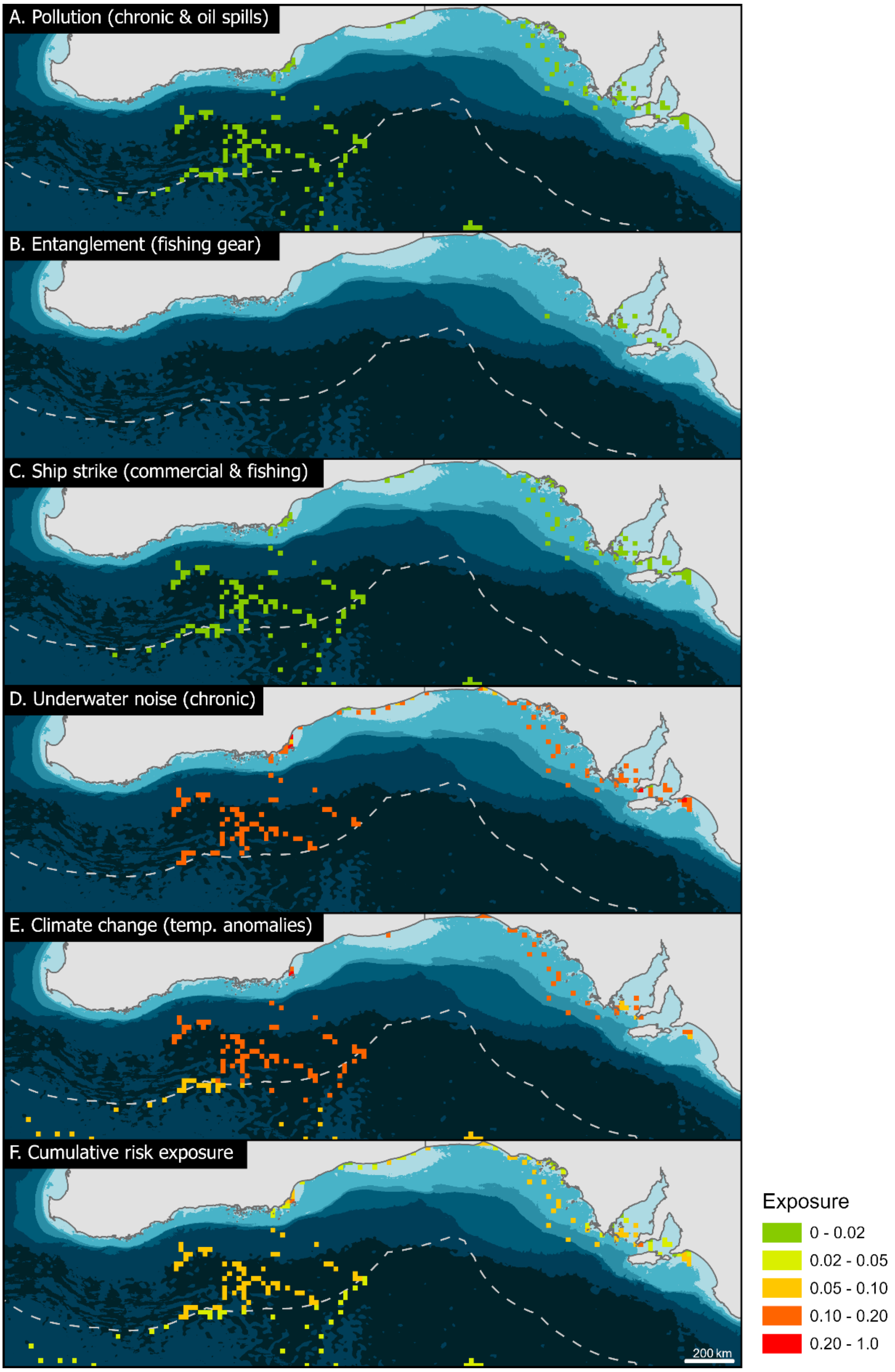

Figure 4. Risk exposure of southern right whales (*Eubalaena australis*) in southern Australia to (A) pollution, (B) entanglement, (C) ship strike, (D) chronic underwater noise, (E) climate change, and (F) cumulative threats. Risk exposure is characterised as the density of the threat layer multiplied by the number of whales occurring within the grid cell and is normalised between 0 (none) and 1 (maximum). Dashed contour indicates the Australian Exclusive Economic Zone.

