Marine and Coastal

National Environmental Science Program

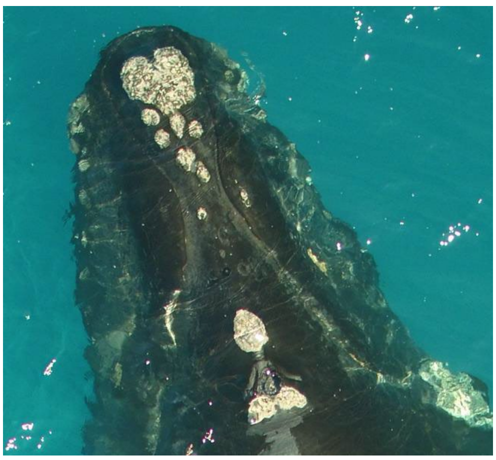
FINAL REPORT

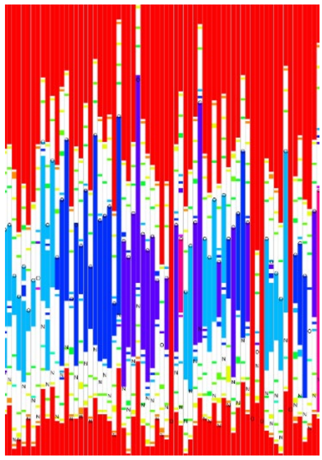
Project 3.15

June 2025

Subcomponent 3: Expanding utilisation of southern right whale datasets for estimation of national population parameters

David Peel, Luke Lloyd Jones, Karen Evans





CSIRO

Milestone number: 5

Research Plan number: 2023

Please address inquiries to: David Peel, CSIRO.

Preferred citation

Peel, D., Lloyd-Jones, L., Evans, K. (2024) Informing southern right whale management through continued monitoring, determination of aggregation areas and development of approaches to increase data flow efficiencies and utility: Subcomponent 3 Expanding utilisation of southern right whale datasets for estimation of national population parameters. Report to the National Environmental Science Program. CSIRO.

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 Technology Sydney, The University of Sydney, University of Tasmania, University of Western Australia, The University of Wollongong

Disclaimer

Cover images: AWRPIC; John Bannister

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

Contents

Executive summary **1**

1. Introduction **5**

1.1 Objectives 7

2. Stage 1: exploration of currently held photo-identification sightings data ... **8**

2.1 Photo identification data 8

2.1.1 Composition of sightings 9

Demographics *9*

Sighting platforms *10*

Resights of individuals *10*

2.2 Considerations of the data 13

2.2.1 Temporal correlation of sightings 13

2.2.2 Breeding cycle 14

2.2.3 Sampling effort 15

Temporal Sampling Bias *15*

Animal temporal fidelity *16*

Spatial Mixing/Site Fidelity *17*

2.2.4 Uncertainties in demographic classification 18

2.3 Next steps 19

3. Stage 2: simulation modelling and exploration of sampling strategies **23**

3.1 A spatial model for southern right whales in south-east Australia 24

3.1.1 Biological Population Model 24

3.1.2 Movement Model 25

3.1.3 Sampling Model 27

3.2 A population dynamics model fitted to simulated photo-identification data 28

3.2.1 Model components 28

3.2.2 Probability of individual sighting histories 32

3.2.3 Joint survival observation sighting probabilities 33

3.2.4 Implementation 34

3.3 Exploration of sampling scenarios to be able to discern population trends 36

3.3.1 Sampling alternate years/skipping years 38

3.3.2 Spatial expansion of the population 41

3.3.3 Temporal change in mortality 41

3.3.4 Western population interaction 41

4. Discussion **44**

4.1 Sampling strategies 45

4.2 Challenges associated with the simulation approach and future improvements 46

4.3 Implications for management 47

5. Recommendations **48**

5.1 Data Collection 48

5.2 Sampling Design 48

5.3 Implementation 48

6. References **50**

Appendix 1 .... **55**

List of figures

Figure 1. Spatial distribution of southern right whale sightings extracted from ARWPIC.

Figure 2. The spatial distribution of cow and calf (top left), adult (top right) and sub-adult (bottom right) sightings and number of individuals sighted per demographic group (bottom left).

Figure 3. The spatial distribution of sightings from land (top left), aircraft (top right) and vessels (bottom right) sightings and number of individuals sighted per platform (bottom left).

Figure 4. Periodicity of resights of cows with calves.

Figure 5. Distribution of days that sightings were observed (all data) by platform.

Figure 6. Distribution of days that sightings were observed, all data (left) and NSW only (right).

Figure 7. Distribution of days that sightings of individual cows and calves were recorded.

Figure 8. Spatial connectivity of inter-annual sightings of cow and calves between mainland locations (top-right) including the straight-line distance between sightings (top-left) and spatial connectivity of sightings within same year (bottom).

Figure 9. Spatial connectivity (top-left) distance (direct) between adult sightings across different years (top-right) map of connectivity of repeated sightings within same year (bottom) map of connectivity of sightings across different years.

Figure 10. The simulation and modelling process undertaken.

Figure 11. Representation of the population model in the simulation.

Figure 12. Example of the movements of the population of adult females in a year. Each column in the right panel corresponds to an individual whale. Each colour corresponds to a state corresponding to the states defined in the left panel with travel between states depicted in white. “N” indicates when a calf is born and “O” when southern migration to foraging areas has been initiated.

Figure 13: Directed graph for the female reproductive cycle, with transition probabilities as functions of the parameters (from Cooke and Rowntree 2003).

Figure 14: True simulated adult female population (black points) numbers with estimates (blue) and 95% confidence interval error bounds (blue dotted lines) for the estimate. The title shows the simulation name the minimum coefficient of variation (CV) on the adult female abundance over the time series and the estimate of rate of change and its CV.

Figure 15. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), for the selected population and sampling scenarios described in Tables 8 and 9.

Figure 16. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), for annual sampling at aggregation/nursery areas (top), tri-annual sampling at aggregation/nursery areas (middle) and tri-annual sampling with higher effort (bottom).

Figure 17. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), when a population is increasing (left) and increasing and spatially expanding (right) for the sampling strategies described in Table 9.

Figure 18. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), when the south-eastern subpopulation remains stable while the western subpopulation is increased for the sampling strategies described in Table 9.

List of tables

Table 1. Resighting matrix for all sightings data extracted from ARWPIC. Each row corresponds to an individual animal and each number indicates the number of sightings made of that animal in the calendar year (column).

Table 2. Resighting matrix for cow and calf sightings data extracted from ARWPIC. Each row corresponds to an individual animal and each number indicates the number of sightings made of that animal in the calendar year (column).

Table 3. Example of possible temporal correlation in then sightings of the individual animal ID 2345 in 2018.

Table 4. Animal ID 2115 sighting status through time.

Table 5. The six movement models specified for the simulated population. Typical movement is represented by linkages between potential areas where whales could be observed, with the width of the solid black lines corresponding to the frequency the path is taken by an animal.

Table 6. The full Leslie matrix used in the probabilistic model of individual reproductive histories.

Table 7. Summary of parameter estimates from single simulation run of model and estimation performed in TMB. SE is the standard error.

Table 8. The three population scenarios tested.

Table 9. The five sampling strategies tested.

Executive summary

Background

Southern right whale (*Eubalaena australis*) populations were significantly depleted as a result of commercial whaling operations throughout the Southern Ocean. Estimates of the species prior to whaling are unknown, although catch records suggest that at least 26,000 whales were harvested from the Australian/New Zealand region (Dawbin 1986).

Up until the recording of sightings during the 1950s and 1960s southern right whales were considered exceedingly rare within Australian waters (Bannister et al. 2016). With the occurrence of slowly increasing numbers of sightings along the south coast of Australia various efforts have been initiated to monitor the recovery of species, guided by a succession of Commonwealth recovery and conservation management plans. These monitoring efforts have identified two subpopulations of southern right whales in Australian waters, one in the south-west and one in the south-east. The south-eastern subpopulation is estimated to be smaller and to have a lower rate of growth than the south-western population. Monitoring efforts in the south-eastern parts of Australia have not all been continuous and have been largely opportunistic in nature. Because of the lack of systematic data from the eastern subpopulation, an evaluation of population growth is somewhat limited at present largely because opportunistic datasets do not meet the statistical assumptions of many analytical approaches available. As a result, opportunistic observations are largely only currently used qualitatively within research applications. Developing methods that allow for the utilisation of opportunistic datasets would expand the information required by conservation management plans, substantially improve the ability to determine the effectiveness of those plans and provide for the first time, particularly for the eastern population, important metrics for the species.

This project aims to explore the potential for application of integrative methods that allow for the combination of opportunistic observations with more formally collected observations (e.g. systematic surveys) utilising photo identification mark-recapture data from the south-east of Australia.

Approach

The project was focused around two activities:

(i) An evaluation of the suitability of sightings data currently held in the Australasian Right Whale Photo Identification Catalogue (ARWPIC) for use in population modelling

(ii) Dependent on the outcome of the evaluation step either (a) apply integrative statistical modelling approaches to estimate population abundance or (b) undertake a simulation exercise to identify a minimum data set required for identifying population change and the monitoring framework required to obtain such a dataset.

Results

Stage 1: exploration of currently held photo-identification sightings data.

All sightings collected from Australian waters to the east of Spencer Gulf for which there was at least a three-star photo (highest quality) available, and for which there was a date, location and details of the collection platform available (i.e., aircraft, land, vessel) were extracted from the Australasian Right Whale Photo Identification Catalogue (ARWPIC). The extracted dataset spanned 1/07/2008 - 9/09/2018, consisting of 355 sightings of 288 individuals. From this dataset 89 sightings of 59 individual cows with calves spanning the period 10/06/2014 - 9/09/2018 were identified. When summarised into a matrix of capture histories, the dataset comprised 40 resights of identified individuals, 19 of which were inter-year resights and when filtered for cows and calves, the data available for any analyses is reduced to 14 resights of which 12 were inter-year resights.

Given the very low numbers of sightings in the dataset, and in particular, cows with calves (from which population parameters are determined), and unknown spatial and temporal effort, directly using the data for the purposes of the project was determined as difficult due to potential capture probability heterogeneity that cannot be resolved. It was considered that undertaking a simulation study where various scenarios of true underlying populations that break standard mark-recapture assumptions could be tested would be useful for progressing the project objectives.

Stage 2: simulation modelling and exploration of sampling strategies

The next steps undertaken by the project involved building an individual-based simulation of a whale population, tracking each animal's life stages and daily movements. To this simulated population a proposed spatial and temporal sampling strategy is then applied to produce a simulated capture history. The capture history data can then be fitting using a mark-recapture model and the results compared to the original “true” population.

This involved developing two population models, the first a population model based on reported demographic parameters and broadly understood movements and aggregation/nursery areas across south-east Australia and the second a mark-recapture model incorporating photo-identification data similar to those used on populations of southern right whales in the Southern Hemisphere.

Potential sampling strategies and their ability to discern population changes were explored by applying multiple strategies to a simulated population to produce a simulated capture history. The capture history data was then be fitted using the mark-recapture model and the results compared to the original “true” population. Three initial population scenarios were included: increasing, steady, and decreasing and five sampling strategies were explored:

- Sampling everywhere all the time so most of the available whales are sampled.
- Targeted sampling at aggregation/nursery areas with high sampling effort and detectability elsewhere

- Targeted sampling at aggregation/nursery areas with lower sampling effort and detectability elsewhere
- Sampling at the three aggregation/nursery areas only.
- Sampling at a single specified nursery only.

These were then expanded upon to explore non-annual sampling, sampling under spatial expansion of the population, a temporal change in mortality (causing the population to reverse growth) and mixing of south-eastern and western subpopulations.

Under the various population scenarios examined, all of the five sampling strategies were able to discern population trends, although with varying variance. The only exceptions to this were scenarios where spatial expansion of the population was occurring, but sampling was limited to aggregation/nursery areas and where potential mixing of sightings from the two subpopulations of southern right whales was explored and the south-eastern population was held at a stable population trajectory while increasing the western subpopulation.

The simulation exercise suggests that data collection should have a primary focus on aggregation/nursery areas and include building datasets that allow for population discrimination (e.g. genomic datasets) to ensure that population parameters are not biased by transitory animals. In addition, some effort should be placed into regions outside of aggregation/nursery areas to ensure that any spatial expansion of populations and the emergence of new aggregation/nursery areas is captured.

In undertaking this exercise, we found that even when simulating a dataset containing realistic numbers of individuals based on those population estimates available (300 individuals of which 90-100 individuals were adult females), there were still challenges in fitting a population model similar those used elsewhere to estimate populations of southern right whales. This suggests that at present, if used directly, such models are unsuitable for use on very small datasets and alternative approaches are needed if population estimation is a primary objective. Further exploration of alternative indices and metrics for assessing trends should be considered to ensure biological realism in estimates of populations and their trajectories.

Recommendations

Given the outputs from this project and the associated limitations identified in current datasets available for progressing the objectives of the current Recovery Plan for southern right whales, six recommendations for future work can be identified:

1. Provision of information on calf survival rates that is compatible with the model described in Cooke and Rowntree (2023). This will require effort to be placed on recording initial calf sightings and resighting calves as well as mothers.

2. Recording of effort being placed into identifying and resighting individuals, particularly at known aggregation/nursery areas. The current opportunistic approach to data collection does not provide datasets suitable for establishing parameters and trends where effort can be

accounted. In addition, the current small size of datasets introduces large uncertainty into parameters calculated.

3. Collection of data that can assist with the discrimination of eastern and western sub-populations. Regarding sightings data, this includes ensuring all sightings within a year collected is submitted to ARWPIC. This will require additional effort into coordination across projects. The collection of additional genomic datasets should be explored with a view of assessing the viability of approaches such as close-kin mark recapture.

4. A greater focus on annual data collection at all known aggregation/nursery areas is needed with less-formal flexible monitoring across other areas. This less formal monitoring is needed to ensure early awareness of developing aggregation/nursery area that could then transition to annual data collection. Having continuous time series from aggregation/nursery areas is fundamental for understanding the recovery of this species and given the species' non-annual breeding cycle, skipping years can miss important indicators, thereby providing misleading information on recovery rates.

5. To support mark-recapture modelling with a focus on population monitoring, the greatest effort should be put towards collecting data from aggregation/nursery areas and from resident animals only. This will also allow for definitive evaluation of sub-population connection/linkages. Any efforts, whether based around photo-identification methods or other methods (e.g. genetic approaches) needs to consider how best to account for the multiple uses of the area in establishing datasets for population estimation.

6. To prioritise efforts and tasks and identify pathways to achieve the above, a research prioritisation workshop should be held that brings together conservation managers, data holders, population modellers and funding agencies. This would allow the identification of tasks of the highest priority and for supporting the Recovery Plan, identify the capability needed in carrying out the work and funding pathways for facilitating the work.

Conclusion

This project provides clear guidance on what is needed for monitoring the south-eastern subpopulation and building the datasets required for progressing the objectives for the Recovery Plan for southern right whales and addressing the above action items. If implemented early in the lifetime of the Recovery Plan (the current Recovery Plan is planned to span ten years), considerable progress could be achieved against these actions.

Keywords: southern right whale, photo-identification, population dynamics modelling, sampling strategies, simulation testing

1. Introduction

Southern right whale (*Eubalaena australis*) populations were significantly depleted as a result of commercial whaling operations throughout the Southern Ocean. Within Australian waters, they were the focus of shore-based whaling throughout the early 1800s, particularly along the south-east coast of Tasmania (Nash 2003) and western Victoria, South Australia and southern Western Australia (Bannister 2001). Estimates of the species prior to whaling are unknown, although catch records suggest that at least 26,000 whales were harvested from the Australian/New Zealand region (Dawbin 1986).

Up until the recording of sightings during the 1950s and 1960s southern right whales were considered exceedingly rare within Australian waters (Bannister et al. 2016). With the occurrence of slowly increasing numbers of sightings along the south coast of Western Australia, an aerial survey was initiated in 1976. This survey constitutes the longest continuous record of southern right whales in Australia and the relative abundance of animals collected by the survey is central to understanding of the recovery of the species post-exploitation in the Australian region (Bannister et al. 2016). Other dedicated efforts in documenting numbers of whales have occurred since, notably the land-based annual survey at the Head of Bight in South Australia, conducted since 1991 (Burnell 2001, Charlton et al. 2019a) and across Victoria, Tasmania and New South Wales over varying time periods (Watson et al. 2015, Stamation et al. 2020, Watson et al. 2021). Efforts in the south-eastern parts of Australia have not all been continuous and have been largely opportunistic in nature, with the exception of an aerial survey conducted twice between Ceduna and Sydney (including Tasmania) in 2013 and 2014 (Watson et al. 2015).

Within Australian waters, southern right whales are listed as *Endangered* under the *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act). A recovery plan for the species was first released in 2005 (DEH 2005). Recognising that the objectives of the plan were unlikely to be achieved within the lifetime of the plan (2005-2010), if the plan was to be successful, continued recovery close to or at the optimum biological rate, continued expansion of the population into suitable habitat and maintenance or improvement of domestic and international protection schemes should occur. An assessment of the recovery plan conducted at the end of the plan lifetime, identified that with abundance of the species well below historical estimates and occupancy also below historical utilisation of habitats, a recovery plan was still required (GHD 2010).

The following Conservation Management Plan for the southern right whale (DSEWPaC 2012), set five interim recovery objectives for the period 2011-2021. These were focused on identifying the population abundance of southern right whales in Australian waters, understanding the nature and degree of difference between the two sub-populations of the species in the south-east and south-west of Australia and ensuring ongoing recovery of the species. The review of the Conservation Management Plan (unpublished) identified that all objectives had only been partially met, and that the action areas identified in the plan needed to be continued. The 2024 Recovery Plan (DCCEEW 2024) identifies a similar set of objectives and actions to the 2011-2021 Conservation Management Plan, with the addition of explicit objectives and actions focused on improving the capability of a number of groups including First Nation Australians in contributing to progressing the Recovery Plan.

Southern right whales utilise areas close to the southern coast of Australia during the austral winter to calve and mate, predominantly between the months of May to November. Their distribution and migratory pathways once they leave Australian waters are largely unknown, although a counter-clockwise migratory pattern in the waters south of Australia as far as the ice edge off Antarctica has been postulated (Bannister et al. 1999, Burnell 2001). More recently, electronic tagging of individuals and stable isotope analyses suggest extensive utilisation of Southern Ocean waters south of Australia and the potential for individuals to associate with spatially defined foraging regions (MacKay et al. 2020, Derville et al. 2023, Sprogis et al. 2024).

