NIWA
Taihoro Nukurangi

NZ sea lion: demographic assessment of the causes of decline at the Auckland Islands

Demographic model options: demographic assessment

Prepared for Department of Conservation

August 2014

Prepared by:
Jim Roberts, Dan Fu, Ian Doonan, Chris Francis

For any information regarding this report please contact:

Rosemary Hurst
Chief Scientist, Fisheries
Fisheries
+64-4-386 0867
Rosemary.Hurst@niwa.co.nz

301 Evans Bay Parade
Hataitai
Wellington 6021

Phone +64 4 386 0300

NIWA CLIENT REPORT No: WLG2014-60
Report date: August 2014
NIWA Project: POP2012-02

© All rights reserved. This publication may not be reproduced or copied in any form without the permission of the copyright owner(s). Such permission is only to be given in accordance with the terms of the client's contract with NIWA. This copyright extends to all forms of copying and any storage of material in any kind of information retrieval system.

Whilst NIWA has used all reasonable endeavours to ensure that the information contained in this document is accurate, NIWA does not give any express or implied warranty as to the completeness of the information contained herein, or that it will be suitable for any purpose(s) other than those specifically contemplated during the Project or agreed by NIWA and the Client.

Contents

Executive summary **10**

1 Introduction **11**

2 Methods **12**

2.1 Methodological overview 12

2.2 Demographic assessment 14

2.2.1 Observations 14

Mark-resighting observations 14

Pup census observations 17

Age distribution observations 18

2.2.2 SeaBird demographic model 19

Partitioning 19

Time steps 21

Transitions 21

2.2.3 Parameter estimation 22

Survival 22

Likelihoods for mark-recapture observations 23

Likelihoods for absolute abundance, by-catch or parameter observations 26

Likelihoods for age distribution observations 26

2.2.4 Functional forms 27

Age-at-first-pupping 27

Survival 27

Pupping rate 27

2.2.5 Model development and implementation 28

3 Results **31**

3.1 Demographic assessment of females at Sandy Bay 31

3.1.1 Exploratory analysis of age, cohort and year effects on demographic rate estimates 31

3.1.2 Model development 33

3.1.3 MCMC parameter estimates 34

3.1.4 Additional model validation 37

Breakpoint analysis 37

Retrospective analysis 38

Estimation of tag loss rate & models fit to pup census observations 39

Models fits to age distribution observations 40

3.2 Demographic assessment of females at Dundas 40

4 Discussion 42

4.1 Model configuration, observations and parameter estimation 42

4.2 Age and cohort effects on demographic rate estimates 45

4.3 Estimation of pupping-related parameters 45

4.4 Estimation of survival 46

4.5 Use of demographic rate estimates in the correlative assessment 47

4.6 The demographic causes of population decline at the Auckland Islands 48

5 Acknowledgements 48

6 References 49

Appendix A Summary plots of mark-recapture observations 51

Appendix B Model configuration and estimates 53

Model configuration 53

Posterior distributions of all parameters in model run 8 67

Assessment of degree of correlation between parameter estimates from model run 8 79

Estimates from model validation runs 82

Demographic assessment of females at Dundas 87

MCMC parameters estimates 87

Posterior distributions of all parameters in model run 9 89

Assessment of degree of correlation between parameter estimates from model run 9 97

Appendix C Exploratory analysis of mark-type effect on individual resighting frequency on females at Sandy Bay. 99

Appendix D Analysis of cohort effects on pupping parameters using estimates from population model runs 100

Appendix E Age-specific survival estimates for New Zealand sea lions *Phocarctos hookeri* (MARK assessment) 102

Tables

Table 1-1: Project milestones and outputs. 12

Table 2-1: Estimated annual number of female pups that died prior to tagging at Sandy Bay and Dundas; and calculated number of "phantom tags" to be added to mark recapture observations 16

Table 2-2: Annual female pup count estimates at Sandy Bay (used in model run 12). 17

Table 2-3: Age distribution of lactating females at Sandy Bay (used in model run 13). 18

Table 2-4: Pupping status definitions used in this assessment. 21

Table 2-5: Symbols used in likelihood equations. 23
Table 2-6: Formulae for calculating negative-log likelihoods for different error distributions. 26
Table 2-7: Model configurations used in this assessment. 30
Table 3-1: Demographic parameter estimates to be carried forward to the correlative modelling phase of the project. 34
Table 3-2: Annual tag loss rates estimates for females at Sandy Bay (model run 11) compared with estimates from other assessments. 39
Table 4-1: Summary of model configurations used in demographic assessments of NZ sea lions at the Auckland Islands. 43

Table B-1: Model configurations used in this assessment; “MR” - tag-resighting data, “PP” - pup production, “AD” - age distribution. 53
Table B-2: Detailed model configuration of all models developed during the model optimisation process. 54
Table B-3: Demographic parameter estimates to be carried forward to the correlative modelling phase of the project. 66

Figures

Figure 1-1: Annual pup census estimates of NZ sea lion at the main breeding rookeries of the Auckland Islands. 11
Figure 2-1: Methodological overview of project approach. 13
Figure 2-2: Summary of mark-resighting observations of animals tagged as pups and resighted at Sandy Bay with data subsets and pupping status described as above. 15
Figure 2-3: Summary of mark-resighting observations of animals tagged as pups and resighted at Dundas with data subsets and pupping status described as above cap. 15
Figure 2-4: Partitioning and transitions used in candidate demographic models (Partitioning Type I). 20
Figure 2-5: Model partitioning used in model runs estimating tag loss parameters (Partitioning Type II). 20
Figure 3-1: Parameter estimates for model exploring age-effects on survival, resighting probability and probability of pupping of females at Sandy Bay (model run 1). 32
Figure 3-2: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). 36
Figure 3-3: MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay (model run 8). 36
Figure 3-4: MCMC estimates of pupping probability of female NZ sea lions at Sandy Bay (model run 8). 36
Figure 3-5: Year group estimates from the breakpoint analysis and MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). 37