3.4 Photo-identification and biopsy sampling

Eight southern right whales, including the four satellite tagged individuals, were photo-identified during the boat-based fieldwork in Encounter Bay, South Australia. Whales were identified between 17th and 22nd of June 2024, and in groups comprised of 1 to 4 individuals. None of these individuals had an accompanying calf at the time of the identification and were all considered either sub-adult or adult whales based on their approximate length. The identified individuals were tentatively matched against the Encounter Bay Southern Right Whale Catalogue, which contained 194 individuals, but no matches were found.

Of the four satellite tagged individuals, one was also successfully biopsy sampled. No other individuals were biopsy sampled during the fieldwork due to either an unsuccessful attempt or no suitable opportunity. Due to only one biopsy sample being collected, genetic analysis of population structure was not conducted. However, based on the tagging data, all four whales moved in a southerly and westerly direction, suggesting that all four individuals may be part of what is considered the western population. Genetic sexing via PCR was performed on the biopsy sample obtained, and the individual was identified as a female.

Figure 5. Photo-identification of four satellite tagged southern right whale (*Eubalaena australis*) cows and unaccompanied adults (UAs) in Encounter Bay, South Australia.

Figure 6. Photo identification images of four additional southern right whales not satellite tagged.

4. Indigenous engagement

The Flinders University research team collaborated with Ngarrindjeri Nation Elders and The City of Victor Harbor to bring to life the project *Kondoli* Dreamtime Story Lantern Workshops as part of the 2025 Winter Whale Fest. The Winter Whale Fest fosters connections between community, science, and culture, raising awareness of marine ecosystems, and through this project shared the dreamtime story of *Kondoli* the Whale Man. The project engaged various First Nations artists, local schools, young families and other members of the community in creating lanterns inspired by the Dreamtime story of *Kondoli* during a week (24-28th of June) of lantern-building and storytelling workshops (Figures 6 and 7). The project fostered cultural exchange, artistic collaboration, and community engagement through large-scale illuminated sculptures, which culminated in a community event celebration at the end of the festival on Sunday, 29th of June, attracting approximately 150 people (Figure 7). The project objectives included:

- Cultural Connection & Education: Interactive storytelling and artistic practices with First Nations artists.
- Creative Collaboration: Hands-on workshops with local schools constructing cane and paper lanterns representing the story of *Kondoli* the Whale Man.
- Community Engagement: Public art experience culminating in a showcase event.
- Skill Development: Professional development for first nations artists and the local youth.

Figure 7. Poster of the *Kondoli* Dreamtime Story Lantern Workshops and Parade for the 2025 Winter Whale Fest, Victor Harbor, South Australia

Figure 8. Composite photo of workshop activities as part of the *Kondoli* Dreamtime Story, 2025 Whale Fest, Victor Harbor, South Australia

5. Recommendations

5.1 Research

To gain a more comprehensive and accurate understanding of southern right whale habitat use, movement patterns, and exposure to threats, further studies on their movement ecology are essential. This could include satellite tagging of a larger and more diverse sample of individuals from both the eastern and western populations, encompassing different age classes, sexes, and reproductive states. While short-term effects from consolidated tags are known to occur (e.g., local swelling, tag-site depression, pigmentation changes) (Robbins et al. 2016; Charlton et al. 2023), no apparent medium-term impacts of tagging have been observed (Charlton et al. 2023). Additionally, the viability of less invasive tagging methods like shorter consolidated blubber tags (Zerbini et al., 2026) should be explored to minimise potential stress or long-term impacts on the whales.

Integrating tagging efforts with passive acoustic monitoring could also enhance the detection of whale presence and movement in key areas, particularly those with high entanglement risks, by providing real-time data even when the whales are not visible or tagged. This combined approach would offer a more representative understanding of southern right whale distribution, while also informing about environmental factors that influence movement patterns and potential changes in habitat use of the species over time.

Moreover, prioritising biopsy sampling in under-sampled areas and conducting genomic analyses is crucial to advancing our understanding of the population structure, gene flow, and genetic health of the Australian southern right whale population(s). Such studies would help clarify the level of genetic exchange between Australian populations and those of adjacent regions, such as New Zealand and South Africa.