Catch records suggest no discontinuity in the distribution of the population reflective of structuring, however differences have been reported in the rates of recovery post whaling between southern right whales in the western parts of the southern Australian coastline and those in the east (DCCEEW 2024). The population west of the South Australian border with Victoria has been estimated to be growing at 6-7 percent per annum (Bannister 2011, Charlton et al. 2019a), although more recently this has been estimated to have slowed to 5.3 percent (Smith et al. 2023). The part of the population to the east of the South Australian/Victorian border is estimated to be growing at just under 5 percent per annum (Stamation et al. 2020). Structuring of maternal genetic lineages has been observed between whales occurring in the south-west and those in the south-east (Carroll et al. 2011), and there have been low numbers of recorded movements between the south-east and south-west of Australia (Carroll et al. 2011a, Stamation et al. 2020, Watson et al. 2021, Evans et al. 2021), or between Australian breeding areas and those in New Zealand (Pirzl et al. 2009).

Long-term monitoring of southern right whales at several sites across their distribution have recorded female reproductive intervals of 2 – 5 years, with the majority of females estimated to calve every three years (Best et al. 2001, Burnell 2001, Cooke et al. 2001, Davidson et al. 2017, Watson et al. 2021). It should be noted that these do not necessarily reflect true calving intervals because effort has varied across sites and so not all mothers with calves or calvings are observed (e.g. mothers might be seen prior to calving or seen some distance from their calf, or may be in a group where an association between a mother and calf is difficult to discern) (Cooke et al. 2001). Systematic surveys and opportunistic data collection of the south-western population is showing that as the species recovers, habitats used for calving and nursing are expanding (e.g., Charlton et al. 2019b). They also suggest that some population parameters are becoming more variable and may be changing (Evans et al. 2021).

Population modelling of species such as southern right whales is highly complex largely due to this non-annual breeding cycle (Cooke and Rowntree 2003). Application of mark-recapture statistics to a catalogue of photographically identified individuals therefore requires some understanding of the population dynamics of the species, how these dynamics might influence survival and sightings probabilities (see Caswell et al 1999; Fujiwara and Caswell

2001). It also requires an understanding of whether the population dynamics, and in particular breeding intervals, are changing as a response to environmental conditions or population recovery (Leaper et al. 2006). Finally, any modelling approach needs to account for variability in sightings and resightings associated with variation in effort, as numbers of individuals identified do not necessarily reflect the numbers of individuals present in a region (Cooke et al. 2001).

Because of the lack of systematic data from the eastern subpopulation, an evaluation of population growth is somewhat limited at present largely because opportunistic datasets do not meet the statistical assumptions of many analytical approaches available (Evans et al. 2022). As a result, opportunistic observations are largely only currently used qualitatively within research applications.

The inability to utilise these datasets to establish biological and population parameters undermines current plans focused on the conservation management of the species where measuring and monitoring population recovery are central measures of success of those plans. Developing methods that allow for the utilisation of opportunistic datasets would expand the information required by conservation management plans, substantially improve the ability to determine the effectiveness of those plans and provide for the first time, particularly for the eastern population, important metrics for the species.

1.1 Objectives

This project aims to explore the potential for application of integrative methods that allow for the combination of opportunistic observations with more formally collected observations (e.g. systematic surveys) utilising photo identification mark-recapture data from the south-east of Australia. The project is focused around two activities:

(iii) An evaluation of the suitability of sightings data currently held in the Australasian Right Whale Photo Identification Catalogue (ARWPIC) for use in population modelling

(iv) Dependent on the outcome of the evaluation step either (a) apply integrative statistical modelling approaches to estimate population abundance or (b) undertake a simulation exercise to identify a minimum data set required for identifying population change and the monitoring framework required to obtain such a dataset.

The outputs from this project component will provide guidance on the suitability of data currently held in Australia's national photo-identification repository for population modelling. It will also provide guidance on the ability of various monitoring approaches to identify and track change in the population in south-east Australia. Ultimately the outputs from this project aim to progress the objectives of the national recovery plan in building understanding of both the eastern subpopulation and the population at a national scale.

2. Stage 1: exploration of currently held photo-identification sightings data

2.1 Photo identification data

A proposal for a data agreement was submitted to the ARWPIC Steering Committee in July 2023 and was finalised in February 2024. This agreement requested the use of data of two forms:

- Presence data (including associated metadata) collected opportunistically with information on sampling bias;
- Presence data derived from the same region that consists of data collected via structured surveys, less formal surveys and opportunistic data (including associated metadata).

Information on recaptures of individuals within each of the above datasets, including confidence/certainty metrics was also requested.

Following finalisation of the data agreement, all sightings of animals for which there was at least a three-star photo (highest quality) available, and for which there was a date, location and details of the collection platform available (i.e., aircraft, land, vessel) were extracted from the catalogue. Where available number of individuals in each sighting and of those, the number of adults, sub-adults, calves, and females (cows) was also requested. This structuring of the data extraction request follows that used previously in the NESP Biodiversity Hub project A13 and routinely incorporated into studies utilising photo identification techniques (e.g., Carroll et al. 2011, Constantine et al. 2012). Limiting sightings to three-star photos minimises uncertainty in resightings caused by lack of clarity in features and assists in reducing biases that might be introduced by resightings associated with distinctive features (that might be more obvious in lower quality photographs), thereby introducing capture heterogeneity into the dataset. Southern right whale behavioural patterns, and hence recapture rates, vary by sex, reproductive status and age (Rowntree et al. 2001, Carroll et al. 2013), so assuming all demographic classes have the similar recapture probabilities would be erroneous. Further, it was important to be able to identify sightings across platforms utilised as each have different detection probabilities, thereby affecting recapture probabilities.

The spatial area of the request was set as all areas east of the Spencer Gulf, and from southern Tasmania to Sydney to ensure all areas within which the majority of the south-eastern sub-population of SRWs were likely to occur was included, following genetic sub-population structuring of the species in Australian waters (Carroll et al. 2011). Following finalisation of the data request, a data extraction report was added to ARWPIC, ensuring that if the data extraction needed to be repeated by any of the data contributors, it could be.

The extracted dataset spanned 1/07/2008 - 9/09/2018, consisting of 355 sightings of 288 individuals. Spatially, the data covered the longitudinal range of the data extraction domain (Figure 1).

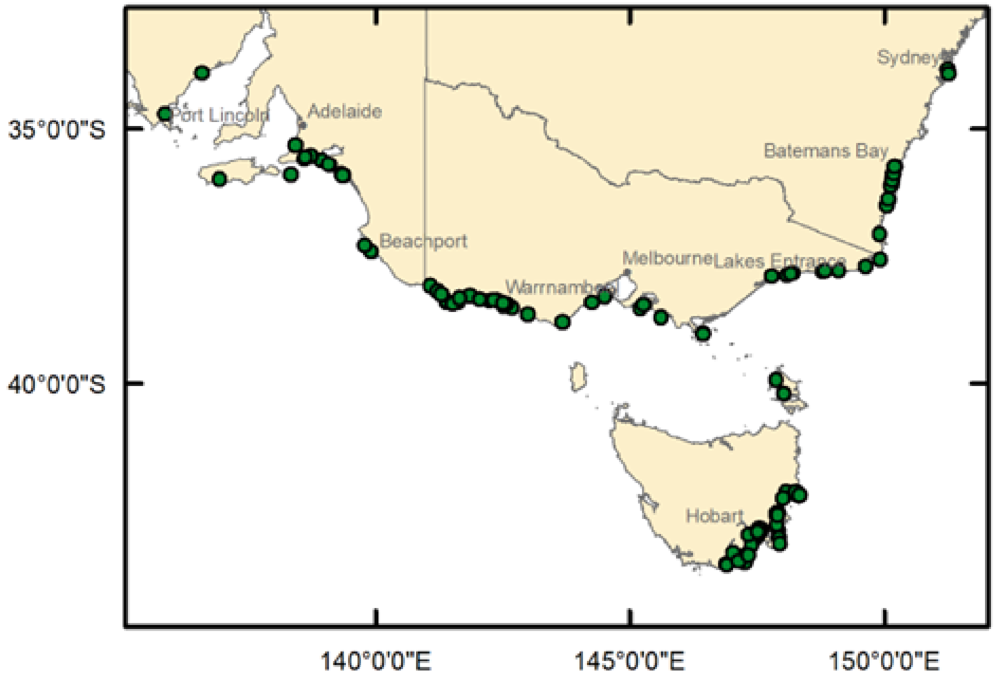


Figure 1. Spatial distribution of southern right whale sightings extracted from ARWPIC.

2.1.1 Composition of sightings

Demographics

Individuals were classified into four categories:

- Cow (female) with Calf
- Calf
- Sub-adult
- Adult

The majority of individuals in the dataset were identified as adults (Figure 2), with smaller numbers of cows with calves, sub-adults and calves (1 individual). The dataset contained 89 sightings of 59 individual cows with calves spanning the period 10/06/2014 - 9/09/2018. Adults and cows with calves covered similar spatial extents within the data extraction domain, cows and calves appeared to be more clustered in their distribution (Figure 2). Subadults were only sighted in Tasmanian and western Victorian waters.

Sighting platforms

Three platforms were associated with the sightings data: aircraft, land-based, and (water) vessels. The majority of sightings were collected utilising aircraft followed by land-based with only a small number collected from vessels (Figure 3). The spatial distribution of sightings varied across the platforms, with land-based sightings limited to the western half of the spatial domain and those from vessels to Victoria and New South Wales only.

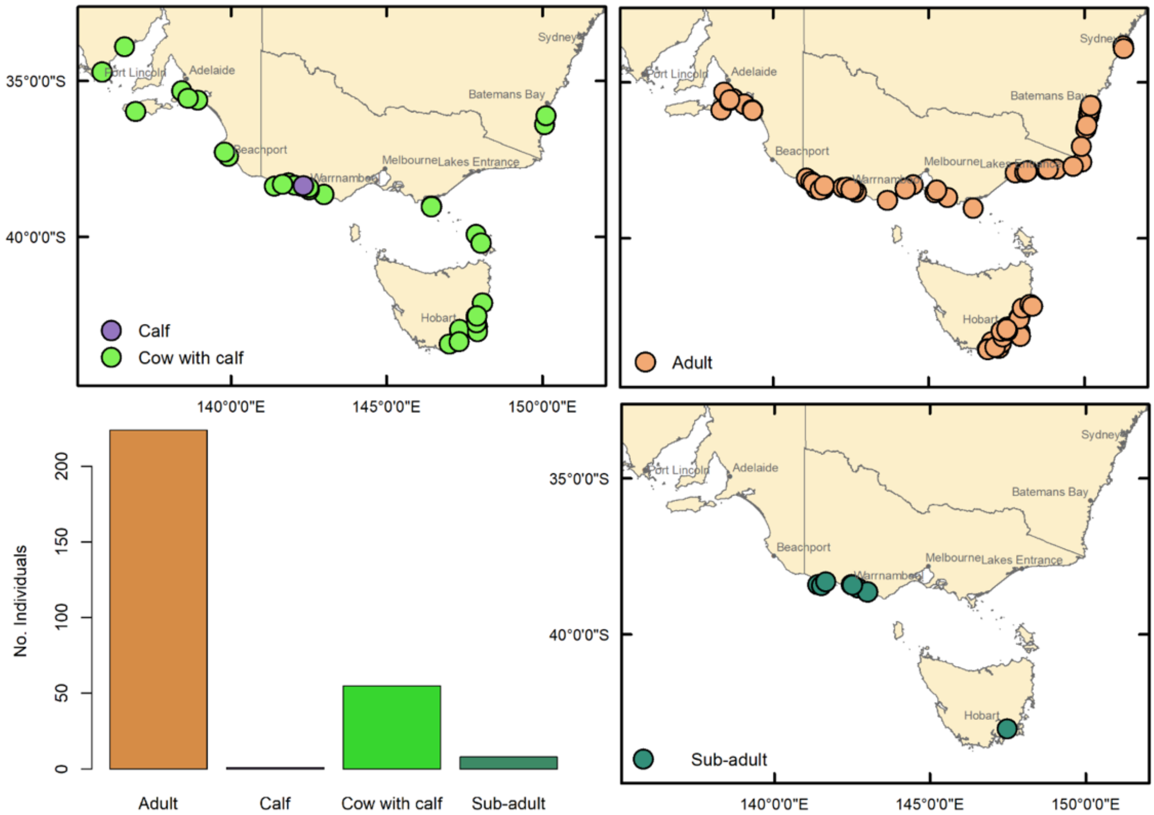


Figure 2. The spatial distribution of cow and calf (top left), adult (top right) and sub-adult (bottom right) sightings and number of individuals sighted per demographic group (bottom left).

Resights of individuals

The sightings data can be summarised into a matrix of capture histories (Table 1), where each row is the data for an individual animal, and the entries in the columns correspond to the number of sightings of that animal in each calendar year. Of all sightings, 40 were resights of identified individuals, 19 of which were inter-year resights (Table 1).

In order to investigate the potential of the capture history dataset for exploring population parameters and trends, the dataset was further filtered to only include females (cows) with calves following Payne et al. (1990) and Cooke et al. (2001). Limiting the dataset to females with calves is considered appropriate because:

i. In the vast majority of cases the sex and age class of a female is confirmed by the presence of a calf. Those individuals not seen with a calf are in most instances recorded as being of an unknown gender and a probable age class (unless obviously a juvenile). The probability of a whale occurring at an aggregation/nursery area may well depend on gender and maturity, which therefore influences the probably of being observed.

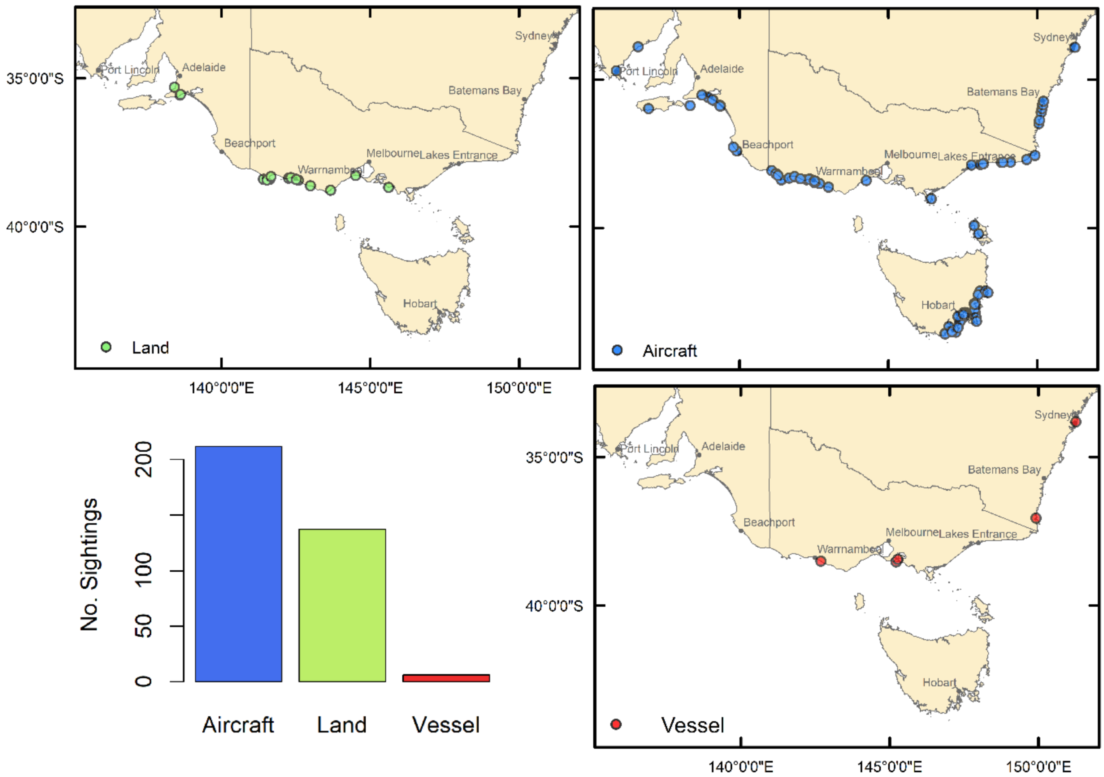


Figure 3. The spatial distribution of sightings from land (top left), aircraft (top right) and vessels (bottom right) sightings and number of individuals sighted per platform (bottom left).

Table 1. Resighting matrix for all sightings data extracted from ARWPIC. Each row corresponds to an individual animal and each number indicates the number of sightings made of that animal in the calendar year (column).

ID	**1995**	**2001**	**2002**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
1230	0	0	0	0	0	0	0	0	0	0	0	0	2
1889	0	0	0	1	0	0	0	0	0	0	0	4	0
1897	0	0	0	0	2	0	0	0	0	0	0	0	0
1898	0	0	0	0	2	0	0	0	0	0	0	0	0
1900	0	0	0	0	2	0	0	0	0	0	0	0	0
1913	0	0	0	0	0	0	4	0	0	0	0	0	0
1914	0	0	0	0	0	0	3	0	0	0	0	0	0
1940	0	0	0	0	0	0	0	1	0	0	2	0	0
1943	0	0	0	0	0	0	0	3	0	0	0	0	0
1953	0	0	0	0	0	0	0	0	2	0	0	0	0
1978	0	0	0	0	0	0	2	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	2	0	0	0	0	0
2000	0	0	0	0	0	0	2	0	0	0	0	0	0
2007	0	0	0	0	0	0	2	0	0	0	0	0	0
2008	0	0	0	0	0	0	1	1	0	0	0	0	0
2015	0	0	0	0	0	0	1	0	0	0	0	1	0
2081	0	1	0	0	0	0	0	0	1	0	0	0	0
2083	0	0	1	0	1	0	0	0	0	1	0	0	0
2086	1	0	0	0	0	1	0	0	0	0	0	4	0
2087	0	0	1	1	0	0	0	0	0	0	0	0	0
2115	0	0	0	1	0	0	0	0	2	0	0	0	4
2159	0	0	0	2	0	0	0	0	0	0	0	0	0
2172	0	0	0	0	0	2	0	0	0	0	0	0	0
2182	0	0	0	0	0	1	1	0	0	0	0	0	0
2186	0	0	0	0	0	0	2	0	0	0	0	0	0
2228	0	0	0	0	0	0	0	1	0	0	0	2	0
2256	0	0	0	0	0	0	0	0	1	0	0	0	2
2257	0	0	0	0	0	0	0	0	1	0	0	0	1
2259	0	0	0	0	0	0	0	0	1	0	0	0	1
2286	0	0	0	0	0	0	0	0	0	2	0	0	0
2345	0	0	0	1	0	0	0	0	2	0	0	0	4
2390	0	0	0	0	0	0	0	1	0	0	0	0	2
2395	0	0	0	0	0	0	0	0	1	0	0	1	0
4279	0	0	1	0	0	0	0	1	0	1	0	0	0

ID	1995	2001	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
4900	0	0	0	0	0	0	0	0	0	0	0	2	0
4906	0	0	0	0	0	0	0	0	0	0	0	2	0
5547	0	0	0	0	0	0	0	0	0	0	0	0	2
5599	0	0	0	0	0	0	0	0	0	0	1	1	0
5604	0	0	0	0	0	0	0	0	0	0	0	0	2
5605	0	0	0	0	0	0	0	0	0	0	0	0	2

ii. Although some females might return to an aggregation/nursery area in years in which they do not calve, a sighting of a female without a calf does not necessarily imply that a calf is not present. Calves may not be distributed sufficiently close to a female to be associated with that female or there may be multiple animals in close proximity limiting clear association of a calf with a mother. Further, females might be observed prior to when a calf is born. It therefore becomes difficult to divide datasets into reproductive classes and account for potential influences on the probability of being observed.

iii. Previous studies have identified that a female is much more likely to be seen in a study area with a calf than when the female does not have a calf. Because most mark recapture models require independence of sightings probabilities between years, inclusion of females without calves in the dataset results in this requirement not be able to be fulfilled.