Figure 3-6: Year group estimates from the breakpoint analysis and; MCMC estimates of probability of puppers pupping in year +1 (left) and non-puppers pupping in year+1 (right) of female NZ sea lions at Sandy Bay (model run 8). 38
Figure 3-7: Year group estimates from the breakpoint analysis and MCMC estimates of age-at-first-pupping parameters $\Pr B1st_a$ (left) and *oddsmult* (right) of female NZ sea lions at Sandy Bay (model run 8). 38
Figure 3-8: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Dundas (model run 9). 41
Figure 3-9: Comparison of MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay and Dundas (model runs 8 and 9). 41
Figure 3-10: MCMC estimates of age-specific survival of female NZ sea lions at Dundas (model run 9). 41

Figure A-1: Summary of mark-resighting observations of female NZ sea lions flipper-tagged as pups at Sandy Bay and resighted at Sandy Bay. 51
Figure A-2: Summary of mark-resighting observations of female NZ sea lions flipper-tagged as pups at Dundas and resighted at Dundas. 52
Figure A-3: Summary of mark-resighting observations of female NZ sea lions flipper-tagged as pups at Dundas and resighted at Sandy Bay. 52
Figure B-1: Estimated parameter values for model exploring age-effects on survival, resighting probability and probability of pupping (model run 1). 55
Figure B-2: Model estimates of survival for model exploring cohort-effects on survival, resighting probability and probability of pupping of females at Sandy Bay (model run 2). 56
Figure B-3: Scatterplot of model estimates of survival. 57
Figure B-4: Model estimates of resighting probability for model exploring cohort-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 2). 57
Figure B-5: Model estimates of pupping probability for model exploring cohort-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 2). 58
Figure B-6: Model estimates of survival for model exploring year-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 3). 59
Figure B-7: Model estimates of resighting probability for model exploring year-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 3). 60
Figure B-8: Model estimates of pupping probability for model exploring year-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 3). 61
Figure B-9: : Fits of tag resighting frequency by cohort (one plot for each cohort) and year of resighting (y-axis), comparing model estimates (“e”) and observed values (“o”). 62
Figure B-10: Effect of inclusion of phantom tags on model estimates of cohort survival to age 2. 63
Figure B-11: MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay (model run 8). 63

Figure B-12: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). 64
Figure B-13: MCMC estimates of age/status-specific resighting probability of female NZ sea lions at Sandy Bay (model run 8). 64
Figure B-14: MCMC estimates of pupping probability of female NZ sea lions at Sandy Bay (model run 8). 65
Figure B-15: MCMC estimates of age at maturation parameters $\Pr B1st_a$ (left) and *oddsmult* (right) of female NZ sea lions at Sandy Bay (model run 8). 65
Figure B-16: Cumulative proportion of individuals that will have pupped at age, derived from year-varying estimates of parameters from model run 7. 65
Figure B-17: Posterior distributions of MCMC estimates of survival at age 0 (model run 8). 67
Figure B-18: Posterior distributions of MCMC estimates of survival at age 1 (model run 8). 68
Figure B-19: Posterior distributions of MCMC estimates of cohort survival to age 2 (model run 8). 69
Figure B-20: Posterior distributions of MCMC estimates of survival at age 2-5 (model run 8). 70
Figure B-21: Posterior distributions of MCMC estimates of survival at age 6-14 (adu_1) and 15+ (adu_2) (model run 8) . 71
Figure B-22: Posterior distributions of MCMC estimates of age-at-first-pupping parameter PrB1sta (model run 8). 72
Figure B-23: Posterior distributions of MCMC estimates of age-at-first-pupping parameter oddsmult (model run 8). 73
Figure B-24: : Posterior distributions of MCMC estimates of the probability of non-puppers pupping in yr+1 (model run 8). 74
Figure B-25: Posterior distributions of MCMC estimates of the probability of puppers pupping in yr+1 (model run 8). 75
Figure B-26: Posterior distributions of MCMC estimates of annual resighting probability at ages 1-2 and 3 (model run 8). 76
Figure B-27: Posterior distributions of MCMC estimates of annual resighting probability at ages 4-5, 6 and 7 (model run 8). 77
Figure B-28: Posterior distributions of MCMC estimates of annual resighting probability of non-puppers (model run 8). 78
Figure B-29: Correlation coefficients between MCMC annual estimates of age-specific resighting probability and survival. 79
Figure B-30: Correlation coefficients between MCMC annual estimates of survival comparing different age groupings. 80
Figure B-31: Correlation coefficients between MCMC annual estimates of maturation parameters and pupping rate estimates. 81
Figure B-32: Year group estimates from the breakpoint analysis and MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). 82
Figure B-33: Year group estimates from the breakpoint analysis and; MCMC estimates of probability of pupping. 82
Figure B-34: Year group estimates from the breakpoint analysis and MCMC estimates of age-at-first-pupping parameters $\Pr B1st_a$ (left) and *oddsmult* (right) of female NZ sea lions at Sandy Bay (model run 8); . 82