Maintaining and expanding national and international collaborations, such as those through the Southern Ocean Research Partnership (SORP-IWC), is also vital for sharing long-term data. This will contribute to a more thorough understanding of southern right whale migratory routes and risk exposure, especially in the face of global environmental changes and increasing human impacts.

By addressing these research limitations and improving collaborative efforts, the effectiveness of conservation strategies and management decisions for southern right whales can be greatly enhanced.

5.2 Management

Results from this study support the implementation of the National Recovery Plan for Southern Right Whales (DCCEEW, 2024). The movements and behaviour of these satellite tagged southern right whales complement the geographic boundaries of biologically important areas (BIAs) identified for reproduction and migration (DCCEEW, 2024). They also provide evidence needed for state-governed inshore and Commonwealth-governed offshore development planning and should be taken into consideration when designing risk mitigation measures. The dive behaviour of cow-calf pairs is of particular interest, as long surface intervals and shallow diving behaviour could increase the risk towards whales at this critical life stage, particularly from vessel traffic. One of the tagged cows in this study also visited multiple stopover sites within South Australia, likely with her newborn calf, most of which have not been identified as critical calving aggregation areas for this population. With the expansion of the population post-whaling, however, sites such as Streaky Bay, where this female stayed resting for multiple days (Fig 1G), need to be monitored as potential candidates for increased State protection such as slow zones for vessels or future designation as Whale Nursery Protection Areas. Additionally, inshore South Australian waters revealed some of the highest cumulative risk values across all four whale tracks, which has implications for coastal planning and vessel strike mitigation.

All four tagged whales spent significant time in Commonwealth waters offshore, which was expected given the offshore foraging and migratory behaviour for the species. A substantial risk identified for all four of these whales while in Commonwealth waters was ship strike, given that major shipping lanes between Perth, Adelaide and Melbourne occur through the area. While there are only a handful of ship strike casualties reported for southern right whales in Australia (Peel et al., 2018), this area is relatively remote and offshore, meaning the likelihood of a whale struck by a ship both floating to shore and being in condition for cause of death to be identified as ship strike is relatively limited. Should substantial evidence be collected to identify offshore collision risk areas, future management measures could include seasonal risk advisories to industry, the need for onboard Marine Mammal Observers to spot whales prior to collision, or mandatory slow zones in peak seasons. Additionally, offshore development and infrastructure approvals need to have risk that is already present built into the approval process, to limit further cumulative risk to the species.

As more data on whale movements and risk exposure becomes available, it will be crucial to further integrate risk assessments into marine planning, fisheries management, and shipping regulations to minimise cumulative impacts on these recovering right whale populations. Additionally, management should prioritise co-management with First Nations communities, ensuring that cultural knowledge, traditional stewardship, and community participation are central to conservation decision-making and public awareness.

6. Conclusions

This study provides new insights into the movements, connectivity, behaviour, and risk exposure of southern right whales in southern Australian waters and the Southern Ocean, based on individuals satellite-tagged at Encounter Bay, South Australia, near the geographic boundary between the eastern and western populations. Satellite tracking revealed extensive coastal and offshore movements, previously undocumented nursery areas in SA, predominantly shallow diving behaviour, and clear spatial overlap with various anthropogenic threats, underscoring ongoing challenges to the recovery of this endangered species. While limited sample sizes constrained genetic inference, predominantly westward and south-westward movement patterns suggest a strong association with the western population and emphasise the need for continued monitoring to improve understanding of population connectivity, habitat use, and threat exposure. Importantly, the integration of scientific research with Ngarrindjeri-led cultural activities demonstrates the value of collaborative approaches that support both conservation outcomes and community connection, providing a holistic framework for the future management and protection of southern right whales. This work directly contributes to the research objectives outlined in the National Recovery Plan for the Southern Right Whale, which aims to minimise anthropogenic threats and facilitate the recovery of this species in Australian waters.

7. References

Bannister, J.L. (1990). Southern Right Whales Off Western Australia. *Report of the International Whaling Commission, Special Issue 12.*

Bannister, J.L. (2001). Status of Southern Right Whales (*Eubalaena Australis*) Off Australia. *Journal of Cetacean Research and Management*, *Special Issue* 2, 103–110. https://doi.org/10.47536/jcrm.vi.273.