However, when filtered for cows and calves, the data available for any analyses is reduced to 14 resights of which 12 were inter-year resights (Table 2).

2.2 Considerations of the data

2.2.1 Temporal correlation of sightings

There appears to be some temporal correlation between sightings within season that suggests that sightings may not be independent. This is indicated by the clustering of sightings of the same animal within consecutive or near consecutive days (e.g., Table 3). Further investigation would be needed to determine if sightings recorded subsequent to the first were truly independent, or if they were informed by the animal being seen in the area first on the 23/08/2018. At present, metadata recorded with each sightings in ARWPIC limits such an investigation. To avoid issues with potential temporal correlation, any analyses would need to be temporally grouped at annual scales and treat multiple observations of an animal within a season as a single sighting (recapture).

Table 2. Resighting matrix for cow and calf sightings data extracted from ARWPIC. Each row corresponds to an individual animal and each number indicates the number of sightings made of that animal in the calendar year (column).

ID	2001	2002	2009	2010	2013	2014	2015	2016	2017	2018
1889	0	0	1	0	0	0	0	0	4	0
1940	0	0	0	0	1	0	0	2	0	0
1943	0	0	0	0	3	0	0	0	0	0
2081	1	0	0	0	0	1	0	0	0	0
2083	0	1	0	1	0	0	1	0	0	0
2086	0	0	0	0	0	0	0	0	4	0
2087	0	1	1	0	0	0	0	0	0	0
2115	0	0	1	0	0	1	0	0	0	2
2228	0	0	0	0	1	0	0	0	2	0
2256	0	0	0	0	0	1	0	0	0	2
2257	0	0	0	0	0	1	0	0	0	1
2259	0	0	0	0	0	1	0	0	0	1
2345	0	0	1	0	0	0	0	0	0	4
4279	0	1	0	0	1	0	1	0	0	0

2.2.2 Breeding cycle

Long-term monitoring of southern right whales at several sites across their distribution have recorded female reproductive intervals of 2 – 5 years, with the majority of females estimated to calve every three years (Best et al. 2001, Burnell 2001, Cooke et al. 2001, Davidson et al. 2017, Watson et al. 2021). It should be noted that these do not necessarily reflect true calving intervals, because effort has varied across sites and so not all mothers with calves or calvings are observed (e.g. mothers might be seen prior to calving or seen some distance from their calf, or may be in a group where an association between a mother and calf is difficult to discern) (Cooke et al. 2001). Population modelling of southern right whales as a result is highly complex because individuals do not have equal probability of being sampled (sighted) in each year.

The sightings data of cows and calves extracted from ARWPIC appear to reflect a breeding cycle ranging 2-5 years with a strong mode at four years (Figure 4). The distribution of the interval between sightings is similar to that reported elsewhere and also previously in the Australian region, where the majority of observations associated with resight intervals are less than 5 years and demonstrate a clear peak at 3-4 years (Best et al. 2001, Cooke et al. 2001, Evans et al. 2021, Charlton et al. 2022). For the same reasons as those outlined above, we note that these figures should not be associated with calving intervals and therefore should be considered with caution.

Table 3. Example of possible temporal correlation in then sightings of the individual animal ID 2345 in 2018.

event_date	platform
23/08/2018	Land
25/08/2018	Land
28/08/2018	Land
29/08/2018	Aircraft

2.2.3 Sampling effort

The data extracted from ARWPIC does not have metadata available that details associated effort. Specifically, it only provides data on when individual sightings were collected and provides no information of when the various platforms recording those sightings were on effort (i.e., looking for individuals), but failed to see any animals or successfully collect a photograph of individuals that were seen. Therefore, we do not know if temporal coverage was complete and temporally uniform. Unknown and uneven temporal effort can cause unequal capture probabilities especially if animals have a temporal within-season preferences to migration (e.g., certain animals always move through regions or occur in aggregation/nursery areas earlier or later in the season). Even if effort is temporally uniform overall, there will still be challenges in estimating capture probabilities if there is a temporal bias at any given location as animals do not fully mix spatially.

There are three exacerbating factors to considering sampling effort: temporal sampling bias, temporal fidelity of individuals and spatial mixing of individuals.

Temporal Sampling Bias

To explore any indications of temporal sampling bias, we looked at the distribution of number of days per week a sighting was made within the season (Figure 5). However, sampling bias is confounded with animal temporal density and because information on sampling effort is not available, this is unable to be resolved. Even if sampling was reasonably uniform through time, if animal density varies over time, these plots would still show non-uniformity due to the change in whale density within the season. We tried to minimise this effect by plotting counts of sighting days, rather than number of sightings per day, but this does not completely fix the issue, again because we have no information on sampling effort.

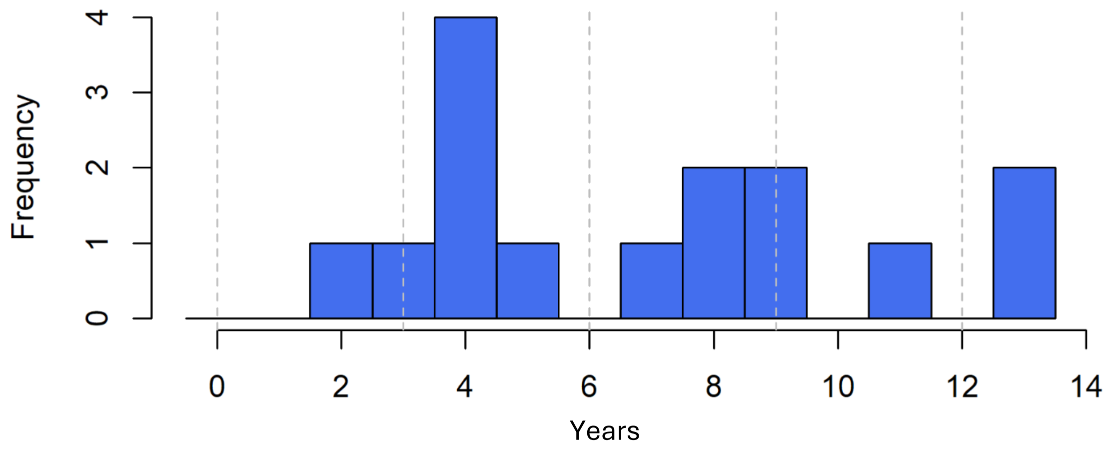


Figure 4. Periodicity of resights of cows with calves.

When the data is explored on the basis of regional areas (i.e., states), there are indications of localised temporal sampling (e.g., Figure 6). This may be reflective of animals arriving later in the season in waters off New South Wales (NSW). Alternatively, it may be a result of the small sample size, rather than a reflection of varying temporal effort.

Animal temporal fidelity

To further explore if the data provided any indication of animals showing with-in season temporal fidelity (i.e., individual animals preferring to migrate at around the same time within the season), we plotted the week of the year re-sightings were recorded for each individual. The number of sightings for each individual, however, is so low that no definite patterns can be discerned across the whole dataset (Figure 7). If we look at individuals, there are potential indications of some cows with calves (individuals 2256, 2257, 2345) demonstrating temporal fidelity, but counter to this, other animals (2083, 4279) show no signs of any temporal patterns in sightings.

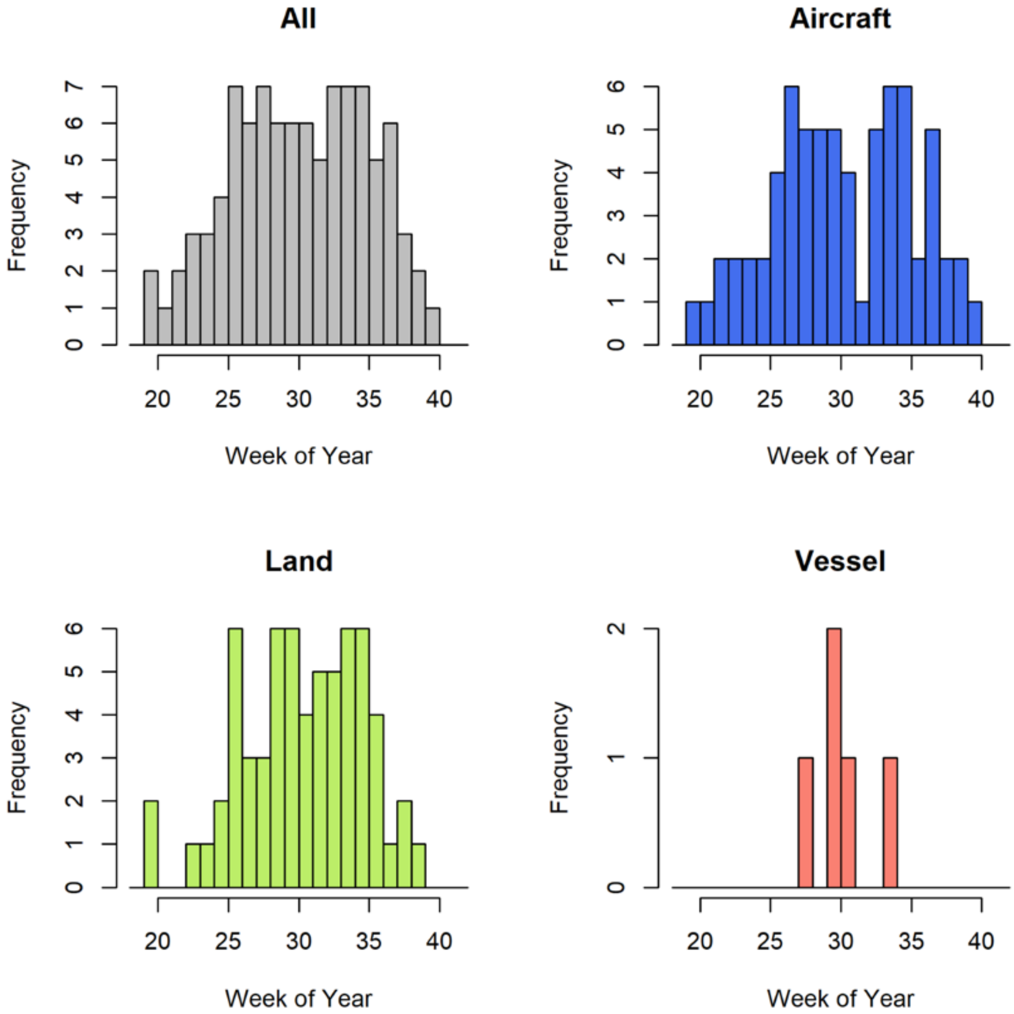


Figure 5. Distribution of days that sightings were observed (all data) by platform.

Spatial Mixing/Site Fidelity

Southern right whales and in particular, cows with calves, have been recorded across their range to demonstrate site fidelity. Within Australian waters this includes a number of well-known aggregation/nursery areas located mostly along the south-western coastline of Australia (Evans et al. 2021). Across the south-east Australian region, aggregation/nursery areas are less well established with small numbers of cows and calves utilising Logans Beach in Warrnambool for several decades (Watson et al. 2021). More recently, Encounter Bay, South Australia is regarded as an emerging aggregation/nursery area (Evans et al. 2021) and some emerging patterns in opportunistic sightings are reported to be occurring along the NSW coastline (Susan Crocetti and Andrew Marshall, pers. comm).

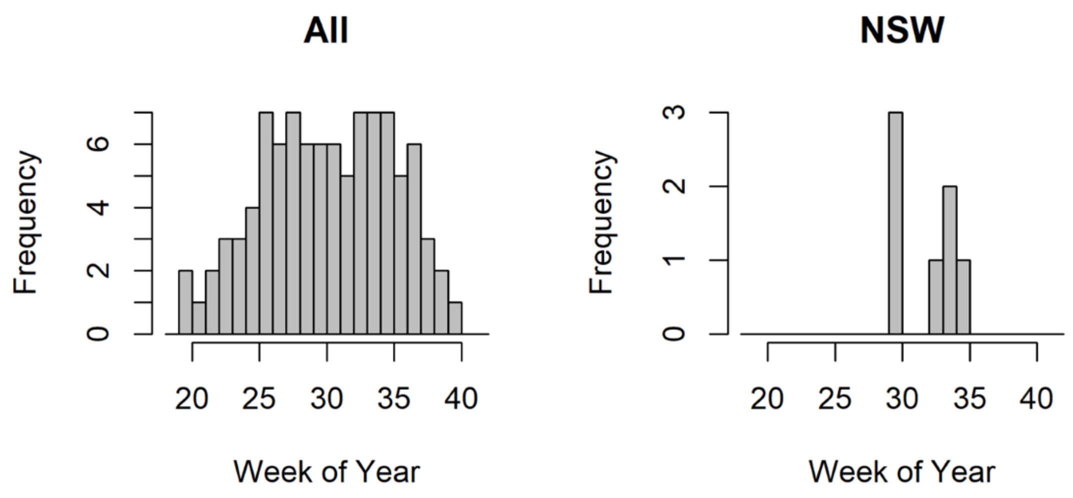


Figure 6. Distribution of days that sightings were observed, all data (left) and NSW only (right).

When sightings are spatially examined, there is some suggestion that some sightings of animals within Tasmanian waters are those that are transiting to mainland Australia. This includes animals recorded within a season first off Tasmania and then at locations off South Australia and New South Wales (Figures 8 and 9). When inter-annual movement is examined, some animals appeared to exhibit site fidelity, while other animals showed large annual movement. Some of these movements may reflect animals either sighted whilst transiting or resting in an area on their migration to a final destination to which they have a site fidelity. Additional metadata associated with each sighting such as behaviour would assist in better resolving this.

2.2.4 Uncertainties in demographic classification

As previously outlined, a sighting of a female without a calf does not necessarily imply that a calf is not present. Calves may not be distributed sufficiently close to a female to be associated with that female or there may be multiple animals in close proximity limiting clear association of a calf with a mother. Further, females might be observed prior to when a calf is born. It therefore becomes difficult to divide datasets into reproductive classes and account for potential influences on the probability of being observed. As an example, animal 2115 was observed over a number of years both as an individual adult and a cow with calf, with the timing of sightings suggesting that perhaps it had not calved when it was first sighted within a year, or the calf was not evident in those early sightings (Table 4). If temporal sampling effort is not consistent, or biased to particular times of the season, a cow with a calf could be missed.

Table 4. Animal ID 2115 sighting status through time.

event_date	sighting_status
13/08/2009	Cow with calf
23/07/2014	Adult
28/08/2014	Cow with calf
19/06/2018	Adult
2/07/2018	Adult
27/07/2018	Cow with calf
2/08/2018	Cow with calf

2.3 Next steps

This project is aiming to explore if integrative methods that allow for the combination of opportunistic observations with more formally collected observations (e.g. systematic surveys) into statistical approaches for estimating population parameters could be applied to sightings data from SRWs in south-eastern Australian waters. To do this, it needs to establish distributions, densities and habitat utilisation of individuals. Given the very low numbers of sightings in the dataset, and in particular, cows with calves (from which population parameters are determined), and unknown spatial and temporal effort, directly using the data for our purposes will be difficult due to potential capture probability heterogeneity that cannot be resolved.

To further the objectives of this project, it was considered that undertaking a simulation study where various scenarios of true underlying populations that break standard mark-recapture assumptions could be tested would be useful. This would provide for the determination of a minimum dataset that would need to be established to meet mark-recapture assumptions. In addition, this would allow for various sampling/survey strategies to be explored to determine their ability to deliver datasets that can be utilised to determine population parameters and associated uncertainties robustly, and under what conditions trends could be established with rigor. These scenarios could include a range of sampling strategies, ranging from the current status quo of opportunistic sightings with unknown temporal and spatial effort, through to structured surveys of varying temporal intervals. Testing a simulated dataset in such a way would allow for the development of a tool that can provide guidance on how much of an issue the capture probability heterogeneity is under various assumptions. This will be useful for any future efforts in both (i) understanding biases and uncertainties in datasets and (ii) acknowledging the influence of those biases and uncertainties.

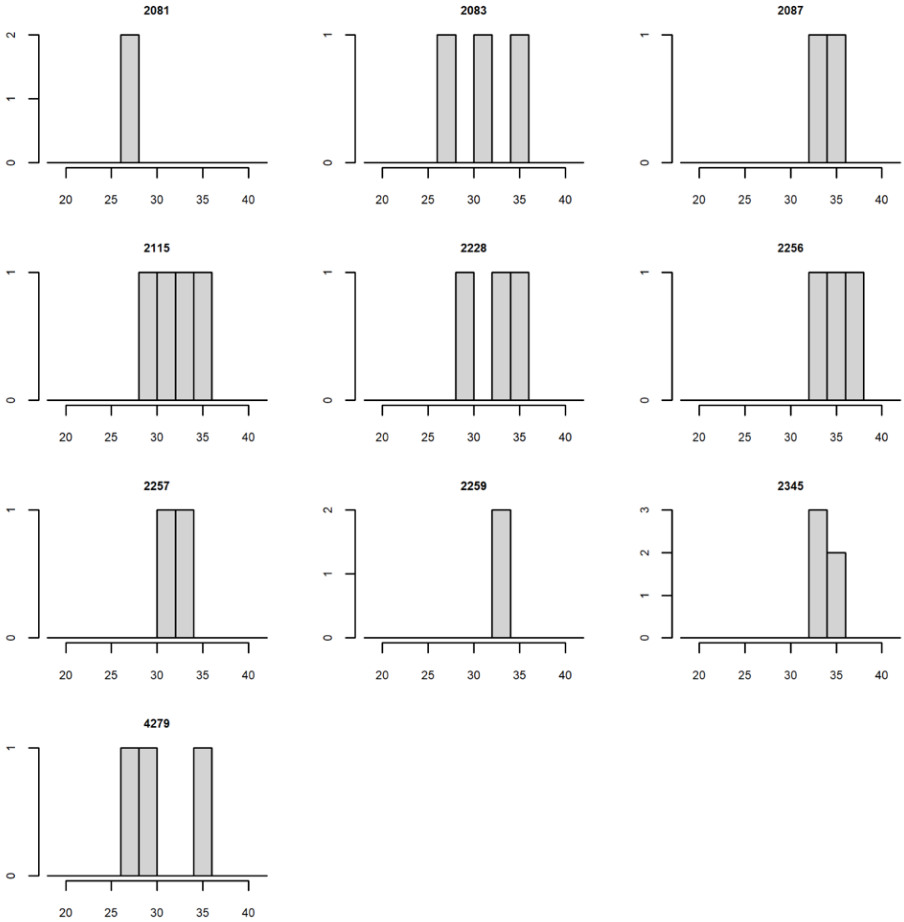


Figure 7. Distribution of days that sightings of individual cows and calves were recorded.