Figure B-35: Retrospective analysis showing dataset time series and year effects on estimates. 83
Figure B-36: Retrospective analysis showing dataset time series and year effects on estimates. 83
Figure B-37: Estimates of survival at ages 0 and 6-14 for model run with tag loss parameters. 84
Figure B-38: Model fits to pup census observations. 84
Figure B-39: Model estimates of survival, pupping probability and resighting probability from the model fit to pup census observations (model run 12) compared with MCMC median estimates and confidence intervals (model run 7). 85
Figure B-40: Model fits to age distribution observations (model run 13). 86
Figure B-41: : Model estimates of survival at age 0 and 6-14 from the model fit to age distribution observations (model run 13) compared with MCMC median estimates and confidence intervals (model run 7). 86
Figure B-42: MCMC estimates of age-specific survival of female NZ sea lions at Dundas (model run 9). 87
Figure B-43: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Dundas (model run 9). 87
Figure B-44: Comparison of MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay and Dundas (model runs 8 and 9). 88
Figure B-45: Comparison of MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay and Dundas (model runs 8 and 9). 88
Figure B-46: Posterior distributions of MCMC estimates of survival at age 0 (model run 9).89
Figure B-47: Posterior distributions of MCMC estimates of survival at age 1 (model run 9).90
Figure B-48: Posterior distributions of MCMC estimates of cohort survival to age 2 (model run 9). 91
Figure B-49: :Posterior distributions of MCMC estimates of survival at age 2-5 (model run 9). 92
Figure B-50: Posterior distributions of MCMC estimates of survival at age 6-14 (adu_1) and 15+ (adu_2) (model run 9). 93
Figure B-51: Posterior distributions of MCMC estimates of annual resighting probability at ages 1-2 and 3 (model run 9). 94
Figure B-52: Posterior distributions of MCMC estimates of annual resighting probability at ages 4-5, 6 and 7 (model run 9). 95
Figure B-53: Posterior distributions of MCMC estimates of annual resighting probability at age 8+ (model run 9). 96
Figure B-54: Correlation coefficients between MCMC annual estimates of survival comparing different age groupings. 97
Figure B-55: Correlation coefficients between MCMC annual estimates of age-specific resighting probability and survival. 98
Figure C-1: Cohort effect on resightings of females at Sandy Bay over lifetime that were recorded as PIT-tagged only at the time of resighting (and not flipper tagged or branded) as a proportion of resightings from all mark types. 99
Figure D-1: Pupping rate derived from model estimates of numbers in each model partition, from the model run fit to pup census observations (model run 12). 100
Figure D-2: Cohort effects on the proportion of individuals that have pupped at age. 101

Reviewed by	Approved for release by
Vidette McGregor	Dr Rosie Hurst

Executive summary

- A demographic assessment was conducted of female NZ sea lions, aimed at identifying the proximate demographic causes of population change of NZ sea lion populations at the Auckland Islands, focussing on the two largest breeding colonies at Sandy Bay (Enderby Island) and Dundas.
- State space demographic models fitted to mark-recapture, pup census and age distribution observations were developed using NIWA's demographic modelling software SeaBird to estimate year-varying survival, probability of pupping and age-at-first-pupping.
- For the Sandy Bay population, variation was observed in all demographic rate estimates when using the optimal model configuration (model run 8). Generally low pupping rates (including occasional years with very low estimates), a declining trend in cohort survival to age 2 since the early 1990s and relatively low adult survival (age 6-14) since 1999 may be sufficient to explain declining pup counts at Sandy Bay since the late 1990s. However, the lack of resighting effort prior to 1998 limits the assessment of demographic rates during the period of increasing pup production prior to 2000.
- Similar time-trends in survival at age were obtained with respect to year for the Dundas population when adopting a similar model configuration to that used for Sandy Bay (model run 9).
- The demographic rate estimates obtained for Sandy Bay were then used in a correlative analysis aimed at identifying the ultimate causes of population change, which accompanies this report (Roberts et al., 2014).

1 Introduction

New Zealand sea lions (*Phocarctos hookeri*) are listed as Nationally Critical (Baker et al., 2009), they have a limited breeding range (almost all pupping at Auckland Islands and Campbell Island in the NZ Sub-Antarctic) and an approximate 40% decline in pup production has been observed at the Auckland Islands between the late-1990s and 2012 (field seasons runs from 1 December to 30 November, denoted by year end, e.g. 2012 = 2011/12) (Chilvers 2012), with all rookeries showing a declining trend (Childerhouse et al., 2013) (Figure 1-1). A number of candidate causes of this decline have been identified including: the direct and indirect effects of fishing, disease-related mortality, predation, genetic bottleneck effects, changes in ocean climate and others (Robertson & Chilvers, 2011). However, despite a large body of research on this population, the proximate demographic and ultimate causes of the decline remain poorly understood.