Beltran, R.S., Hernandez, K.M., Condit, R., Robinson, P.W., Crocker, D.E., Goetsch, C., et al., (2023). Physiological tipping points in the relationship between foraging success and lifetime fitness of a long-lived mammal. *Ecology Letters, 26* (5), 706–716.

Burnell, S.R. (2001). Aspects of the Reproductive Biology, Movements and Site Fidelity of Right Whales Off Australia. *Journal of Cetacean Research and Management*, 89-102. https://journal.iwc.int/index.php/jcrm/article/view/272.

Carroll, E.L., Patenaude, N., Alexander, A., Steel, D., Harcourt, R., Childerhouse., S., Smith, S., Bannister, J., Constantine, R., Scott Baker, C. (2011). Population structure and individual movement of southern right whales around New Zealand and Australia. *Marine Ecology Progress Series, 432*, 257-268. https://doi.org/10.3354/meps09145.

Carroll, E.L., Baker, C.S., Watson, M., Alderman, R., Bannister, J., Gaggiotti, O.E., Grocke, D.R., Patenaude, N. & Harcourt, R. (2015). Cultural Traditions across a Migratory Network Shape the Genetic Structure of Southern Right Whales around Australia and New Zealand. *Scientific Reports* 5. https://doi.org/10.1038/srep16182.

Charlton, C., McCauley, R.D., Brownell Jr., R.L., Ward, R., Bannister, J.L., Salgado Kent, C. & Burnell, S. (2022). Southern Right Whale (*Eubalaena Australis*) Population Demographics at Major Calving Ground Head of Bight, South Australia, 1991–2016. *Aquatic Conservation: Marine and Freshwater Ecosystems, 32*(4), 671-686. https://doi.org/10.1002/aqc.3771.

Charlton, C., Christiansen, F., Ward, R., Mackay, A.I., Andrews-Goff, V., Zerbini, A.N., Childerhouse, S., Guggenheimer, S., O'Shannessy, B., Brownell Jr., R.L. (2023). Evaluating short- and medium-term effects of implantable satellite tags on southern right whales *Eubalaena australis. Diseases of Aquatic Organisms,* 155, 125-140.

DCCEEW (2024). National Recovery Plan for the Southern Right Whale. Department of Climate Change, Energy, the Environment and Water, Canberra. https://www.dcceew.gov.au/environment/biodiversity/threatened/recovery-plans/southern-right-whale

Derville, S., Torres, L.G., Zerbini, A.N., Oremus, M., Garrigue, C. (2020). Horizontal and vertical movements of humpback whales inform the use of critical pelagic habitats in the western South Pacific. *Scientific Reports*, *10*(1), 4871. https://doi.org/10.1038/s41598-020-61771-z.

Erbe, C., Peel, D., Smith, J., Schoeman, R. (2021). Cumulative sound exposure from shipping in the Australian EEZ [Dataset] https://metadata.imas.utas.edu.au/geonetwork/srv/eng/catalog.search#/metadata/480847b4-b692-4112-89ff-0dcef75e3b84.

Evans, K., Charlton, C., Townsend, A., Watson, M., Carroll, E., Double, M., Upston, J., Carlyon, K. & Alderman, R. (2021). Estimation of Population Abundance and Mixing of Southern Right Whales in Australian and New Zealand Regions. *Report to the National Environmental Science Program, Marine Biodiversity Hub and CSIRO Oceans and*

Atmosphere. https://www.nespmarine.edu.au/document/estimation-population-abundance-andmixing-southern-right-whales-australian-and-new-zealand.

Ferreira, L.C., Möller, L., Thums, M. (2025) Project 4.8 – Potential impacts of offshore wind developments on Eastern Indian Ocean pygmy blue whales (*Balaenoptera musculus brevicauda*). Unpublished report, prepared for NESP Marine and Coastal Hub Australian Institute of Marine Science, Perth. (49 pp).

Fortune, S.M., Ferguson, S.H., Trites, A.W., Hudson, J.M., Baumgartner, M.F. (2020). Bowhead whales use two foraging strategies in response to fine-scale differences in zooplankton vertical distribution. *Scientific Reports, 10* (1), 20249. https://doi.org/10.1038/s41598-020-76071-9.