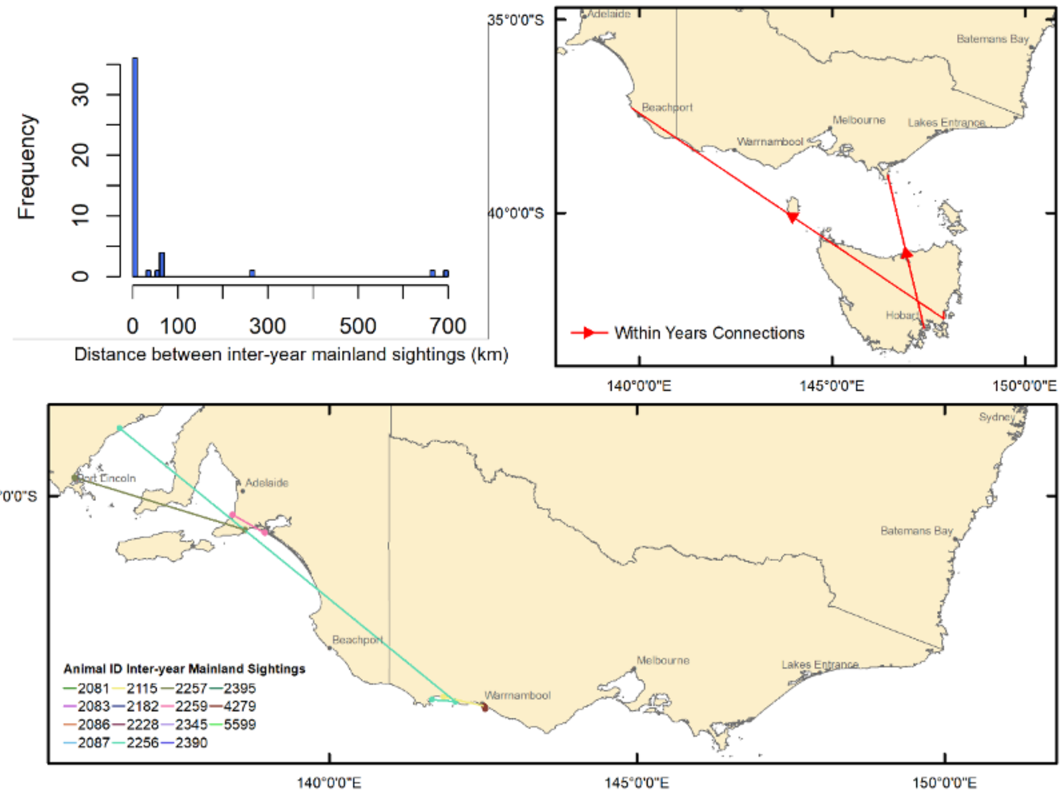


Figure 8. Spatial connectivity of inter-annual sightings of cow and calves between mainland locations (top-right) including the straight-line distance between sightings (top-left) and spatial connectivity of sightings within same year (bottom).

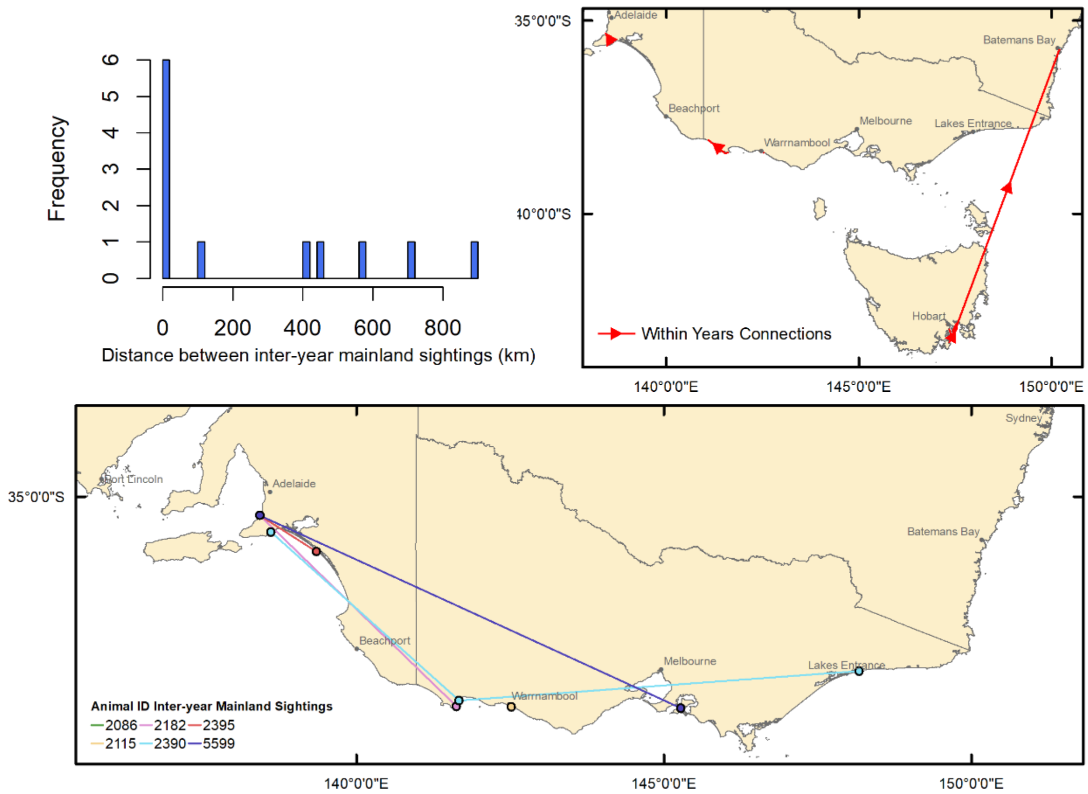


Figure 9. Spatial connectivity (top-left) distance (direct) between adult sightings across different years (top-right) map of connectivity of repeated sightings within same year (bottom) map of connectivity of sightings across different years.

3. Stage 2: simulation modelling and exploration of sampling strategies

The next steps undertaken by the project involved building an individual-based simulation of a whale population, tracking each animal's life stages and daily movements. To this simulated population a proposed spatial and temporal sampling strategy is then applied to produce a simulated capture history. The capture history data can then be fitting using a mark-recapture model and the results compared to the original “true” population.

This involved developing two population models, the first a population model based on reported demographic parameters and broadly understood movements and aggregation/nursery areas across south-east Australia and the second a mark-recapture model incorporating photo-identification data similar to those used on populations of southern right whales in the Southern Hemisphere (Figure 10).

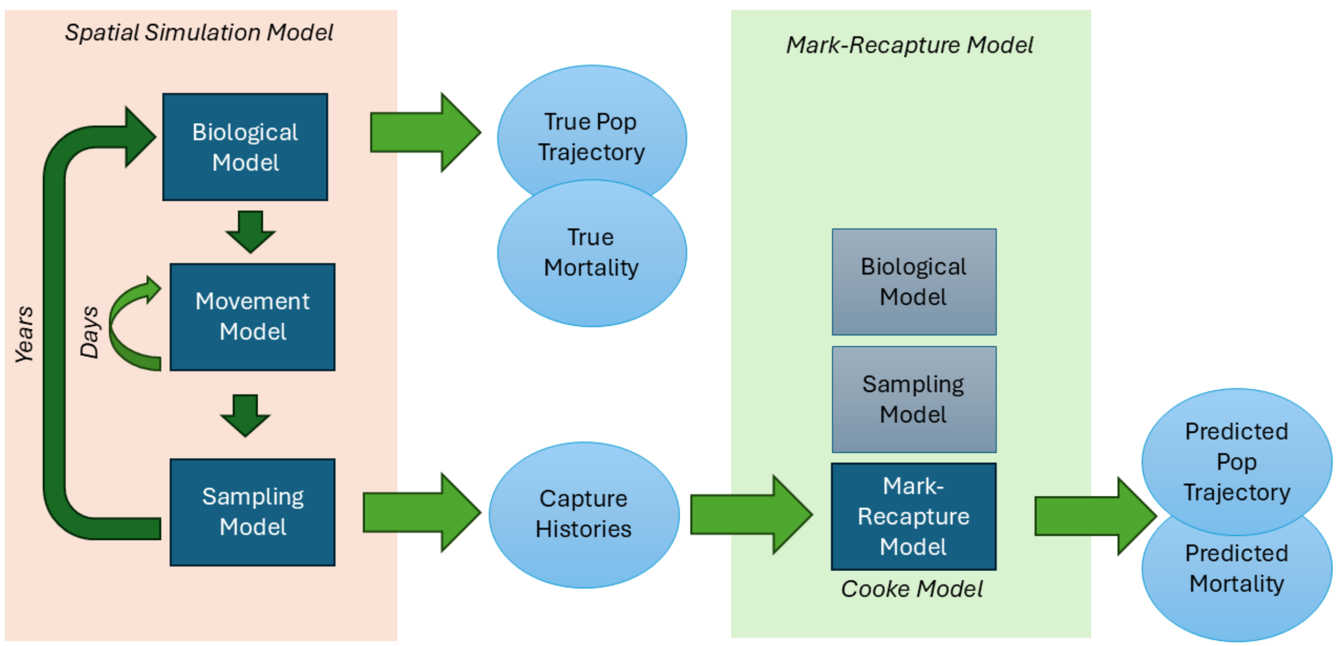


Figure 20. The simulation and modelling process undertaken.

Here we provide a high-level overview of both models. Full details of the code developed and the Leslie Matrix produced and simulation outputs are available at: https://bitbucket.csiro.au/users/llo080/repos/southern-right-whales/browse.

3.1 A spatial model for southern right whales in south-east Australia

The spatial model used to simulate photo-identification data is made up of three components: (i) a biological population model, (ii) a movement model and (iii) a sampling model.

3.1.1 Biological Population Model

The biological model steps through each year replicating a birth-death process (Figure 11) based on specified population demographic parameters (Appendix 1). The model was developed independently to the mark-recapture population model (See Section 3.2) to avoid optimising it to a particular model structure. However, the adult calving interval can be parametrised to align with that used in the mark-recapture model to make parameter comparison easier.

For whales identified as calving, further specific events are randomly generated including: the day of the year the migration north from foraging areas to Australian waters begins, the day of the calf's birth, and the day at which southward migration back to foraging areas begins (Appendix 1). Finally, a daily mortality rate is applied to the calves (equivalent to the annual specified calf mortality rate) and the day of death recorded (as the mother will be observed as an adult rather than a mother calf-pair after that day).

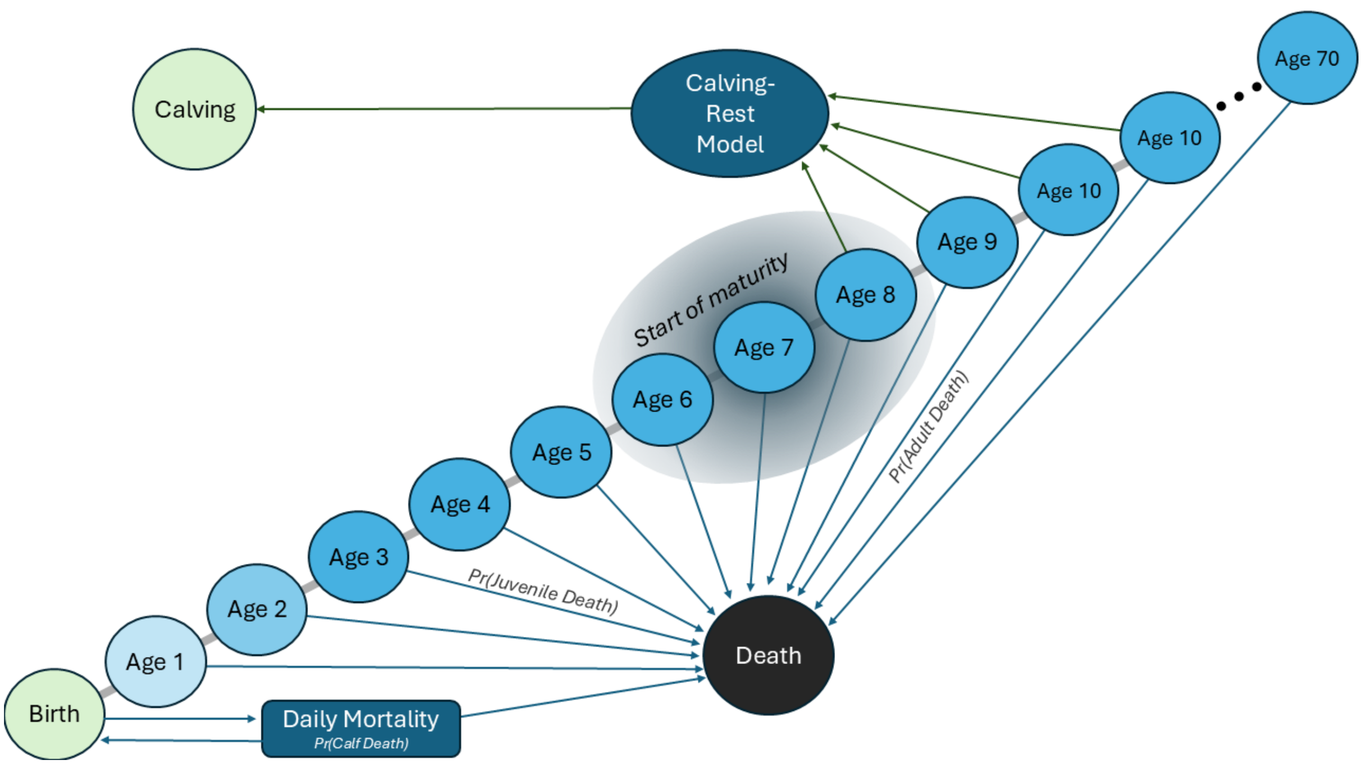


Figure 11. Representation of the population model in the simulation.

3.1.2 Movement Model

For each female identified in the model as having a calf, movement was simulated using a simple state space model, with each state corresponding to a location, or area. Links are specified between these states to denote possible movement. Specifically, each whale moves through the model in a Markovian manner with a daily time step. At each time step the animal is given a choice on which state (location) to move to next (including staying in its current state/location). This choice is based on the pre-specified probabilities assigned to each link/path. Approximate distance between state locations was calculated and average animal daily swim speed (Appendix 1) used to estimate travel time between states.

To simulate site-fidelity in individuals to aggregation/nursery areas and different animal behaviour, multiple movement models can be specified. At birth an animal is assigned the same movement model as its mother. The model includes the ability to specify local carry capacities at an aggregation/nursery area and for some animals to change movement model/site fidelity if carrying capacity at that site is exceeded. Three sub-movement models corresponding to animal behaviour are specified within each movement model: (i) migration to the aggregation/nursery area prior to when the calf is born, (ii) movement after the calf is born (to allow more frequent resting in rest areas) and (iii) migration back to foraging areas.

We specified six movement models corresponding six sub-populations with different site fidelity (Table 5). An example of the resulting movement is shown in Figure 12.