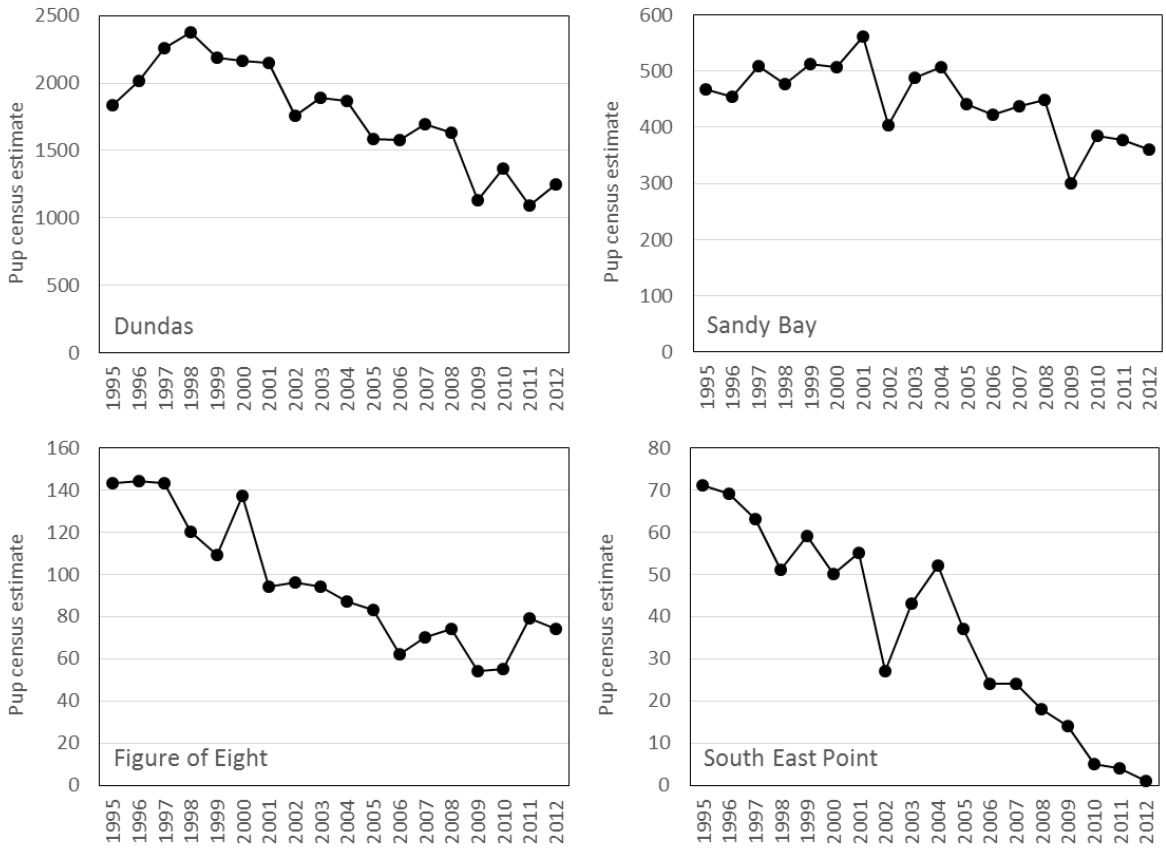

Figure 1-1: Annual pup census estimates of NZ sea lion at the main breeding rookeries of the Auckland Islands. (Childerhouse et al., 2013)

This project broadly aims to determine the factors driving the decline of New Zealand sea lions at the Auckland Islands. The project objectives can be divided into two components:

1. To identify which demographic parameters are the key drivers of the observed population decline at the Auckland Islands (e.g. do we see variation in survival or breeding rates and are there differences comparing sub-populations?).

2. To identify potential demographic mechanisms through which both the direct and indirect effects of fishing can impact on sea lion population size at the Auckland Islands, or increase susceptibility of the population to such effects (e.g. if we see variation in juvenile survival then what are the probable biological mechanisms for this decline – with a focus on the potential direct/indirect effects of fishing?).

This is the draft final report in fulfilment of project milestone 5, summarising a demographic assessment that addressed the first of these project objectives (Table 1-1). The assessment focussed on the estimation of demographic rates for the female component of the population.

Table 1-1: Project milestones and outputs.

Project milestone	Description of outputs
1 Data obtained	Relevant data sets obtained, groomed and exploratory analyses complete. Presentation of data summary and methodology to the CSP Technical Working Group.
2 Model options developed	A report describing a number of candidate models for conducting the analyses. Presentation of modelling options to the CSP Technical Working Group.
3 Final model(s) developed	One (or more) model options are further developed, with due consideration of feedback from technical review of model options. Presentation of the final model(s) to the CSP Technical Working Group.
4 Initial results	A report detailing initial results from the final model(s). Presentation of results to the CSP Technical Working Group.
5 DRAFT Final Report	A manuscript of a draft final report(s) describing all activities, data collected, results found and recommendations made under each specific objective. Presentation of results to the CSP Technical Working Group.
6 Final Report	Final Report suitable for DOC Publication

2 Methods

2.1 Methodological overview

The research conducted in this project has been divided into two components, which address the project objectives in the order in which they were presented above (Figure 2-1):

- **A demographic modelling component**, which dealt with the estimation of an annual time series in key demographic rates, i.e. survival-at-age, pupping probability of different demographic groupings, or maturation. This had the aims of:
  - Identifying the demographic processes that are likely to be driving the decline in the NZ sea lion population at the Auckland Islands (proximate causes of decline)

- Providing a time-series of demographic rates to be used in the second project component.

- **A correlative analysis component**, which used the demographic rate estimates from the first project component and related them to biological (e.g. pup mass or milk quality), environmental (e.g. climate indices) and fishery-related correlates (e.g. estimated captures relating to fishing operations) to identify the ultimate causes of the decline in the Auckland Islands population.

Here we report on the first of these project components: a demographic modelling assessment of female NZ sea lions at the Auckland Islands. The correlative analysis is reported on separately (Roberts et al., 2014), though aspects of model selection, precision of parameter estimates and associated biases are highlighted in the discussion, where relevant to their usage in the correlative assessment.