Gilmore, W. Characterising population identity, spatial distribution, and connectivity of Southern Right Whales, *Eubalaena australis* from Encounter Bay, South Australia.

Honours thesis, Flinders University. 77 pp.

Grundlehner, A., Smith, J.N., Bannister, J.L., Andrews-Goff, V., Brasier, M., Double, M.C., & Corney, S.P. (2025). The End of an Era? Trends in Abundance and Reproduction of Australian Southern Right Whales (*Eubalaena australis*) Suggest Failure to Re-Establish Pre-Whaling Population Size. *Global change biology*, *31*(5), e70218. https://doi.org/10.1111/gcb.70218.

Heide-Jorgensen, M., & Øien, N. (2001). A New Technique for Deploying Satellite Transmitters on Baleen Whales: Tracking a Blue Whale (*Balaenoptera Musculus*) in the North Atlantic. *Marine Mammal Science, 17*(4), 949-954. https://doi.org/10.1111/j.1748-7692.2001.tb01309.x.

IWC (2010) Report of the Workshop on Welfare Issues Associated with the Entanglement of Large Whales. IWC Document IWC/62/15.

Jenouvrier, S., Barbraud, C., Weimerskirch, H., Caswell, H., (2009). Limitation of population recovery: a stochastic approach to the case of the emperor penguin. *Oikos, 118* (9), 1292–1298.

Jonsen, I.D., Grecian, W.J., Phillips, L., Carroll, G., McMahon, C., Harcourt, R.G., Hindell, M.A., Patterson, T.A. (2023). aniMotum, an R package for animal movement data: rapid quality control, behavioural estimation and simulation. *Methods in Ecology and Evolution, 14*(3), 806–816. https://doi.org/10.1111/2041-210X.14060.

Kemper, C.M., Steele-Collins, E., Al-Humaidhi, A., Segawa Fellowes, T., Marsh, O. & Charlton, C. (2022). Encounter Bay, South Australia, an Important Aggregation and Nursery Area for the Southern Right Whale, *Eubalaena Australis* (Balaenidae: Cetacea). *Transactions of the Royal Society of South Australia,* 1-21. https://doi.org/10.1080/03721426.2021.2018759.

Langrock, R., King, R., Matthiopoulos, J., Thomas, L., Fortin, D., & Morales, J. M. (2012). Flexible and practical modeling of animal telemetry data: Hidden Markov models and extensions. *Ecology*, *93*, 2336–2342. https://doi.org/10.1890/11-2241.1.

London (2020). pathroutr: An R Package for (Re-)Routing Paths Around Barriers (Version v0.1.1-beta). Zenodo. http://doi.org/10.5281/zenodo.4321827.

McClintock, B.T., Michelot, T. (2018) momentuHMM: R package for generalised hidden Markov models of animal movement. *Methods in Ecology and Evolution*, *9*, 1518-1530. https://doi.org/10.1111/2041-210X.12995.

Nielson, M.L.K, Sprogis, K.R., Bejder, L., Madsen, P.T. & Christiansen F. (2019). Behavioural development in southern right whale calves. *Marine Ecology Progress Series, 629*, 219-234. https://doi.org/10.3354/meps13125.

Nowacek, D.P., Johnson, M.P., Tyack, P.L., Shorter, K.A., McLellan, W.A. (2001). Buoyant balaenids: the ups and downs of buoyancy in right whales. *Proceedings of the Royal Society B, 268*(1478), 1811–1816. https://doi.org/10.1098/rspb.2001.1730.

Pebesma, E. (2018). Simple Features for R: Standardized Support for Spatial Vector Data. *The R Journal*, *10*(1), 439–446. https://doi.org/10.32614/RJ-2018-009.

Peel, D., Smith, J.N. & Childerhouse, S. (2018) Vessel Strike of Whales in Australia: The Challenges of Analysis of Historical Incident Data. *Frontiers in Marine Science,* 5(69), 69. https://doi.org/10.3389/fmars.2018.00069.

Pirzl, R. (2008) Spatial Ecology of E. Australis: Habitat Selection at Multiple Scales. Ph.D, Deakin University.