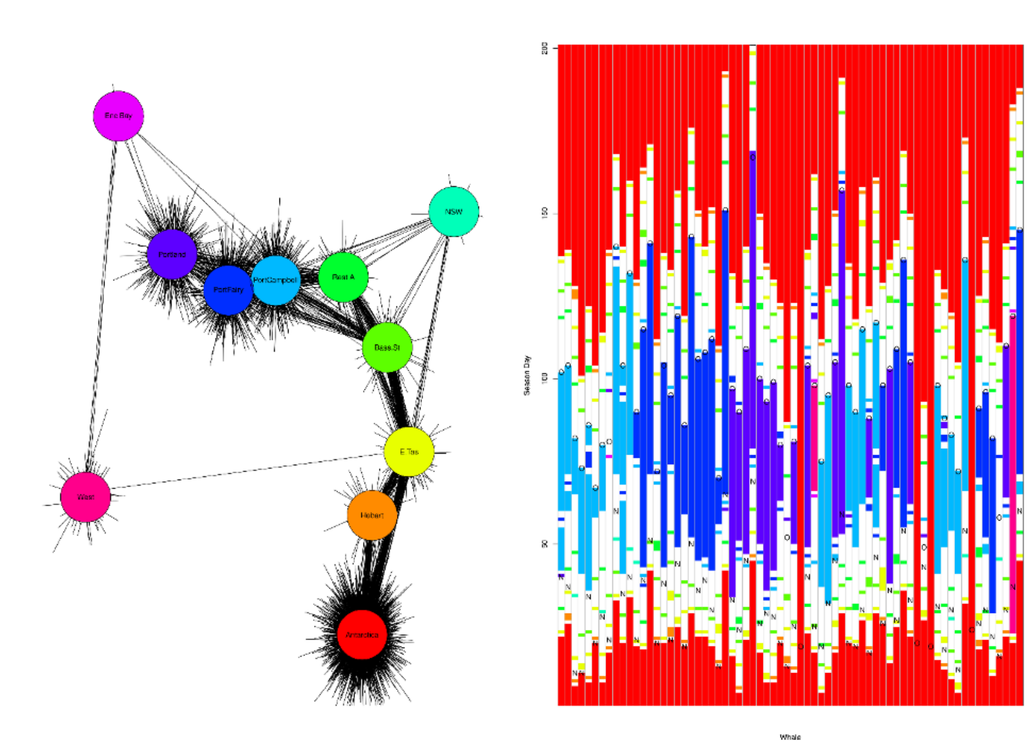
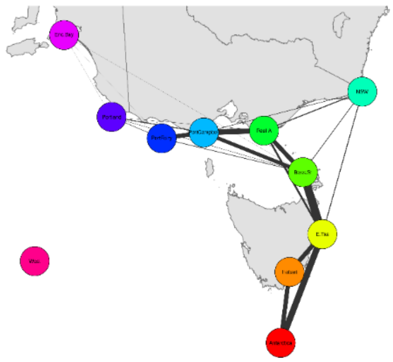
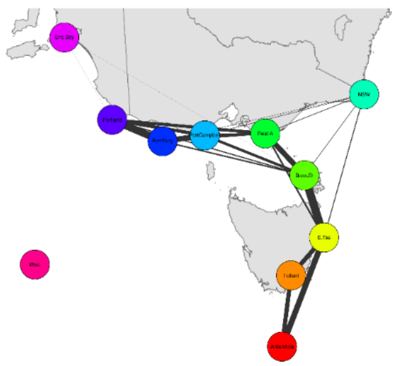
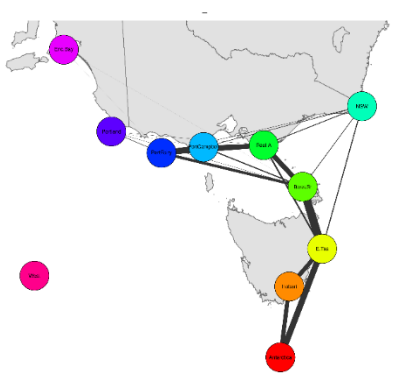
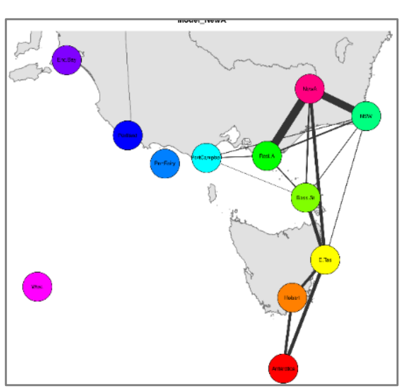
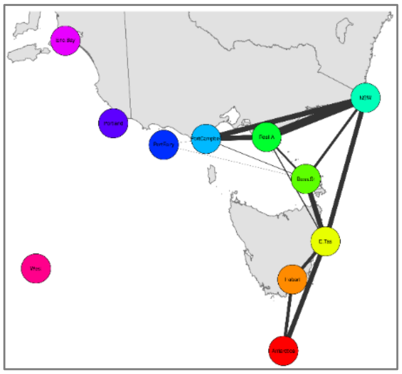
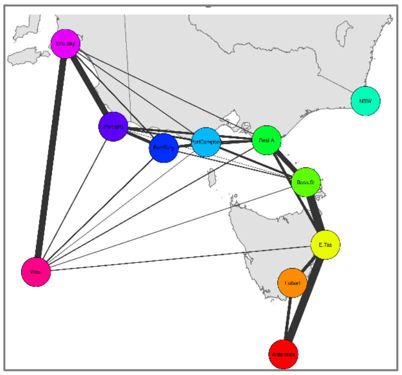


Figure 12. Example of the movements of the population of adult females in a year. Each column in the right panel corresponds to an individual whale. Each colour corresponds to a state corresponding to the states defined in the left panel with travel between states depicted in white. “N” indicates when a calf is born and “O” when southern migration to foraging areas has been initiated.

Table 5. The six movement models specified for the simulated population. Typical movement is represented by linkages between potential areas where whales could be observed, with the width of the solid black lines corresponding to the frequency the path is taken by an animal.

Name	Typical Movement	Description
Port Campbell		Animals that are associated with an aggregation/nursery area near Port Campbell. Travel by individuals is primarily direct, with occasional movement by individuals to other locations before arrival at the aggregation/nursery area.
Portland		Animals that are associated with an aggregation/nursery area near Portland. Travel by individuals is primarily direct, with occasional movement by individuals to other locations before arrival at the aggregation/nursery area.
Port Fairy		Animals that are associated with an aggregation/nursery area near Port Fairy. Travel by individuals is primarily direct, with occasional movement by individuals to other locations before arrival at the aggregation/nursery area..
New aggregation/nursery area		Animals that are associated with a new previously unreported aggregation/nursery area.

Name	Typical Movement	Description
NSW Wanderers		Animals observed in New South Wales waters but not associated with an established aggregation/nursery area.
Western sub-population		Animals that contribute to the western sub-population animals that utilise south-east Australia as part of their migratory corridor.

3.1.3 Sampling Model

A sampling strategy is parametrised as binary effort at locations for each day of the season. Specifically, each location (state in the movement model) has a corresponding matrix of effort year x season day and a 0 or 1 entry to track if effort occurred that year on that day at that location.

Each location also has a set detection probability that corresponds to the complete photo identification process, that is a probability that a whale is in a location, that it will be seen by the observer, a photo is taken successfully, and it is uploaded to ARWPIC and the whale is cross-matched. This probability varies depending on the location that whale might be sighted and the methods (e.g. platforms) used in association with the sighting. For example a location corresponding to a small bay will have a reasonably high detection probability if a whale is present, whereas a location associated with a large coastal area will have a lower probability of detection (Appendix 1) .

3.2 A population dynamics model fitted to simulated photo-identification data

3.2.1 Model components

The model developed is based on the 'receptive, calving and resting' model of Cooke and Rowntree (2003) used to estimate the demographic parameters of South African and Argentinian southern right whale populations (Cooke et al. 2015, Brandão et al. 2023). The model is described in a reduced form here with content drawn from Cooke and Rowntree (2003) and the exposition is for easy reference to the implementation below.

To infer demographic parameters, two models are used: (i) a probabilistic model for individual whale reproductive maturity and observations, and (ii) an aggregate population model linking individual maturity timelines to population-level metrics such as size, growth, survival, and reproductive rates. These parameters are estimated using the simulated sighting histories.

The female reproductive cycle is modelled in four stages (Figure 13): receptive (ready to conceive), calving (giving birth), resting (one or more years after calving), and dead (mortality). Transitions between these stages follow a standard 3-year cycle (calving → resting → receptive → calving), with deviations defined by probabilities for skipping rest, extending rest, or not producing a surviving calf. Mortality has been estimated to be low (˜2%) in previous studies and here assumed constant across stages.

Since receptive and resting whales are indistinguishable, the probabilities of remaining in either state are combined under the parameter for extended rest. The chance of a receptive whale returning to rest without producing a calf is treated as a separate event, extending the calving interval by two years. A 1-year calving interval is considered negligible based on gestation period estimates and observations of mothers with consecutive calves (Best, 1994, Brandão et al. 2023 and, Cooke and Rowntree 2003).

The transition probabilities are represented in a matrix format (1), where columns correspond to (left to right) calving (0), resting (1), receptive (2), and dead (3) states.

$$\boldsymbol{Q}_t = \begin{pmatrix} 0 & (1-\alpha_t)(1-\mu_t) & \alpha_t(1-\mu_t) & \mu_t \\ 0 & \beta_t(1-\mu_t) & (1-\beta_t)(1-\mu_t) & \mu_t \\ (1-\gamma_t)(1-\mu_t) & \gamma_t(1-\mu_t) & 0 & \mu_t \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

The matrix entries show the probability of a whale transitioning between these stages from year to year, with the dead state being the final row entries (0, 0, 0, 1). This matrix applies both to individual transitions and population-level stage proportions.

To model recruitment of new adult females, the transition matrix is extended into a Leslie matrix (Table 6). Juvenile survival and maturation rates are incorporated, however survival from calf to maturity is condensed into a single parameter (S) because observations from juvenile are not included. The sex ratio is assumed to be 50/50, but only females are tracked in the model.

Female maturation is categorised into three stages: (i) pre-mature (1-4 years), (ii) maturing (5-14 years), and (iii) fully mature (15+ years). The maturation probability increases with age and is estimated from observations. In the model detailed in Cook and Rowntree (2003), the youngest observed female to calve was six years old, having conceived at five.

The full Leslie matrix integrates the adult transition matrix and juvenile classes, with mothers giving birth to one calf. Males are excluded after age one since they don't contribute to the reproductive analysis.

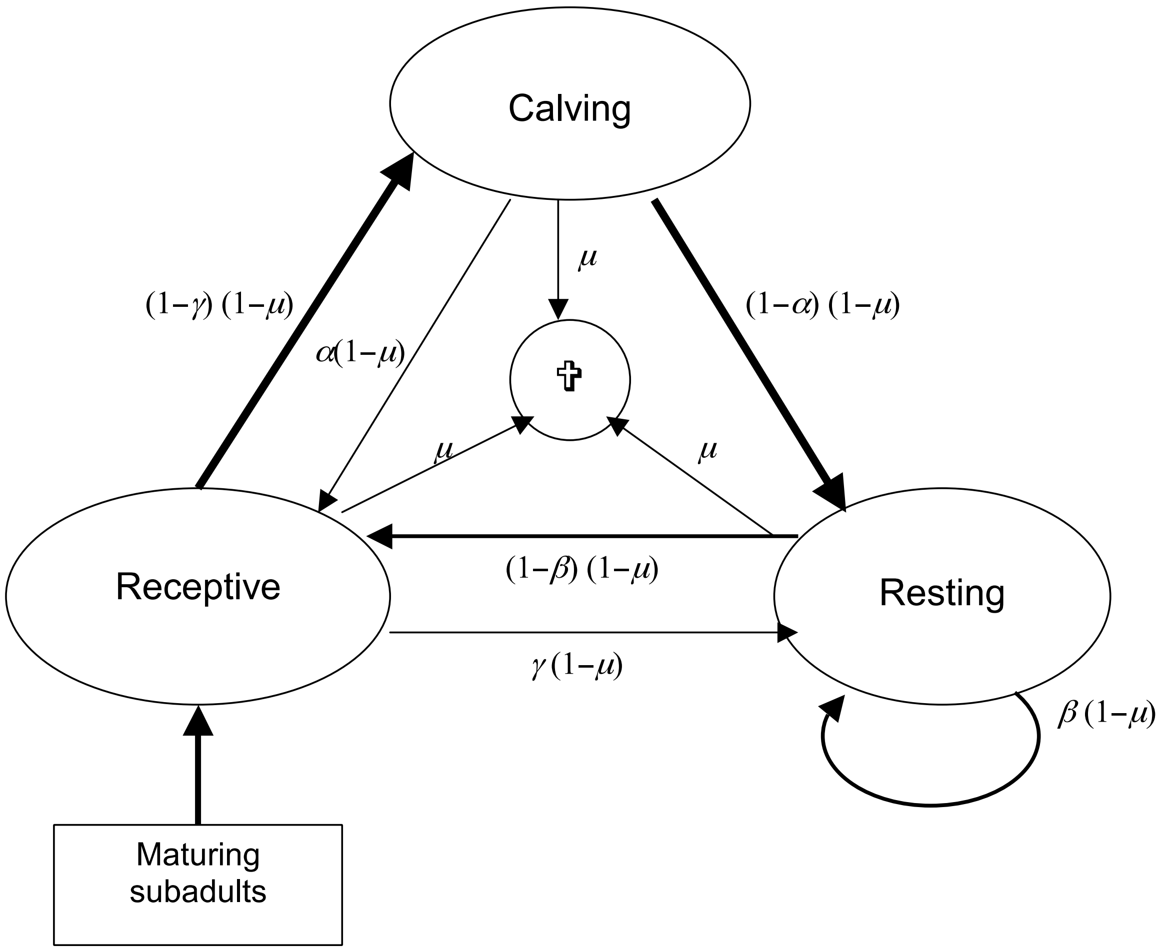


Figure 13: Directed graph for the female reproductive cycle, with transition probabilities as functions of the parameters (from Cooke and Rowntree 2003).

The parameter $\phi_{a,t}$ (for a = 5, . . ., 14) denotes the probability that a female, immature at age a − 1 in year t − 1, becomes sexually mature at age a in year t. For ages 5 through 14, the log-odds ratio (2) is assumed to increase linearly with age.

$$\zeta_{a,t} = \log\left(\frac{\phi_{a,t}}{1-\phi_{a,t}}\right) = \kappa + \lambda a \quad (2)$$

This defines a logistic maturation function. The intercept (κ) and slope (λ) parameters are estimated as part of the model-fitting process. These parameters are estimated based on simulated observations of known-age animals and represented by sightings associated with an individual when at first a calf and then resights when a cow with a calf. The full Leslie matrix $\boldsymbol{L}_t$ used is provided in Table 5.

The expected population numbers in year *t* are given by multiplying the current population structure $\boldsymbol{z}_t$ by the Leslie matrix $\boldsymbol{L}_t$ with the update:

$$\boldsymbol{z}_{t+1} = \boldsymbol{z}_t \boldsymbol{L}_t \quad (3)$$

Since the initial age structure is unknown, it is assumed that the population began with a stable age distribution based on the Leslie matrix $\boldsymbol{L}_0$. An eigenvector λ_0 of $\boldsymbol{L}_t$ scaled is used so that the mature population stages sum to one. The population vector in year *t* is (4) where N_0 is the initial mature female population size and one of the model parameters to estimate.

$$\boldsymbol{z}_t = N_0 \boldsymbol{\lambda}_0 \prod_{i=1}^{T_{\max}} \boldsymbol{L}_t \ldots (4)$$

We explore the use of a fixed geometric age structure for the initial stable age distribution, as eigenvector distributions looked near uniform in their expected age stage distributions for initial pilot parameters sets. For modeling sighting histories, the individual transition matrix is almost the same as the Leslie matrix (Table 6), except for the 1-entry near the bottom left, which is set to zero since identifying marks aren’t inherited.

Table 6. The full Leslie matrix used in the probabilistic model of individual reproductive histories.

	Calf	**Age 1**	**Age 2**	**Age 3**	**Age 4**	**Age 5**	**Age 6**	**Age 7**	**Age 8**	**Age 9**	**Age 10**	**Age 11**	**Age 12**	**Age 13**	**Age 14**	**Calving**	**Resting**	**Receptive**	**Dead**
Calf	0	$0.5S$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$(1\text{-}0.5S)$
Age1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Age 2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Age 3	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Age 4	0	0	0	0	0	$1\text{-}\varphi_5$	0	0	0	0	0	0	0	0	0	0	0	φ_5	0
Age 5	0	0	0	0	0	0	$1\text{-}\varphi_6$	0	0	0	0	0	0	0	0	0	0	φ_6	0
Age 6	0	0	0	0	0	0	0	$1\text{-}\varphi_7$	0	0	0	0	0	0	0	0	0	φ_7	0
Age 7	0	0	0	0	0	0	0	0	$1\text{-}\varphi_8$	0	0	0	0	0	0	0	0	φ_8	0
Age 8	0	0	0	0	0	0	0	0	0	$1\text{-}\varphi_9$	0	0	0	0	0	0	0	φ_9	0
Age 9	0	0	0	0	0	0	0	0	0	0	$1\text{-}\varphi_{10}$	0	0	0	0	0	0	φ_{10}	0
Age 10	0	0	0	0	0	0	0	0	0	0	0	$1\text{-}\varphi_{11}$	0	0	0	0	0	φ_{11}	0
Age 11	0	0	0	0	0	0	0	0	0	0	0	0	$1\text{-}\varphi_{12}$	0	0	0	0	φ_{12}	0
Age 12	0	0	0	0	0	0	0	0	0	0	0	0	0	$1\text{-}\varphi_{13}$	0	0	0	φ_{13}	0
Age 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$1\text{-}\varphi_{14}$	0	0	φ_{14}	0
Age 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Calving	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$(1\text{-}\alpha)(1\text{-}\mu)$	$\alpha(1-\mu)$	μ
Resting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$\beta(1-\mu)$	$(1-\beta)(1-\mu)$	μ
Receptive	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	$(1-\gamma)(1-\mu)$	$\gamma(1-\mu)$	0	μ
Dead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

If we define the reproduction matrix $\boldsymbol{R}$ as the matrix of all zeroes except for a 1 in the fourth last row of the leftmost column, then the Leslie matrix $\boldsymbol{L}_t$ is given by:

$$\boldsymbol{L}_t = \boldsymbol{Q}_t + \boldsymbol{R} \quad (5)$$

Where $\boldsymbol{Q}_t$ represents the transitions between stages, and $\boldsymbol{R}$ accounts for reproduction. Cooke and Rowntree (2003) include another parameter ρ that models the probability of a calf remaining recognisable once seen. We fixed this parameter to one in the simulation under the assumption that calf identity loss is low.

3.2.2 Probability of individual sighting histories

In general, if the model has *n* stages and *m* possible observations for each individual at each time point, the observation probability matrix $\boldsymbol{P}_t$ is an *m* × *n* matrix. Here, $\boldsymbol{P}_t\,(\mathrm{i}, \mathrm{j})$ is the probability that observation value i will be obtained for a whale in stage j in year t.

The observation vector in year t for whale k is a vector where all entries are zero except for the actual observation made. For this analysis, there are three types of observations:

1. The whale is seen as a calf (1, 0, 0)
2. The whale is seen with a calf (0, 1, 0)
3. The whale is not seen or seen without a calf (0, 0, 1)

It is assumed that the probability of a whale being mistakenly observed as having a calf is negligible, although there is a higher probability that a whale with a calf might not be seen. The observation probability matrix $\boldsymbol{P}_t$ (size 3 x 19) for year *t* is defined as:

$$\boldsymbol{P}_t = \begin{pmatrix} c_t & 0 & \dots & 0 & \dots & 0 \\ 0 & 0 & \dots & g_t & \dots & 0 \\ 1 - c_t & 1 & \dots & 1 - g_t & \dots & 1 \end{pmatrix} \quad (6)$$

Where g_t is the probability of observing a calving whale in year t, and c_t is the probability that a calf born in year t is correctly identified and added to the dataset These parameters, $c_t$and g_t, are estimated during model fitting but in our base model are the same for each year and sampled that way in simulation.

Let $\mathbf{y}$ represent a sighting history, which is a sequence of observation vectors $\boldsymbol{y}_{*,t}$ where $y_{j,t}$ = 1 if the history contains observation category j in year t, and 0 otherwise. Let $\mathrm{T}(\mathbf{y})$ denote the year of the first observation of a calf or a cow-with-calf in the history $\mathbf{y}$. If all identified whales remain recognisable, the expected number of whales with sighting history y can be expressed as:

$$\mathrm{E}(\mathbf{y}) = N_0\lambda_0\left[\prod_{t=1}^{T(\mathbf{y})}(\boldsymbol{Q}_t + \boldsymbol{R}) < \boldsymbol{y}_{*,t\boldsymbol{P}_t} >\right]\left[\prod_{t=T(\mathbf{y})+1}^{T_{\max}}\boldsymbol{Q}_t < \boldsymbol{y}_{*,t\boldsymbol{P}_t} >\right]\mathbf{1}. \quad (7)$$

Where N_0 is the initial mature female population size, λ_0 is the stable age/stage distribution from the Leslie matrix, and $\boldsymbol{P}_t$ and $\boldsymbol{Q}_t$ represents the transition and observation matrices.