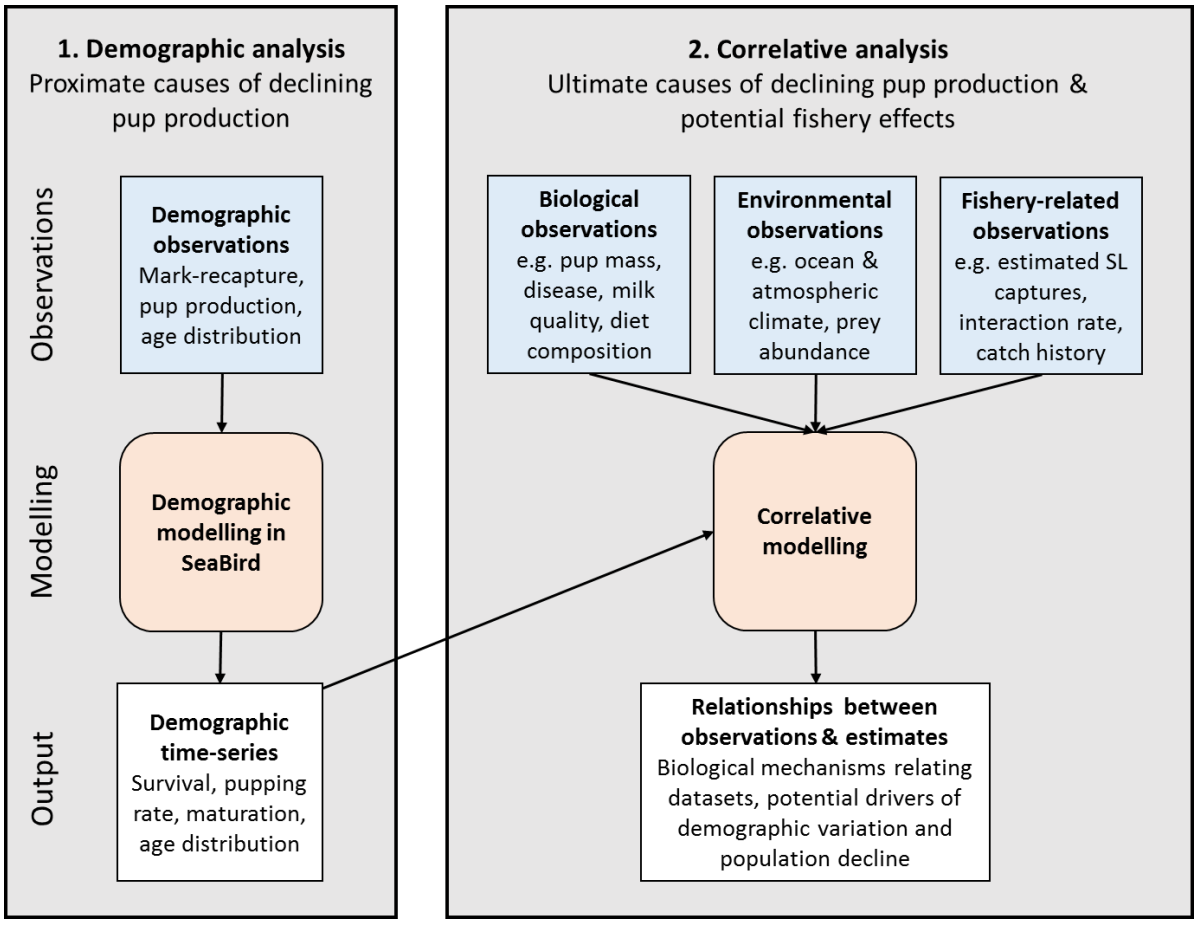

Figure 2-1: Methodological overview of project approach. SeaBird is NIWA's mark-resighting analysis package.

2.2 Demographic assessment

State space demographic models were developed using NIWA's demographic modelling package, SeaBird (Francis & Sagar, 2012) in order to estimate year-varying survival, pupping rates and age-at-first-pupping of female New Zealand sea lions at the Auckland Islands. Candidate models were fitted to mark-recapture observations, pup census estimates and age distribution observations.

SeaBird software has already been used to conduct demographic assessments of four NZ seabird species (e.g. Francis & Sagar 2012). SeaBird allows the analysis of individual (*i.e.* non-aggregated) mark-resighting observations and integrated assessment modelling using different observation types, with Bayesian or likelihood based parameter estimation. Model partitioning (*e.g.* age, area, or breeding status), transitions and equations representing demographic processes are all user-defined.

2.2.1 Observations

Mark-resighting observations

Mark-resighting observations were extracted from the NZ sea lion demographics database maintained by Dragonfly Science (downloaded 18/12/2012):

- A subset of the data was taken including only observations of females tagged as pups at Sandy Bay, Enderby Island (from 1990-1993 & 1998-2011) and resighted at Sandy Bay (from 1999-2012). The assessment of the Dundas population used observations of females tagged as pups and resighted at Dundas Island.
- Animals branded as pups in 2000 were omitted from the assessment as they were not affected by tag loss and the first models did not estimate tag loss rates of non-branded animals. In addition pups were branded in only one tagging year (2000).
- Observations where a chip ID was recorded though the tag ID was not were also omitted from the analysis
- Pupping state (and hence partition to which an observed individual was assigned in a particular year).

All models were fitted to observations of individuals that were flipper-tagged as pups only. Branded and PIT-tagged individuals have a different resighting probability than individuals that are flipper-tagged only (Chilvers & MacKenzie 2010; MacKenzie 2012) and would have necessitated an additional set of partitions for each mark-recapture observation type. Models configured to estimate tag loss using only mark-recapture observations of flipper-tagged individuals required a very large number of partitions (see Partitioning in 2.2.2).

Plots summarising aggregated mark-resighting observations by cohort (pup tagging year), year of resighting and pupping status are given in Figure 4 2 and Figure 4 3.

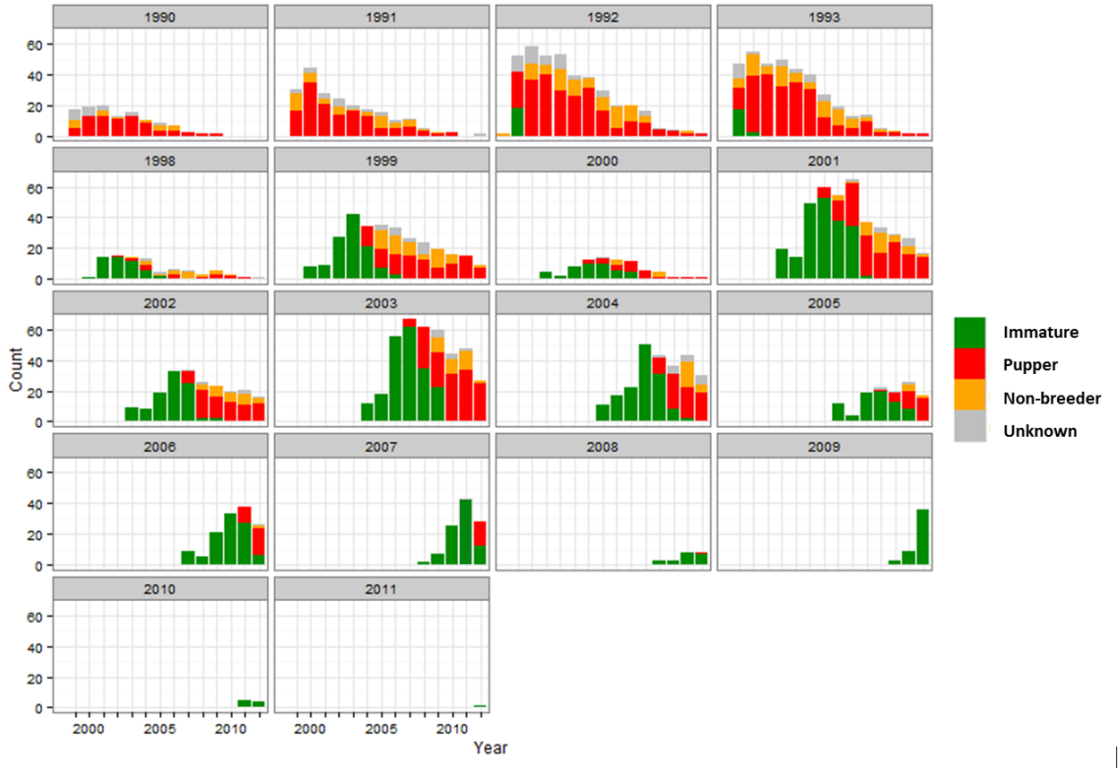

Figure 2-2: Summary of mark-resighting observations of animals tagged as pups and resighted at Sandy Bay with data subsets and pupping status described as above. Cohort birth year is a banner above each plot, x-axis is the resighting year.