Riekkola, L., Sprogis, K.R., Della Penna, A., Andrews-Goff, V., Harcourt, R., Cole, R., Constantine, R., Goetz, K.T., Lundquist, D., Stuck, E., Zerbini, A.N., & Carroll, E.L. (2025). Large-scale differences, mesoscale similarities: Neighbouring marine predator populations provide insights into Southern Ocean productivity. *Global Ecology and Conservation*, e03788. https://doi.org/10.1016/j.gecco.2025.e03788.

Robbins, J., V. Andrews- Goff, P. Clapham, et al. 2016. Evaluating Potential Effects of Satellite Tagging in Large Whales: A Case Study with Gulf of Maine Humpback Whales. *Report to the National Fish and Wildlife Foundation.*

Smith, J.N., Double, M., Kelly, N., Charlton, C. & Bannister, J. (2022). Relative Abundance of the 'Western' Population of Southern Right Whales from an Aerial Survey Off Southern Australia: Final Report on 2021 Survey. *Report to the National Environmental Science Program*. Murdoch University (Lead organisation). https://www.nespmarinecoastal.edu.au/project-1-26final-report-2/.

Sprogis, K., Harcourt, R., Riekkola, L., Childerhouse, S., Zerbini, A. N., Andrews-Goff, V., & Carroll, E. (2024). Western Australian southern right whale coastal and offshore movements. *International Whaling Commission*.

Stamation, K., Watson, M., Moloney, P., Charlton, C. & Bannister, J. (2020). Population Estimate and Rate of Increase of Southern Right Whales *Eubalaena Australis* in Southeastern Australia. *Endangered Species Research,* 41, 373-383. https://doi.org/10.3354/esr01031.

Weir, C.R., Fernandez, S., Jackson, J.A., Miller, A., Sucunza, F., Slesser, H.W., & Zerbini, A.N. (2024). Movements and behaviour of southern right whales satellite-tracked in and beyond a subantarctic archipelago wintering ground. *Endangered Species Research*, *55*, 229–245. https://doi.org/10.3354/esr01371.

Wildlife Computers (2019). SPLASH10 (-F, -BF, -FL, -X, -L, -LX, -FX) TDR10 (-DD, -F, -BF, -X, -L, FL, -FX, -LX, -BX) With host version 1.26.3002 User Guide. 〈https://static.wildlifecomputers.com/SPLASH10-TDR10-User-Guide.pdf〉.

White, T. (2008). The role of food, weather and climate in limiting the abundance of animals. *Biology Review, 83* (3), 227–248.

Zerbini, A.N., Fernández, S., Fermepin, S., *et al.* (2026). Development of a Short, Integrated, Consolidated Satellite Tag Designed to Anchor in the Blubber of Right Whales (*Eubalaena* spp.). *Marine Mammal Science*, *42*(2), e70130.

Zucchini, W., MacDonald, I.L., Langrock, R. (2016). Hidden Markov Models for Time Series: An Introduction using R. Second ed. Boca Raton, FL Chapman & Hall/CRC.

8. Appendices

8.1 Appendix A. Hidden Markov model selection and results

Table 3. Hidden Markov Model (HMM) selection of southern right whale movement behaviour, ranked by Akaike Information Criteria (AIC) scores. Transition covariates include Julian date, distance to shore, distance to seamount extent, and chlorophyll-a concentration. The final model chosen is shown in bold.

Model	Log-likelihood	AIC
M6: Null + WhaleType + JulianDate + Bathymetry + *all transition covariates*	**-14823.6**	**29825.19**
M5: Null + WhaleType + JulianDate + Bathymetry	-15017.67	30165.34
M4: Null + WhaleType + JulianDate	-15003.38	30112.76
M3: Null + WhaleType	-15064.03	30210.05
M2: Null model (no predictors)	-15166.85	30397.71