The diagonalisation operator $< \boldsymbol{x} >$ turns the vector $\boldsymbol{x}$ into a diagonal matrix, and $\mathbf{1}$ is a column vector of ones and assists with the summation. The $\mathrm{E}(\mathbf{y})$ is the expected number of recapture histories that look like $\mathbf{y}$ given the parameters of the model. We treated each recapture history as a matrix \mathbfy where the rows indicate the observation state and the columns the year of sampling (size 3 x $T_{\max}$). This then treats $\boldsymbol{y}_{*,t}$ as a column vector that can take the observation vector forms above and has the correct dimensions for multiplication by $\boldsymbol{P}_t$ and diagonalisation.

Following Cooke and Rowntree (2003), the likelihood of the data set is obtained by treating the observed frequencies of each sighting history as Poisson distributed random variables with expectation given by equation above. The parameters to be estimated are θ = $(N_0, \alpha, \beta, \gamma, \mu, \kappa, \lambda, S, c_t, g_t)$.

3.2.3 Joint survival observation sighting probabilities

In initial simulations, the observed *versus* expected frequencies of calf-only recapture histories were poorly aligned, particularly for calves only seen in their first year (and not in later years). The model underestimated the frequency of these cases, despite their logical prevalence, due to calves often being missed until adulthood or removed due to mortality or being male.

This issue was resolved by conditioning on the first sighting of a calf, assuming zero probability of observation prior to that year. Consequently, the observation probability matrix, $\boldsymbol{P}_t$, was adjusted to include a bottom row of ones until the first observation year. This led to an investigation of the joint model of observation and survival. The details for calculating the joint survival/observation probabilities for four scenarios of sighting or not sighting an individual in year $t-1$ and then sighting or not sighting an individual in year t is provided in Appendix 2.

3.2.4 Implementation

The annual stage transition model and the observation model were used to compute the probability of each observed sighting history. Parameter estimates were obtained via maximising the Poisson log-likelihood objective function the objective function using the `nlminb` function in the R programming language (Gay, 1990; R Core Team, 2024). The gradient is supplied to the optimisation routine and is computed using automatic differentiation via the Template Model Builder (TMB) package (Kristensen et al., 2016), which integrates C++ with R. Automatic differentiation in TMB facilitates the estimation of parameter uncertainty, which is computed for all model parameters. Hessian-based parameter standard errors were obtained using TMB algorithmic differentiation functions and interval estimates were reported by appropriate transformation *e.g. logit* for probabilities and the exponential for positive quantities (e.g., initial number of adult females). The evaluation of the score function of the log-likelihood at the estimates reported from TMB was also evaluated to ensure values were near zero. Inadequate model fit was evaluated by comparing the observed number of recapture histories against the expected number predicted by the model.

Sighting histories across simulations were coded at matrices with each row containing the type of observation. For example, calf (1, 0, 0), whale is seen with a calf (0, 1, 0), or whale is not seen or seen without a calf (0, 0, 1) forming the columns over $T_{\max}$ observation years common to each recapture history. The unique histories were tabled to form the expected number of each recapture history from the sampled simulation data. Initial investigations indicated that sighting probabilities may be estimated with poor accuracy given different simulated data. We explored model fit when c_t and g_t parameters were constrained through a prior that has a Gaussian distribution with expectation $\mu_{c,g}$= 0.8 and $\sigma_{c,g}$= 0.015. Values of 0.8 were used in the simulation following the estimated values of 0.7 – 0.9 used in Brandão et al. (2023), which is why 0.8 was set to the mean of the prior. A derived population rate of increase estimate was computed by differencing the adult female population each year and computing the proportion change from the previous year - these proportion change values were then averaged overage the time series to arrive at a single estimate. Standard errors could be computed from TMB for this derived parameter. Standard errors for adult female abundance were also computed for each year of the time series and coefficient of variation used to measure precision of the adult female census. We observed that ‘warming up’ the dynamics of the population age-stage process for ten years prior to the first year of observation gave more stable parameter estimates.

Figure 14 and Table 7 provide the details of example results generated from a single run of the advanced simulation with nursery-only sampling.

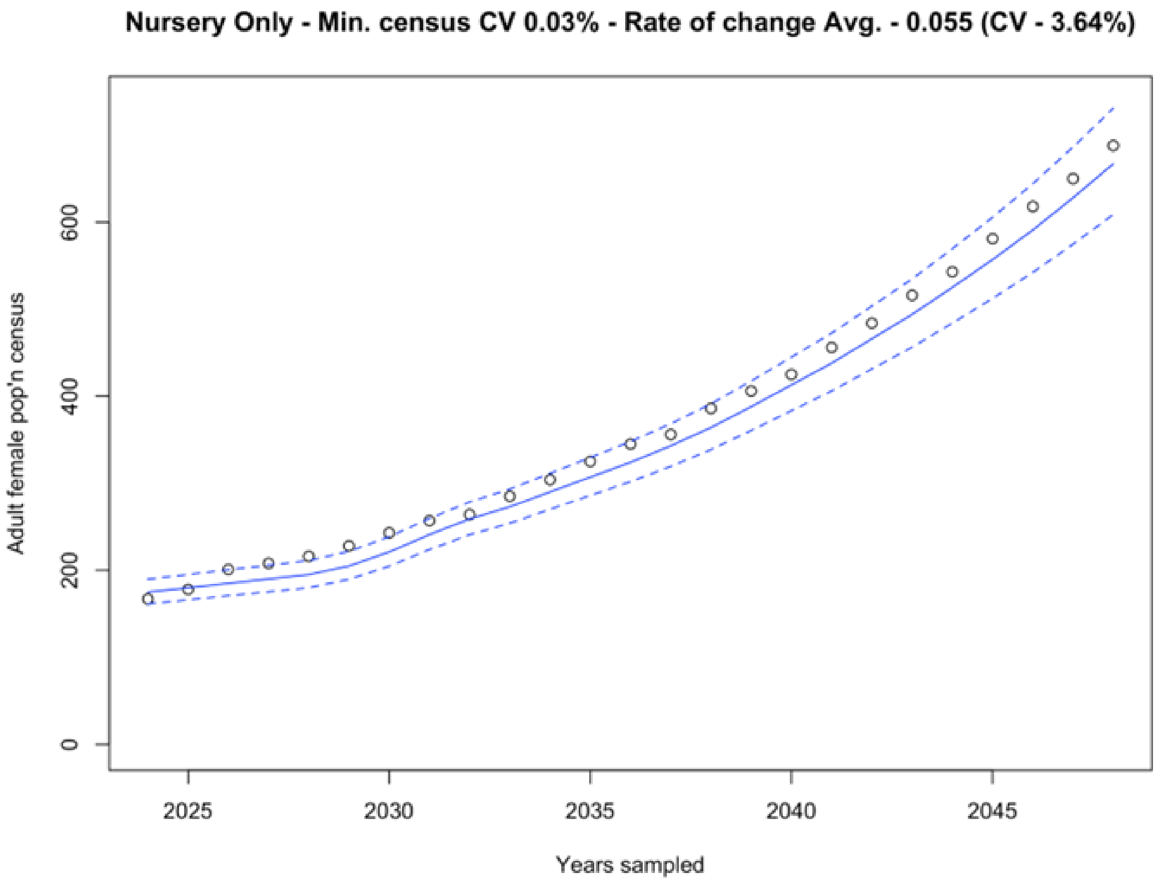


Figure 14. True simulated adult female population (black points) numbers with estimates (blue) and 95% confidence interval error bounds (blue dotted lines) for the estimate. The title shows the simulation name the minimum coefficient of variation (CV) on the adult female abundance over the time series and the estimate of rate of change and its CV.

Table 7. Summary of parameter estimates from single simulation run of model and estimation performed in TMB. SE is the standard error.

Parameter	Estimate	SE
N_0	136	5.46
κ	-11.1	1.09
λ	1.90	0.195
α	0.050	0.000
β	0.543	0.017
γ	0.010	0.000
μ	0.027	0.003
S	0.950	0.000
c	0.735	0.015
g	0.861	0.011
ROC	0.053	0.002

3.3 Exploration of sampling scenarios to be able to discern population trends

Potential sampling strategies and their ability to discern population changes were explored by applying multiple strategies to a simulated population to produce a simulated capture history. The capture history data can then be fitted using the mark-recapture model and the results compared to the original "true" population.

The aim was not to fine-tune a sampling design, as the assumptions of the underlying simulation parameters could bias the performance of specific fine-scale design. Instead, the aim was to inform broader survey strategies. Therefore, it is less critical that the simulation parameters reflect the true population precisely; rather, it is important that the values used reflect the general properties of the population, including:

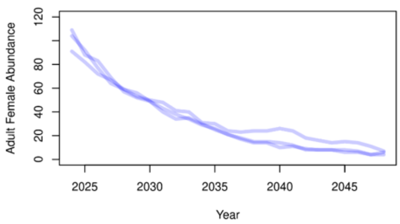
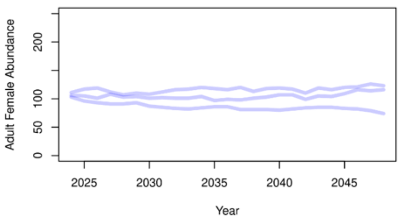
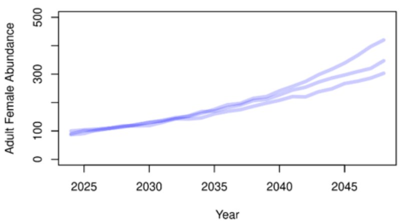
- Aggregation/nursery area site fidelity.
- Cyclic calving at 3-5 years.
- A juvenile phase ending at a variable age at sexual maturity.
- Mortality rates that align with other populations (a growth rate of 5%).
- Travel from foraging to aggregation/nursery areas, with potential resting stops (of a length of 1-2 days),
- Calving somewhere between the foraging and aggregation/nursery areas.

- Departure from the aggregation/nursery area generally after 30 days (based on the minimum reported in Burnell and Bryden 1997 and Charlton 2017) to return to foraging areas with a calf (at a slower speeds and higher numbers of resting stops)
- Sampling of mother-calf pairs only.

Specific parameter values used are given in Appendix 1.

Three population scenarios: increasing, steady, and decreasing (Table 8) and five sampling strategies (Table 9) were tested. This expands on the two scenarios explored by Bannister et al. (2011), who explored two increasing populations with different growth rates and one form of sampling (continuation of an annual aerial survey along the Western Australian coastline). For each population scenario, five replicates were simulated producing 20 simulated populations. Each sampling strategy was also replicated five times providing 25 survey designs. Each of these designs was applied to each simulated population resulting in 500 mark-recapture data sets.

Table 8. The three population scenarios tested.

Scenario		**Description**
Shrinking		Population trajectory is decreasing at approximately 5% per year
Steady		Population trajectory is generally steady
Increasing		Population trajectory is increasing at approximately 5% per year

Under most scenarios, model outputs provided similar trajectories as the simulated population (Figure 15), although when sampling was focused on a single aggregation/nursery area, model outputs consistently underestimated the simulated population. However, even under this scenario, overall trends in the population were able to be captured, although over longer sampling periods. Under all scenarios, the model tended to provide mixed outputs for the stable population, with an overall slight decreasing trend (Figure 15). Some bias however was expected as there are some differences in the model structure used in the simulation and the mark-recapture models.

Table 9. The five sampling strategies tested.

Strategy	**Intensity** ***(pseudo days/ year)***	**Description**
Everywhere	180	Sampling everywhere all the time so most of the available whales are sampled.
Aggregation/nursery + monitoring	24	Targeted sampling at aggregation/nursery areas with high sampling effort and detectability elsewhere.
Aggregation/nursery + low monitoring	24	Targeted sampling at aggregation/nursery areas with lower sampling effort and detectability elsewhere.
Aggregation/nursery only	15	Sampling at the three aggregation/nursery areas only.
Single aggregation/nursery	5	Sampling at a single specified nursery only.

3.3.1 Sampling alternate years/skipping years

Three additional sampling strategies were explored to investigate whether sampling on a non-annual basis allowed for population changes to be able to be discerned. These included:

- NurseryOnly – Sampling occurs at the aggregation/nursery areas annually, but effort outside of these areas is non-annual
- NurseryOnly.AltYears – Sampling is cycled through the three aggregation/nursing areas tri-annually (so each aggregation/nursery area is sampled once every three years)
- NurseryOnly.AltYears.TripleEff – Sampling is cycled through the three nursing areas tri-annually but with three times the effort each year.

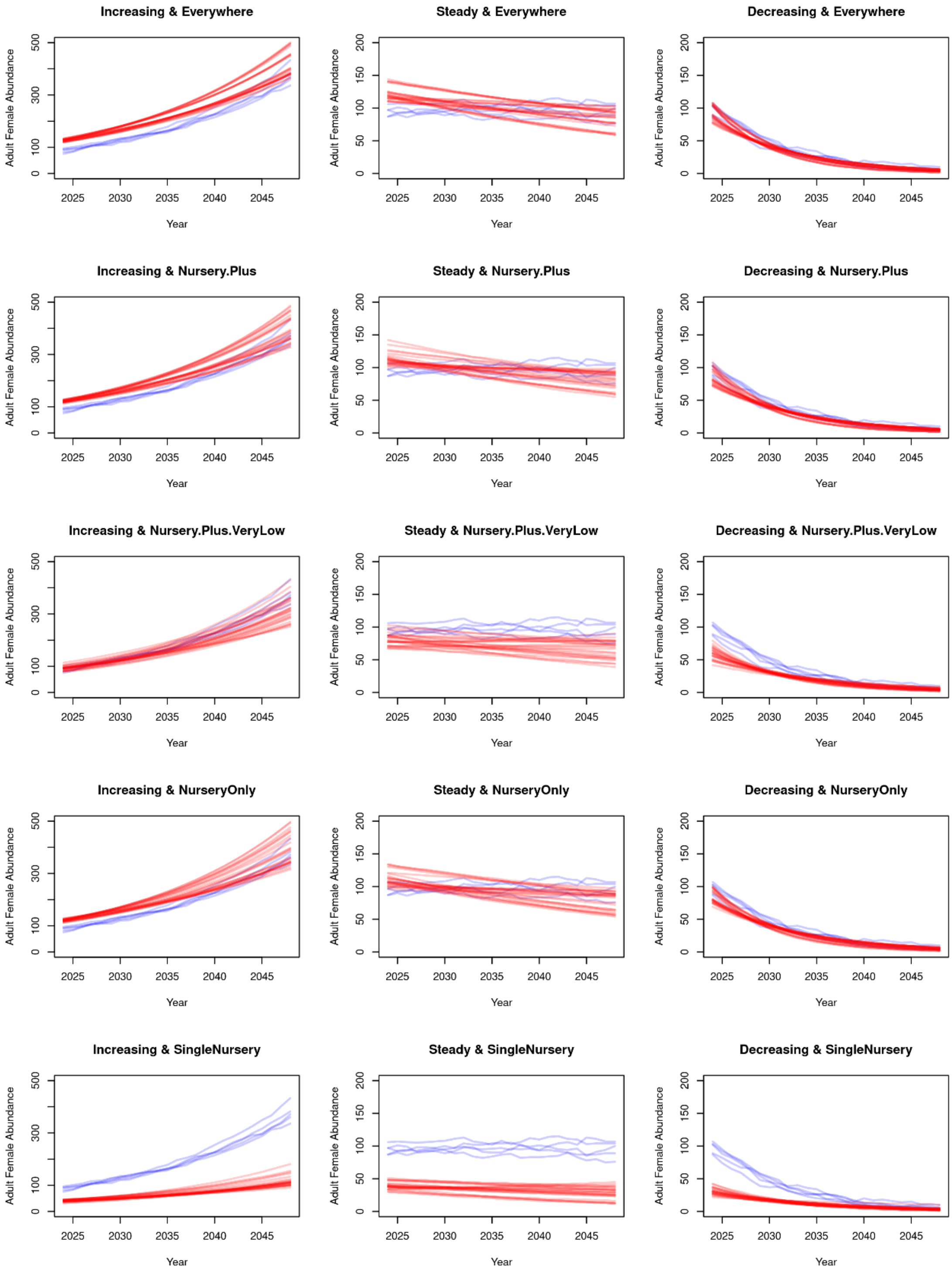


Figure 15. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), for the selected population and sampling scenarios described in Tables 8 and 9.

When compared to annual sampling (Figure 15), not sampling annually introduces some bias although overall trends in the population were still able to be captured (Figure 16). The model performed worst on an increasing population that was sampled at the aggregation/nursery areas tri-annually. Similarly to annual sampling, model outputs suggested an overall slight decreasing trend for the stable population.