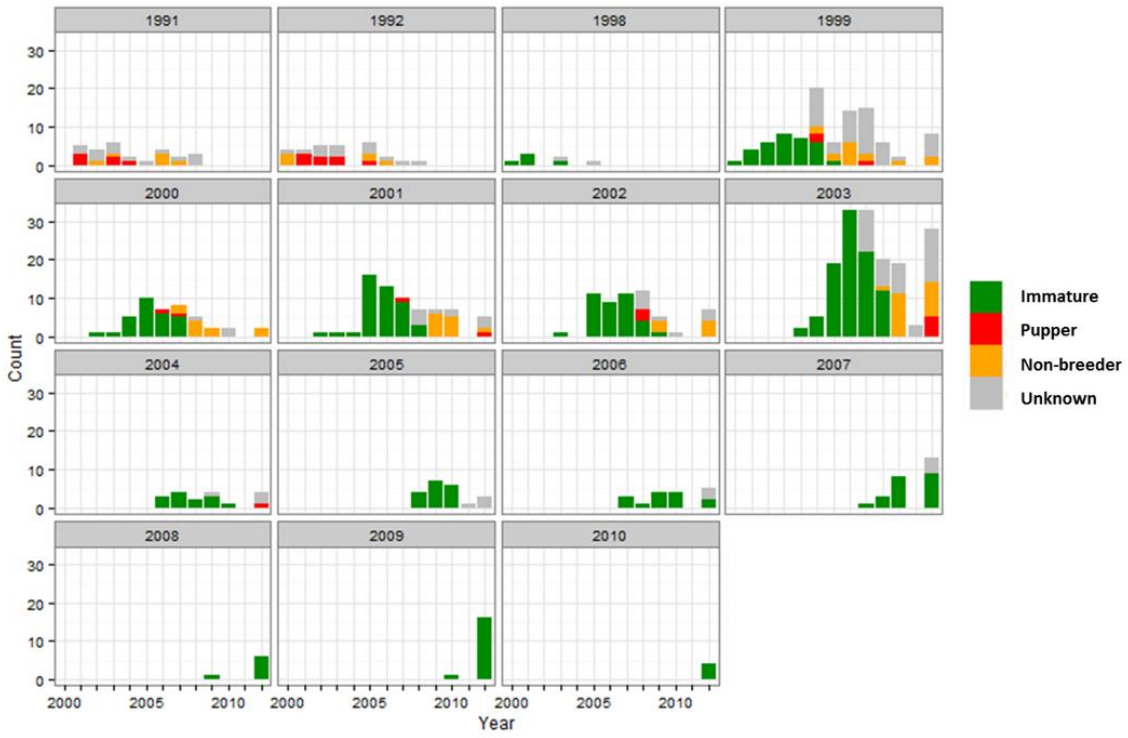

Figure 2-3: Summary of mark-resighting observations of animals tagged as pups and resighted at Dundas with data subsets and pupping status described as above cap. Cohort birth year is a banner above each plot, x-axis is the resighting year.

A number of pups are reported as dead at the time of tagging. Not accounting for these would cause survival at age 0 to be overestimated. For each year, a number of "phantom tags" were therefore assigned to these dead pups and included in the mark-recapture observations as not observed in all subsequent resighting years. Because unobserved tags are indicative of mortality, this allowed observations of dead pups to be included in the model and used to inform estimation of survival. At Sandy Bay the annual number of phantom tags was assumed to be 50% of the number of pups reported dead at the time of flipper-tagging each season (Childerhouse et al., 2013), to give the female component of dead pups. At Dundas, not all pups were tagged each year (typically less than half). For the Dundas population, the annual number of phantom tags was taken to be 50% (female component) of the product of annual censes estimate of dead pups and the proportion of the annual censes estimate of pups that were tagged each year. Counts of dead pups were not routinely conducted in tagging years 1990-1993 and the population-specific pup mortality rate averaged across 1998-2012 (7.57% at Sandy Bay and 11.65% at Dundas) was used to obtain the number of phantom tags from the number of individuals tagged in these earlier years (Table 2-1).

Table 2-1: Estimated annual number of female pups that died prior to tagging at Sandy Bay and Dundas; and calculated number of "phantom tags" to be added to mark recapture observations

	Dundas				Sandy Bay
Tag year	Dead pups	Total pup count	Tagged pups	Phantom tags	Phantom tags
1990			0	0	11*
1991			88	10*	14*
1992			100	12*	17*
1993			0	0	15*
1994			0	0	0
1995			0	0	0
1996			0	0	0
1997			0	0	0
1998	313	1 187	185	49	5
1999	115	1 093	232	24	20
2000	62	1 082	190	11	12
2001	173	1 074	185	30	18
2002	181	878	200	41	42
2003	168	946	263	47	40
2004	60	935	50	3	17
2005	37	794	310	14	15
2006	116	791	317	47	20
2007	53	847	277	17	12
2008	62	818	310	23	12
2009	34	566	298	18	6
2010	76	685	315	35	11
2011	NA	NA	0	0	10

*Average pup mortality rate across years 1998-2012 used to obtain the number of phantom tags in 1990-1993, given the number of sea lions tagged in these years

Pup census observations

In model runs where pup census data were used, the model estimated number of breeders in a year was fitted to census estimates of annual pup production at Sandy Bay, Enderby Islands, for all years from 1990-2012. These were the estimates of total pup production, i.e. inclusive of pups recorded as dead or alive. All observations over this time period have been attributed a high level of confidence (level "1" or "2", Table 1 of Breen *et al.*, 2012). The estimated number of female pups was assumed to be half the census estimate (i.e. a 50:50 male-to-female sex ratio) (Table 2-2).