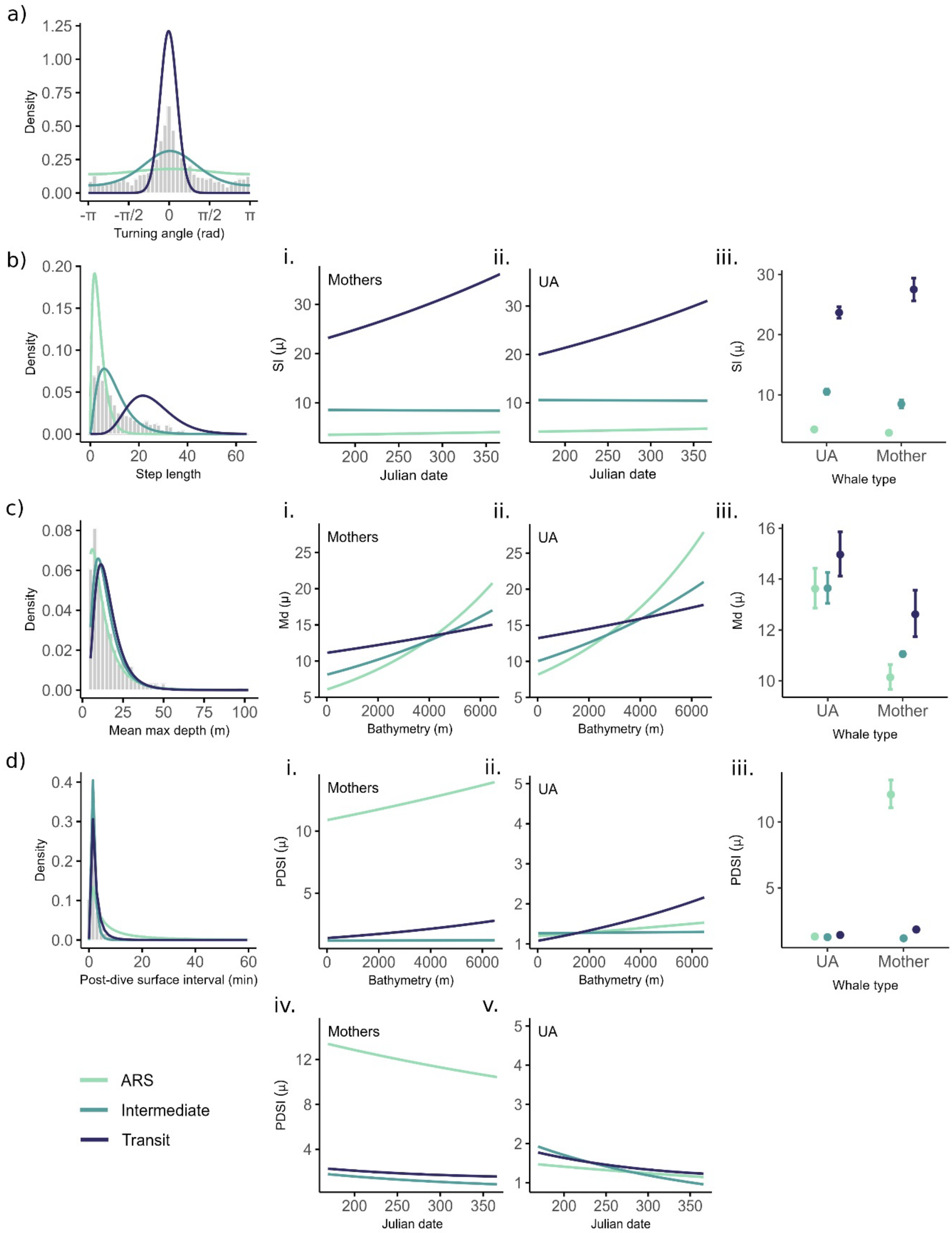

Figure 9. Hidden Markov model (HMM) histograms and decoded states (Viterbi) for area restricted search (ARS; green), intermediate (light blue), and transit (dark blue) behaviour in respect to the HMM data streams: (a) turning angle, (b) step length (*Sl*), (c) mean maximum dive depth (*Md*), and post-dive surface interval (*PDSI*). Covariate effects on the emission probabilities included Julian date on *Sl* and *PDSI*, bathymetry on *Md* and *PDSI*, and whale type (UA or mother) on *Sl*, *Md*, and *PDSI*. Covariate effects are numbered by Roman numerals and correspond to the histogram on the same row; all assume a fixed mean bathymetry of 2,700 m and a day of 245. The *PDSI* histogram only displays values up to 60 min for the sake of visibility, but maximum values reached nearly 600 min.