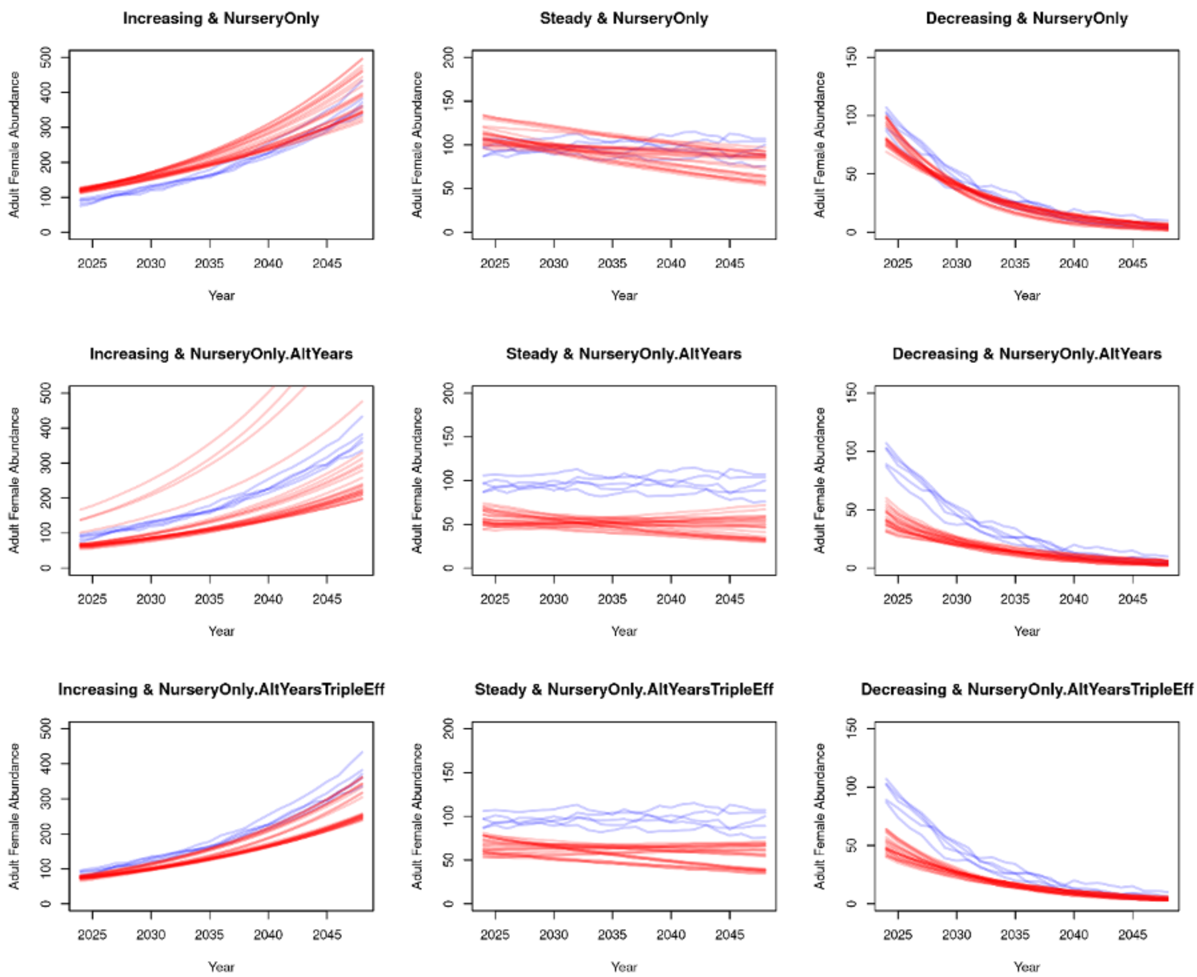


Figure 16. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), for annual sampling at aggregation/nursery areas (top), tri-annual sampling at aggregation/nursery areas (middle) and tri-annual sampling with higher effort (bottom).

3.3.2 Spatial expansion of the population

Although the south-east subpopulation is small, observations collected to date suggest that it is increasing, albeit at a lower growth rate than the western population (Stamation et al. 2020, Evans et al. 2021, Watson et al. 2021). Observations of the western subpopulation have identified that as this subpopulation has grown, spatial expansion of aggregation/nursery areas has occurred as established aggregation/nursery areas have reached carrying capacity (Charlton et al. 2019).

To examine whether the five original sampling strategies (Table 8) were able to discern population trends in a spatially expanding population, we generated a population scenario where the three modelled aggregation/nursery areas were at capacity and whales moved randomly to new aggregation/nursery areas in New South Wales and to a new model state/location located on the southern Australian coast.

Under most scenarios, model outputs provided similar trajectories as the simulated population, although with some negative bias and increased variance (Figure 17). When sampling was focused on a single aggregation/nursery area, model outputs again, consistently underestimated the simulated population and not surprisingly, the model was unable to discern any population trend, given those areas where spatial expansion was occurring were not sampled.

3.3.3 Temporal change in mortality

Given recent reports of slowing growth rates in the western subpopulation (Smith et al. 2023), we explored the ability of the sampling strategies to discern a temporal change in mortality that might cause population growth to stop and subsequently decrease. To create this scenario, mortality was increased everywhere in 2035. However, because the mark-recapture model is parameterised for constant mortality through time, it is not surprising that it did not perform well when this assumption is broken. This resulted in an inability to be able to be able to compare sampling strategies. To evaluate sampling strategies under such a population scenario, a modified mark-recapture model that allowed for temporally changing mortalities would need to be developed. Alternatively, the model could be fitted every year and the results examined for a drop in trend/growth after 2035.

3.3.4 Western population interaction

Because the south-eastern region of Australia is part of the migratory corridor for the western subpopulation (Burnell 2001), we explored the robustness of the sampling strategies to potential mixing of sightings from the two subpopulations. To simulate this situation we examined population scenario where the south-eastern subpopulation was steady, and the western subpopulation was increasing (Figure 18). Unsurprisingly under all of the sampling strategies model outputs are biased by the increase in the western subpopulation.

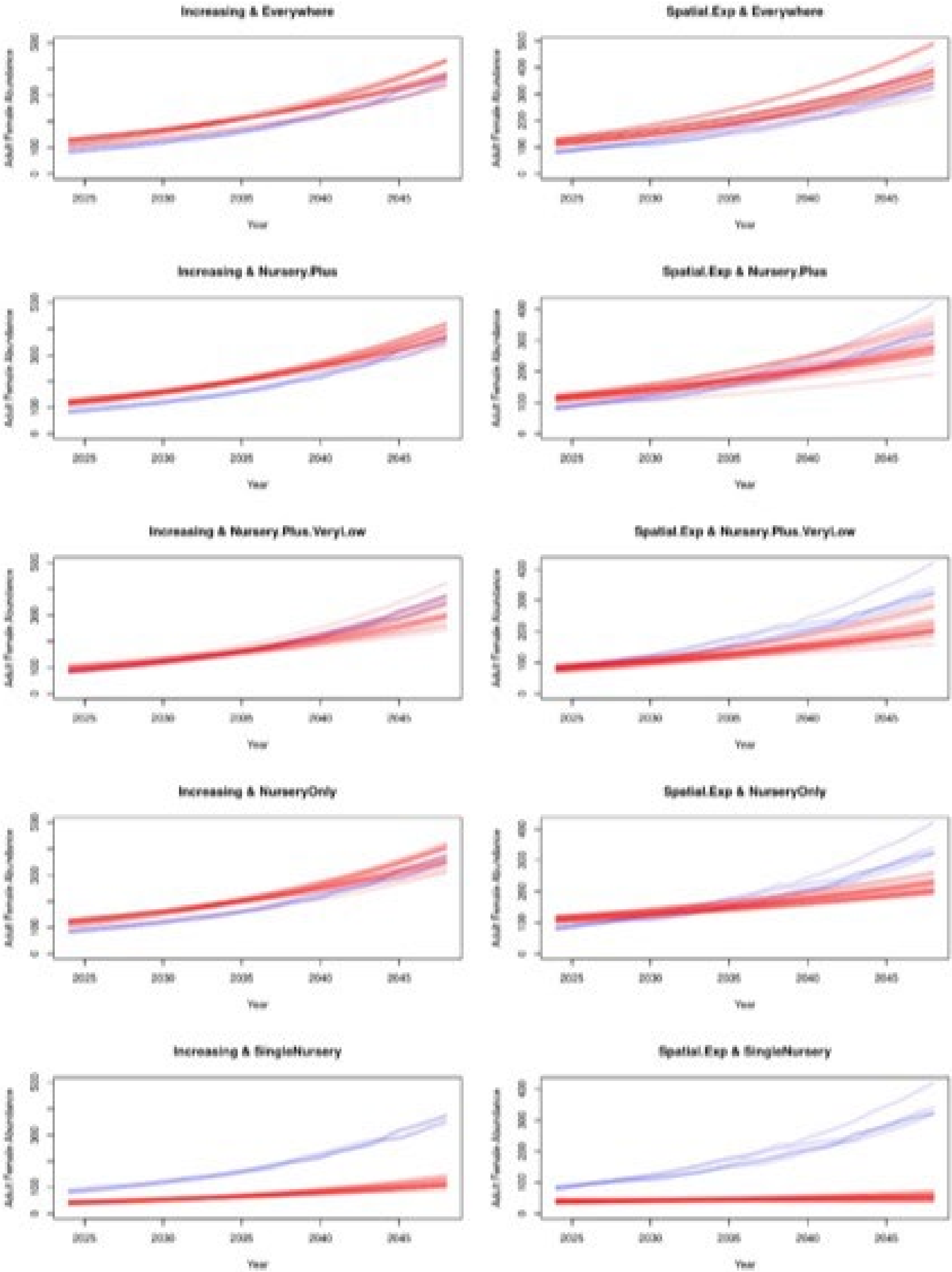


Figure 17. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), when a population is increasing (left) and increasing and spatially expanding (right) for the sampling strategies described in Table 9.

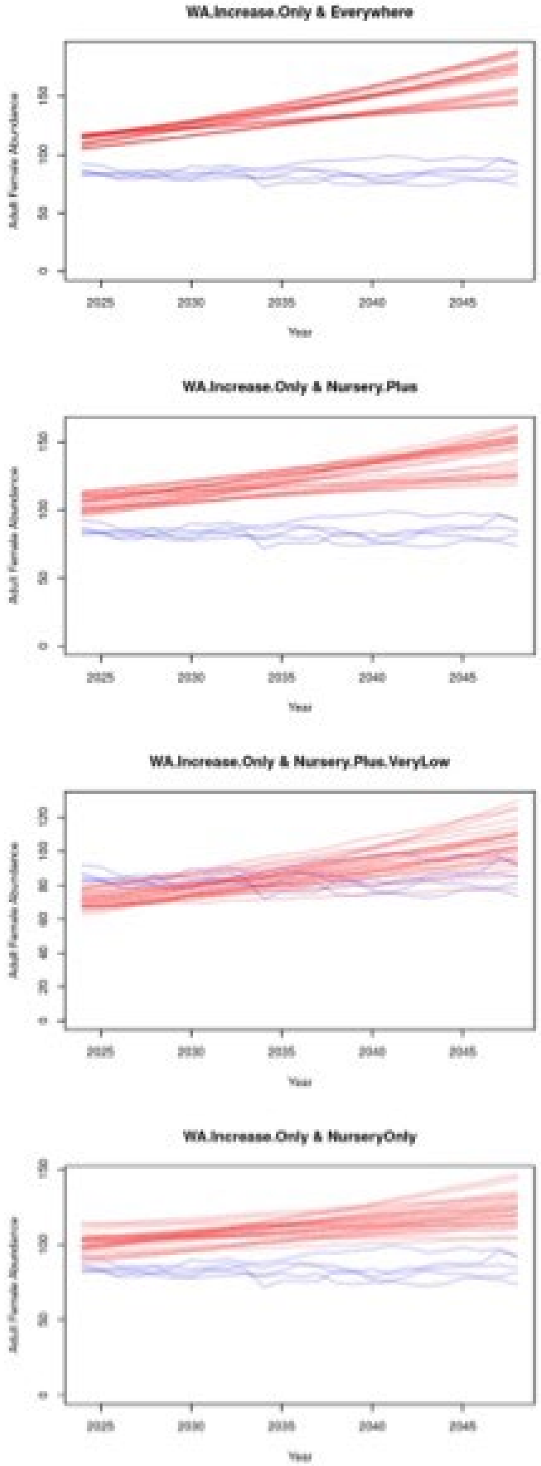


Figure 18. Comparison of population trajectories (blue lines) and the predicted trajectories from the mark-recapture model (red lines), when the south-eastern subpopulation remains stable while the western subpopulation is increased for the sampling strategies described in Table 9.

4. Discussion

This project undertook an evaluation of the sightings data for southern right whales from the south-east Australian region currently managed by the Department of Climate Change Energy, Environment and Water in ARWPIC. When utilising parameter bounds that minimise uncertainty in the initial identification of individual whales and subsequent identification of resights commonly used in other assessment of photo-identification data, the project found that the data currently housed in ARWPIC largely did not meet the requirements for use in population estimation. This was because of two predominant issues: (i) the resulting dataset was very small (40 individuals) and (ii) because of the opportunistic nature of the dataset and a lack of information on important parameters such as temporal and spatial effort, many of the biases associated with the data were unable to be resolved to the point that they could be robustly accounted for in any modelling approach used.

The size of the population for which sightings were available is similar to that identified in Stamation et al. (2020) and Evans et al. (2021), both of which included 37 and 32 females with calves in their analyses, respectively. This indicates that very little additional data has been incorporated into ARWPIC in the intervening period between projects. Recognising the limitations of such a small dataset and the lack of information on important parameters, Evans et al. (2021) applied a simple model that uses the cow/calf count over three years (to allow for the 3-year periodicity in calving and multiplies it by a factor of 3.94 was utilised to provide an estimate of the number of females with calves in each year of the time series. This is similar to the approach applied annual to survey data collected from the sub-population in south-west Australia (Smith et al. 2023).

We found that even when simulating a dataset containing realistic numbers of individuals based on those population estimates available (300 individuals of which 90-100 individuals were adult females), there were still challenges in fitting a population model similar those used elsewhere to estimate populations of southern right whales (see also section 4.1). This suggests that at present, if used directly, such models are unsuitable for use on very small datasets and alternative approaches are needed if population estimation is a primary objective. Further exploration of alternative indices and metrics for assessing trends should be considered to ensure biological realism in estimates of populations and their trajectories.

Further confounding the dataset from south-east Australia is that because sightings are derived from opportunistic photographs collected across the region and the south-east is part of the larger migratory corridor for the species, individuals sighted are likely a mix of those associated with aggregation areas in the south-east and those that are transiting through the area, with an eventual destination of aggregation/nursery areas in south-west Australia (Burnell 2001). The requirement for being able to account for the multiple uses of the area in establishing datasets for population estimation has been raised previously (Evans et al. 2021) and remains an issue to be addressed. While the spatial connectivity of individuals between the two regions was not explored in this project, it was in Evans et al. (2021) and Watson et al. (2021), with approximately 2.5 per cent and 7 per cent of individuals in each of the datasets utilised sighted in both regions respectively. If efforts in estimating population parameters for the south-east subpopulation are to remain based on photo identification mark recapture methods, this will require that all individuals sighted across the range of southern right whales in any one year be made available for matching and cross validation. Complimentary efforts based on the collection and analyses of genetic material from individuals in the south-eastern Australian area would lend some insights into whether sightings represent transitory individuals or those associated with the south-east subpopulation (Carroll et al 2015).

Poor data and data poor methods have been developed for low density and limited sampling applications in fisheries and continue to be an expanding area of research (e.g. Cope and Punt 2009, Jiao et al. 2011, Chrysafi and Kuparinen 2015, Froese et al. 2020). Whether such approaches could be adapted to southern right whales and their asynchronous breeding cycle is yet to be explored, but could be an area for focusing future efforts, if the priority, as set out in the recovery plan for the species is to determine robust measures of the population in the near future. Alternatively, genetic approaches to population estimation that are capable of estimating cryptic components of populations (e.g. in the case of southern right whales, this would include males) and reducing uncertainty in recaptures, such as close-kin mark recapture (Bravington et al. 2016, Conn et al. 2020), provide a potential for providing population estimates. If enough samples can be collected to meet the feasibility requirements for this approach (see Bravington et al. 2016, Lloyd-Jones et al. 2023), it provides an opportunity to not only provide estimates of population size, but also resolve uncertainties in population structure and connectivity of subpopulations at the same time. Further, the approach can be extended to account for spatially biased sampling that is likely to result from opportunistic approaches to sampling (Conn et al. 2020, Marcy-Quay et al. 2020).

4.1 Sampling strategies

Under the various population scenarios examined, all of the five sampling strategies were able to discern population trends, although with varying variance. The only exceptions to this were scenarios where spatial expansion of the population was occurring but sampling was limited to aggregation/nursery areas and where potential mixing of sightings from the two subpopulations of southern right whales was explored and the south-eastern population was held at a stable population trajectory while increasing the western subpopulation.

These scenarios, given reported growth rates for the south-eastern subpopulation (Stamation et al. 2020, Evans et al. 2021, Watson et al. 2021), and the multiple uses of the south-eastern Australian region by both subpopulations (Burnell 2001, Evans et al. 2021, Watson et al. 2021), may be realistic, particularly if observations of population growth rates from the two subpopulations are robust. This suggests that data collection should have a primary focus on aggregation/nursery areas and include building datasets that allow for population discrimination (e.g. genomic datasets) to ensure that population parameters are not biased by transitory animals. In addition, some effort should be placed into regions outside of aggregation/nursery areas to ensure that any spatial expansion of populations and the emergence of new aggregation/nursery areas is captured.

From the simulations undertaken here, the effort placed into regions outside of aggregation/nursery areas does not need to be substantial to be able to discern overall population trends and can be non-annual. As new aggregation/nursery area are confirmed however, effort will need to be adjusted to ensure regular (annual) monitoring of those aggregation/nursery areas in order to be able to build datasets that are capable of capturing trends, particularly given the large inter-annual variability in datasets caused by the asynchronous breeding cycle of southern right whales. In the south-eastern Australian region, any new aggregation/nursery areas identified outside of the migratory corridor for both sub-populations (e.g. along the New South Wales coast) will be particularly important as they are likely to contain only individuals from the south-eastern subpopulation and will therefore not be biased by individuals associated with the western subpopulation in the same way as those in Tasmania and Victoria.

The sampling strategies outlined here align with those proposed by Bannister et al. (2011) and will ensure that any differences in population parameters between survey sites (as they observed) are captured. Given the differences Bannister et al. (2011) observed between survey sites for the western subpopulation, monitoring of only one aggregation/nursery area is unlikely to be sufficient in establishing overall population parameters for the south-eastern subpopulation, particularly if similar differences are present in this subpopulation. This makes the identification on new or emerging aggregation/nursery sites particularly important, given that at present only one aggregation/nursery site at Logans Beach has been identified for the south-eastern subpopulation (Stamation et al. 2020).

4.2 Challenges associated with the simulation approach and future improvements

The model described in Cooke and Rowntree (2003) contains many parameters that need to be estimated and was designed on sightings data sets from populations that utilise aggregation sites in Argentina and South Africa that are much larger than those currently available in ARWPIC. In attempting to simulate much smaller populations, such as those in Australia, it may be useful to condense the model by setting many of the parameters.

In the simulations run, we observed high accuracy and low variance for most parameters of the model with properties were stable across the scenarios investigated. The exception to this were the observation probabilities that needed strong penalties to improve overall model fit (set at 80% for both calves and adults). Similar penalties were applied to observation probabilities in Brandão et al. (2023) and were modelled as random effects in Cooke and Rowntree (2003), resulting in a similar penalty-like property. To explore how this reliance on penalties might be addressed, the transition probabilities for the joint model on observation probabilities and survival were explored with an overall outcome of improved model fit when compared to the base model. Model fit, evaluated by the bias and variance of the adult female abundance time series, was improved with less bias at the start of the time series for increasing populations and lower variance across simulation scenarios.