Table 2-2: Annual female pup count estimates at Sandy Bay (used in model run 12).

Year	Female pup count estimate
1990	217
1991	214.5
1992	244.5
1993	212
1995	233.5
1996	227.5
1997	254.5
1998	238.5
1999	256.5
2000	253
2001	281
2002	201.5
2003	244.5
2004	254
2005	220.5
2006	211
2007	218.5
2008	224
2009	150.5
2010	192.5
2011	189
2012	180.5

Age distribution observations

Model estimated age-frequencies of breeding individuals by year were fitted to age distribution observations of lactating females at Sandy Bay in 1998, 1999, 2000 and 2001 (Childerhouse et al., 2010a). The raw data were supplied by Simon Childerhouse (05/02/2013); see Table 2-3.

Table 2-3: Age distribution of lactating females at Sandy Bay (used in model run 13).

Age (years)	1998	1999	2000	2001
3	0	0.0069	0.0072	0
4	0	0.0138	0.0072	0.014
5	0	0.0414	0.0217	0.021
6	0.0667	0.131	0.0435	0.035
7	0.4667	0.1379	0.1232	0.042
8	0	0.1517	0.1812	0.1678
9	0	0.1034	0.1739	0.1748
10	0.0667	0.0621	0.1014	0.1678
11	0.0667	0.0828	0.0507	0.0769
12	0.1333	0.0414	0.029	0.028
13	0.1333	0.069	0.058	0.042
14	0	0.0345	0.0145	0.014
15	0	0.0552	0.0362	0.035
16	0	0.0276	0.029	0.035
17	0.0667	0.0069	0.0217	0.021
18	0	0.0069	0.0217	0.014
19	0	0.0138	0.029	0.028
20	0	0.0207	0.0507	0.0839

2.2.2 SeaBird demographic model

Partitioning

The set of states that any sea lion can be in for a particular year is called the partition. The model partitioned the population into ages 1 to 20, with the last age class being a plus group. Each age class was further partitioned into a number of states depending on whether the individual was reproductively mature or had produced a pup in that year. The partition therefore accounted for numbers of sea lions by age and pupping status within an annual cycle, where movement between partition states were determined by the transition parameters. Sea lions entered the partition as pups and were removed by mortality.

Three partition schemes were used in the candidate models:

- **Partitioning I** considered that sea lions between ages 0 to 7 are "immature" if they had never pupped (sea lions were assumed not to pup until age 4); a sea lion between age 4 and 20+ became a "pupper" if she produced a pup in that year, or a "non-pupper" if she had produced a pup in a previous year though not in that year. With this partition scheme, the model was able to estimate the probability of first-time pupping at age (Figure 2-4).
- **Partitioning II** considered that sea lions between age 0 and 3 were "immature" and sea lions between age 4 and 20 were either puppers or non-puppers depending on whether a pup was produced in that year. This partition scheme did not differentiate between sea lions that never pupped and those that were "resting" in-between breeding seasons. It was a slight simplification of Partitioning I in that it consisted of fewer partition cells (therefore fewer transitions), and was used in models estimating tag loss rate. Tagging status (number of tags on an individual) was incorporated as a partition variable in addition to age and pupping status. Therefore each of the immature, pupper, and non-pupper state for each age class was further split into three sub-states indicating the number of tags associated with an individual. The tagging statuses considered were 2 (sea lions with both flipper tags), 1 (sea lions with either left or right flipper tag missing) and 0 (sea lions with both tags missing). This partitioning scheme allowed the rate of tag-loss to be estimated within the model (Figure 2-5).
- **Partitioning III** followed the scheme of Partitioning I, except that maturity and pupping status were not defined (there were 21 partitions in all for ages 0 to 20+). This partitioning was used in models used to estimate survival-at-age of the Dundas population.

Accordingly each re-sighting observation in the mark-recapture dataset was assigned a state based on age and pupping status (as well as the number of remaining tags for the tag-loss model). The pupping status was based on the strict definition of puppers as described by Mackenzie & Chilvers (2012), see also Table 2-4.

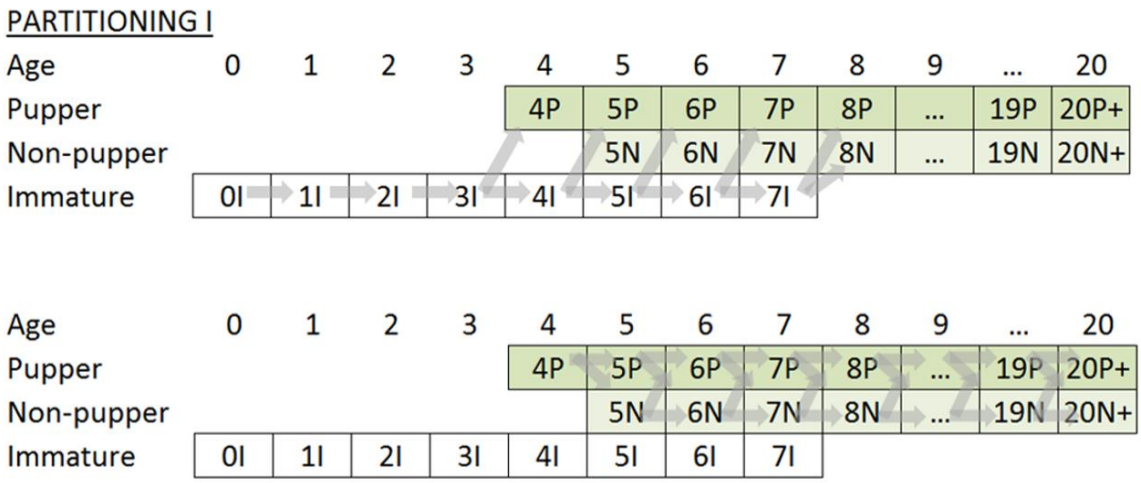

Figure 2-4: Partitioning and transitions used in candidate demographic models (Partitioning Type I). Possible transitions from immature partition at top; transition from "mature" partitions at middle).