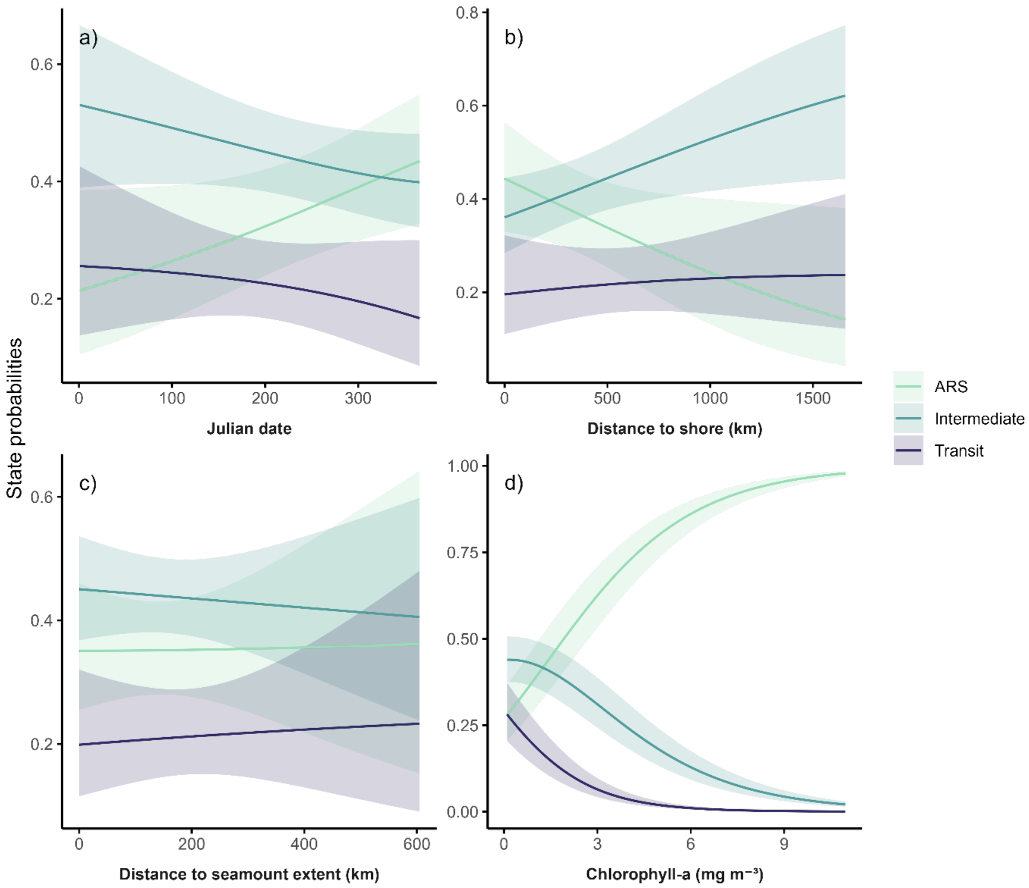

Figure 10. Stationary state probabilities of area restricted search (ARS; green), intermediate (light blue), and transit (dark blue) behaviours as functions of covariates (a) Julian date, (b) distance to shore, (c) distance to seamount extent, and (d) chlorophyll-a concentration.

8.2 Appendix B. Anthropogenic threat layers

Table 4. Spatial layers used to map anthropogenic threat sources and the relevant ecological pressure on southern right whales, modified from Ferreira et al. (2025).

Threat	**Type of data**	**Source**
Entanglement	Gridded fishing hours	Global Fishing Watch
Pollution	Gridded fishing hours	
	Oil & gas platforms, wells, & pipelines	National Offshore Petroleum Information Management System (NOPIMS)
	AIS ship data for 2023	Australian Maritime Safety Authority (AMSA)
Ship strike	AIS ship data for 2023	
	Gridded fishing hours	Global Fishing Watch
Underwater noise	Oil & gas platforms and wells	National Offshore Petroleum Information Management System (NOPIMS)
	Seismic	
	Shipping noise model	Erbe et al. 2021
Climate change	10-y average Sea surface temperature variation	NOAA GISS Surface Temperature Analysis
	Global trend of surface ocean PH	Copernicus Marine Ocean Monitoring Indicator (OMI)

CONTACT

Luciana Möller

Luciana.möller@flinders.edu.au

This project is supported with funding
from the Australian Government under the
National Environmental Science Program.

This project is supported with funding
from the Australian Government under the
National Environmental Science Program.