In our simulation detection probabilities were assumed constant through time. In addition, the observation process is strongly coupled with survival and stage. As a result, non-detection might be mistaken in the model with mortality or absence, biasing both survival and detection estimates. In practice, the challenge of observation probability estimation is exacerbated by heterogeneity in individual survival rates, variation in detection through space, observer variability, time of year, variation in observation effort or gaps in observation. Many super-population models that have been used on southern right whales assume that each individual has an equal capture probability, all individuals have the same survival probability and that the area of capture and recapture is constant (Pollock et al. 1990). Although survivorship in southern right whales, and particularly in adults is likely to be high (see Cooke et al. 2001), it is unlikely that individuals have equal capture probabilities and in the case of the Australian dataset, and in particular the south-east component of the dataset, the area of capture and recapture is not constant between years. Some of these assumptions can be somewhat addressed by limiting datasets to components of the population (e.g. adult females with calves) or utilising alternative mark -recapture datasets (e.g. genetic approaches that allow males and females to be modelled separately; Carroll et al. 2013) to reduce uncertainty in recapture probabilities and capture with confidence other components of the populations (e.g. males). Further development of the simulation model would benefit from incorporating processes that allow for detection probabilities to vary with time, building on the models described in Brandão et al. (2023) and Cooke and Rowntree (2003).

4.3 Implications for management

The Recovery Plan for southern right whales (DCCEEW 2024) identifies a number of action items relevant to the south-eastern subpopulation. These are:

B1. Measure and monitor population demographics and recovery.

- Establish effective monitoring techniques for the eastern population and implement a targeted long-term monitoring program capable of measuring and evaluating population recovery.
- Enable sharing and exchange of information required for monitoring the population recovery of southern right whales through support for national databases (e.g., Australian Right Whale Photo Identification Catalogue) and data processing (e.g., automated image matching).

B2. Characterise population structure.

- Characterise the population structure and degree of connectivity between the Australian western and eastern populations and southern right whales in New Zealand waters using multiple approaches (e.g., photo-identification, molecular and biochemical methodologies).

This project provides clear guidance on what is needed for monitoring the south-eastern subpopulation and building the datasets required for progressing the objectives for the Recovery Plan for southern right whales and addressing the above action items. If implemented early in the lifetime of the Recovery Plan (the current Recovery Plan is planned to span ten years), considerable progress could be achieved against these actions.

5. Recommendations

Given the outputs from this project and the associated limitations identified in current datasets available for progressing the objectives of the current Recovery Plan for southern right whales, six recommendations for future work can be identified:

5.1 Data Collection

1. Provision of information on calf survival rates that is compatible with the model described in Cooke and Rowntree (2023). This will require effort to be placed on recording initial calf sightings and resighting calves as well as mothers.

2. Recording of effort being placed into identifying and resighting individuals, particularly at known aggregation/nursery areas. The current opportunistic approach to data collection does not provide datasets suitable for establishing parameters and trends where effort can be accounted. In addition, the current small size of datasets introduces large uncertainty into parameters calculated.

3. Collection of data that can assist with the discrimination of eastern and western sub-populations. Regarding sightings data, this includes ensuring all sightings within a year collected is submitted to ARWPIC. This will require additional effort into coordination across projects. The collection of additional genomic datasets should be explored with a view of assessing the viability of approaches such as close-kin mark recapture.

5.2 Sampling Design

1. A greater focus on annual data collection at all known aggregation/nursery areas is needed with less-formal flexible monitoring across other areas. This less formal monitoring is needed to ensure early awareness of developing aggregation/nursery area that could then transition to annual data collection. Having continuous time series from aggregation/nursery areas is fundamental for understanding the recovery of this species and given the species' non-annual breeding cycle, skipping years can miss important indicators, thereby providing misleading information on recovery rates.

2. To support mark-recapture modelling with a focus on population monitoring, the greatest effort should be put towards collecting data from aggregation/nursery areas and from resident animals only. This will also allow for definitive evaluation of sub-population connection/linkages. Any efforts, whether based around photo-identification methods or other methods (e.g. genetic approaches) needs to consider how best to account for the multiple uses of the area in establishing datasets for population estimation.

5.3 Implementation

1. To prioritise efforts and tasks and identify pathways to achieve the above, a research prioritisation workshop should be held that brings together conservation managers, data holders, population modellers and funding agencies. This would allow the identification of tasks

of the highest priority and for supporting the Recovery Plan, identify the capability needed in carrying out the work and funding pathways for facilitating the work.

Acknowledgements

The ARWPIC Steering Committee, in particular Mike Double, are thanked for their support of the project. Andy Townsend is thanked for his assistance with data extraction and guidance in interpreting the data housed in ARWPIC. The project team thanks Scott Foster for his guidance on the simulation component of the project.

6. References

Bannister, J.L. 2001. Status of southern right whales (*Eubalaena australis*) off Australia. Journal of Cetacean Research and Management Special issue 2: 103-110.

Bannister, J.L., Hammond, P.S., Double, M.C. 2016. Population trend in right whales off southern Australia 1993-2015. International Whaling Commission document SC/66b/BRG/09.

Bannister, J.L., Hedley, S.L., Bravington, M.V. and Burnell, S.R. 2011. Monitoring population dynamics of right whales off southern Australia. Project 2009/41: Final Report to the Australian Marine Mammal Centre, 13 April 2011. 23pp.

Bannister, J.L., Pastene, L.A., Burnell, S.R. 1999. First record of movement of a southern right whale (*Eubalaena australis*) between warm water breeding grounds and the Antarctic Ocean, south of 60˚S. Marine Mammal Science 15: 1337-1342.

Best, P.B. 1994. Seasonality of reproduction and the length of gestation in southern right whales *Eubalaena australis*. Journal of Zoology 232:175-89.

Best, P.B., Brandão, A., Butterworth, D.S. 2001. Demographic parameters of southern right whales off South Africa. Journal of Cetacean Research and Management Special issue 2: 161-169.

Brandão, A., Ross-Gillespie, A., Vermeulen, E., Butterworth, D.S. 2023. A photo-identification-based assessment model of southern right whales *Eubalaena australis* surveyed in South African waters, with a focus on recent low counts of mothers with calves. African Journal of Marine Science 45:15–27. doi:10.2989/1814232X.2023.2172455

Bravington, M.V., Skaug, H.J., Anderson, E.C. 2016. Close-Kin Mark-Recapture. Statistical Science 31: 259-274. doi:10.1214/16-STS552.

Burnell, S.R. 2001. Aspects of the reproductive biology, movements and site fidelity of right whales off Australia. Journal of Cetacean Research and Management Special issue 2: 89-102.

Burnell, S. R., Bryden, M.M. 1997 Coastal residence periods and reproductive timing in southern right whales, *Eubalaena australis*. Journal of Zoology, London 241: 613621.

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. doi:10.3354/meps09145.

Carroll, E.L., Childerhouse, S., Fewster, R., Patenaude, N.J., Steel, D., Dunshea, G., Boren, L., Baker, C.S. 2013. Accounting for female reproductive cycles in a superpopulation capture recapture framework. Ecological Applications 23: 1677-1690. doi:10.1890/12-1657.1

Caswell, H., Fujiwara, M., Brault, S. 1999. Declining survival probability threatens the North Atlantic right whale. Proceedings of the National Academies of Science USA 96: 3308-3313.

Charlton, C. M. 2017. Southern right whale (*Eubalaena australis*) population demographics in southern Australia. PhD Thesis, Curtin University, Western Australia

Charlton, C., McCauley, R.D., Brownell, 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 the Bight, South Australia, 1991-2016.Aquatic Conservation Marine and Freshwater Ecosystems 32: 671-686. doi:10.1002/aqc.3771.

Charlton, C., Ward, R., McCauley, R.D., Brownell, R.L., Guggenheimer, S., Salgado Kent, C. P., Bannister, J.L. 2019b. Southern right whales (*Eubalaena australis*) return to a former wintering calving ground: Fowlers Bay, South Australia. Marine Mammal Science 35: 1438-1462. doi:10.1111/mms.12611.

Charlton, C., Ward, R., McCauley, R.D., Brownell, R.L., Salgado Kent, C., Burnell, S. 2019a. Southern right whale (*Eubalaena australis*), seasonal abundance and distribution at Head of Bight, South Australia. Aquatic Conservation: Marine and Freshwater Ecosystems 29: 576-588. doi:10.1002/aqc.3032.

Chrysafi, A., Kuparinen, A. 2016. Assessing abundance of populations with limited data: Lessons learned from data-poor fisheries stock assessment. Environmental Reviews. 24: 25-38. doi:10.1139/er-2015-0044.

Conn, P.B., Bravington, M.V., Baylis, S., Ver Hoef, J.M. 2020. Robustness of close-kin mark-recapture estimators to dispersal limitation and spatially varying probabilities. Ecology and Evolution10: 5558-5569. doi:10.1002/ece3.6296.

Constantine, R., Jackson, J.A., Steel, D., Baker, C.S. Brooks, L., Burns, D., Clapham, P., Hauser, N., Madon, B., Mattila, D., Oremus, M., Poole, M., Robbins, J., Thompson, K., Garrigue, C. 2012. Abundance of humpback whales in Oceania using photo-identification and microsatellite genotyping. Marine Ecology Progress Series 453: 249-261. doi:10.3354/meps09613.

Cook, J., Rowntree V. 2003. Analysis of inter-annual variation in reproductive success of South Atlantic right whales (*Eubalaena australis*) from photo-identifications of calving females observed off Península Valdés, Argentina, during 1971-2000. International Whaling Commission document SC/55/023.

Cook, J., Rowntree, V., Sironi, M. 2015. Southwest Atlantic right whales: interim updated population assessment from photo-id collected at Península Valdés, Argentina. International Whaling Commission document SC/66a/BRG/23.

Cooke, J.G., Rowntree, V.J., Payne, R. 2001. Estimates of demographic parameters of southern right whales (*Eubalaena australis*) observed off Peninsula Valdés, Argentina. Journal of Cetacean Research and Management Special issue 2: 125-132.

Cope, J.M., Punt, A.E. 2009. Length-based reference points for data-limited situations: Applications and restrictions. Marine and Coastal Fisheries 1: 169–186. doi:10.1577/C08-025.1

Davidson, A.R., Rayment, W., Dawson, S.M., Webster, T., Slooten, E. 2017. Estimated calving interval for the New Zealand southern right whale (*Eubalaena australis*). New Zealand Journal of Marine and Freshwater Research 52: 372-382. doi:10.1080/00288330.2017.1397034.

Dawbin, W.H. 1986. Right whales caught in waters around south eastern Australia and New Zealand during the nineteenth and early twentieth centuries. Reports of the International Whaling Commission Special issue 10: 261-267.

DCCEEW. 2024. National Recovery Plan for the southern right whale *Eubalaena australis*. Department of Climate Change , Energy, the Environment and Water, Canberra.

DEH. 2005. Southern right whale recovery plan 2005 – 2010. Australian Government Department of Environment and Heritage, Canberra.

Derville, S., Torres, L.G., Newsome, S.D., Somes, C.J., Valenzuela, L.O., Vander Zanden, H.B., Baker, C.S., Bérubé, M., Busquets-Vass, G., Carlyon, K., Childerhouse, S.J., Constantine, R., Dunshea, G., Flores, P.A.C., Goldsworthy, S.D., Graham, B., Groch, K., Gröcke, D.R., Harcourt, R., Hindell, M.A., Hulva, P., Jackson, J.A., Kennedy, A.S., Lundquist, D., Mackay, A.I., Neveceralova, P., Oliveira, L., Ott, P.H., Palsbøll, P.J., Patenaude, N.J., Rowntree, V., Sironi, M., Vermeuelen, E., Watson, M., Zerbini, A.N., Carroll, E.L. 2023. Long-term stability in the circumpolar foraging range of a Southern Ocean predator between the eras of whaling and rapid climate change. Proceedings of the National Academy of Sciences of the United States of America. 120(10):e2214035120. doi:10.1073/PNAS.2214035120.

DSEWPaC. 2012. Conservation management plan for the southern right whale: A recovery plan under the Environment Protection and Biodiversity Conservation Act 1999 (2011–2021). Canberra, Australia: Australian Department of Environment.

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.

Evans, K., Patterson, T., Peel, D. 2023. Project 1.29b: NESP Marine and Coastal Hub scoping study: New approaches to monitoring. Subcomponent: Maximising the utility of opportunistic and citizen science datasets for conservation management. Report to the National Environmental Science Program. CSIRO.

Froese, R., Winker, H., Coro, G., Demirel, N., Tsikliras, A.C., Dimarchopoulou, D., Scarcella, G., Deng Palomares, M.L., Dureuil, M., Pauly, D. 2020. Estimating stock status from relative abundance and resilience. ICES Journal of Marine Science 77: 527–538. doi:10.1093/icesjms/fsz230.

Fujiwara M, Caswell H. 2002. Estimating population projection matrices from multi-stage mark-recapture data. Ecology 83: 3257-3265.

Gay, D.M. 1990. Usage summary for selected optimization routines. Computing Science Technical Report 153. AT&T Bell Laboratories. Available at: https://ms.mcmaster.ca/~bolker/misc/port.pdf.

GHD. 2010. Department of Environment, Water, Heritage and the Arts assessment of cetacean recovery plans 2005-2010. Humpback, southern right, blue fin and sei whales. GHD, Brisbane.

Jiao, Y., Cortés, E., Andrews, K., Guo, F. 2011. Poor-data and data-poor species stock assessment using a Bayesian hierarchical approach. Ecological Applications 21: 2691-708. doi:10.1890/10-0526.1.

Kristiansen, K., Nielsen, A., Willestofte-Berg, C., Skaug, H.J., Bell, B. 2016. TMB: Automatic differentiation and laplace approximation. Journal of Statistical Software 70: 1-21. doi:10.18637/jss.v070.i05.

Leaper, R., Cooke, J., Trathan, P., Reid, K., Rowntree, V., Payne, R. 2006. Global climate drives southern right whale (*Eubalaena australis*) population dynamics. Biology letters 2: 289-92. doi:10.1098/rsbl.2005.0431.

Lloyd-Jones, L.R., Bravington, M.V., Armstrong, K.N., Lawrence, E., Feutry, P., Todd, C.M., Dorrestein, A., Welbergen, J.A., Martin, J.M., Rose, K., Hall, J., Phalen, D.N., Peters, I., Baylis, S.M., Macgregor, N.A., Westcott, D.A. 2023. Close-kin mark-recapture informs critically endangered terrestrial mammal status. Scientific Reports 13: 12512. doi:10.1038/s41598-023-38639-z.

Mackay, A.I., Bailleul, F., Carroll, E.L., Andrews-Goff, V., Baker, C.S., Bannister, J., Boren, L., Carlyon, K., Donnelly, D.M., Double, M., Goldsworthy, S.D., Harcourt, R., Holman, D., Lowther, A., Parra, G.J., Childerhouse, S.J. 2020. Satellite derived offshore migratory movements of southern right whales (*Eubalaena australis*) from Australian and New Zealand wintering grounds. PLoS ONE 15: e0231577. doi:10.1371/journal.pone.0231577.

Marcy-Quay, B., Sethi, S.A., Therkildsen, N.O., Kraft, C.E. 2020. Expanding the feasibility of fish and wildlife assessments with close-kin mark-recapture. Ecosphere 11: e03259. doi:10.1002/ecs2.3259.

Nash, M. 2003. The bay whalers. Tasmanian's shore-based whaling industry. Navarine Publishing, Woden, ACT.

Payne, R.S., Rowntree, V.J., Perkins, J.S. 1990. Population size, trends and reproductive parameters of Right Whales (*Eubalaena australis*) off Peninsula Valdés, Argentina. International Whaling Commission document SC/A88/ID1.

Pirzl, R., Murdoch, G., Lawton, K. 2006. Bigfish: computer assisted matching software and data management system for photo-identification. Horsham, Australia: Skadia Pty Ltd.

R Core Team. 2024. R: A language and environment for statistical computing. https://www.r-project.org/.

Rowntree, V.J., Payne, R., Schell, D.M. 2001. Changing patterns of habitat use by southern right whales (*Eubalaena australis*) on their nursery ground at Península Valdés, Argentina, and in their long-range movements. Journal of Cetacean Research and Management Special issue 2: 133-143.

Royle, J.A. 2008. Modelling individual effects in the Cormack-Jolly-Seber model: a state space formulation. Biometrics 64: 364-370. doi:10.1111/j.1541-0420.2007.00891.x.

Smith, J.N., Double, M., Evans, K., Kelly, N. 2023. Relative abundance of the 'western' population of southern right whales (*Eubalaena australis*) from an aerial survey off southern Australia: Final Report on 2022 survey. Report to the National Environmental Science Program, Murdoch University.

Sprogis, K.R., Harcourt, R., Reikkola, L., Childerhouse, S., Zerbini, A.N., Andrews-Goff, V., Carroll, E.L. 2024. Western Australian southern right whale coastal and offshore movements. International Whaling Commission document SC/69B/SH/15.

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. doi:10.3354/esr01031.

Watson, M., Stamation, K., Charlton, C., Bannister, J. 2021. Calving rates, long-range movements and site fidelity of southern right whales (*Eubalaena australis*) in south-eastern Australia. Journal of Cetacean Research and Management 22: 17-27.

Watson, M., Westhorpe, I., Bannister, J., Harcourt, R. and Hedley, S. 2015. Australian Marine Mammal Centre Grants Program Final Report for Project 13/29: Assessment of numbers and distribution of southern right whales in south-east Australia – Year 2, Macquarie University.

Appendix 1

Table A1. Parameters used in the spatial model.

Parameter		Value [95% CI]	Comment/Reference
N0		300 adults (~90-100 adult females)	
Mortality (as survival rate)	Adult	0.972 [0.994,0.983]	Best et al. (2001)
	Juvenile	0.96 [0.94, 0.97]	Chosen to be a slightly lower survival than adults
	Calf	0.913 [0.6, 0.95]	
Sexual maturity		7.88 [7.17, 9.29]	Best et al. (2001)
Time in aggregation/nursery areas		Not specified directly as a function of migration turn date and arrival at nursery. Model set so maximum time is 70 days	Burnell and Bryden (1997)
Detection probability		Varies due to spatial differences but a maximum of 0.8	Best et al. (2001)
Whale swim speed	Adult	45 km/day	Based on tagging data in Mackay et al. (2020)
	Mother + Calf	30 km /day	
Calving cycle	alpha	0.1	
	beta	0.05	Same as the mark-recapture model
	Gamma	0.01	
Age at sexual maturity		7.88 years [7.17, 9.29]	Best et al. (2001)

Marine and Coastal

National Environmental Science Program

CONTACT

Name: David Peel

Email: david.peel@data61.csiro.au

Web: nespmarinecoastal.edu.au

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