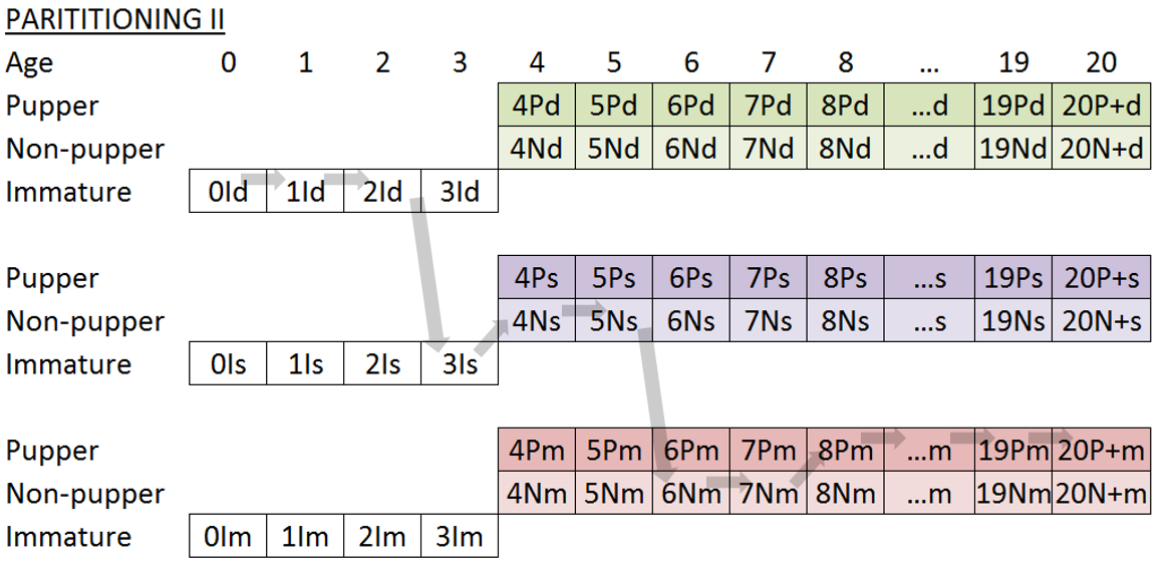

Figure 2-5: Model partitioning used in model runs estimating tag loss parameters (Partitioning Type II). Cell notation is <age><breeding status><number of tag code>, where breeding status is "I" = immature, "N" = did not pup in year-1, and "P" = pupped in year–1, and the number of tags is given by the "d" = double (2 tags); "s" = single (1 tag); "m" = missing (0 tags). In this illustrative example (grey arrows), the sea lion was double flipper tagged as a pup, lost one tag between ages 2 and 3, lost the other tag between ages 5 and 6 and produced a first pup at age 8. Note that there are no resighting observations of individuals in the bottom set of partitions for which there are no tags.

Table 2-4: Pupping status definitions used in this assessment.

Observed status	Model state
Female 3-5 YO, never pupped	Immature
Yearling	Immature
Yearling or 2 YO, suckling	Immature
New born or pup	Immature
Female, confirmed pupped	Pupper
Female, probably pupped	Pupper
Female, pup died	Pupper
Adult female, confirmed no pup	non-pupper
Female, < 3 sightings, no pup	non-pupper
Pregnant female	pupper or non-pupper
Female, nursing yearling	pupper or non-pupper
Dead	pupper or non-pupper or immature
Idle	pupper or non-pupper or immature

Time steps

There can be one or more time steps within a year, with the observation of state at time step t_{trans}. This allowed various process to occur before and after the time of observations, such as recruitment, transition processes, or fishing mortality.

The symbols, n_{ity} and n'_{ity} represent the number of sea lions in the *i*th class of the partition at time step *t* in year *y* before and after the partition process, respectively.

Transitions

Transitions move sea lions from one class of the partition to another as they develop or age (increased from age *a* to age *a*+1) or change behaviour (e.g., do not pup in one year, then produce a pup in the next).

Transitions were achieved using $n'_{ity} = T_{ij} n_{ity}$, where *T*, referred to as the *transition matrix*, is such that T_{ij} is the probability that an individual in partition class *i* will move to class *j* in one time step.

2.2.3 Parameter estimation

Survival

Survival s_{iy}, is the proportion of sea lions in the *i*th partition class that survive natural mortality to the end of year *y*. Potentially we can define f_t, the fraction of the annual natural mortality that occurs before time step *t* in each year, which gives $s_{iy}^{f_t}$. Survival for the whole year is given by $s_{iy} = \prod_t s_{iy}^{f_t}$. Incidental moralities, e.g., from fishing, have been ignored in this investigation although SeaBird can handle them.

Proportional mortality: the user can specify that an observation in time step *t* in year *y* occurred part-way through the mortality that occurred in that time step. Thus, if *p* is the proportion of mortality that had occurred before the observation we need to define $n_{ity;p}$, the number of individuals in the *i*th class at the time of the observation.

SeaBird offered two options for calculating $n_{ity;p}$:

weighted sum (default): $n_{ity;p} = (1-p)n_{ity} + pn'_{ity} = (1-p+pT_{ity})n_{ity}$ and

weighted product: $n_{ity;p} = n_{ity}^{1-p} n'^{p}_{ity} = T_{ity}^{p} n_{ity}$

where n_{ity} and n'_{ity} (= $s_{ity}n_{ity}$) are the numbers before and after the mortality in this time step.

Objective function

Parameter estimation was by maximum likelihood. The objective function is given by:

$$-\sum_i \log\left[L(\mathbf{p} \mid O_i)\right]$$

where **p** is a vector of the free parameters, *L* the likelihood function and O_i the *i*th observation.

For Bayesian fitting the objective functions is:

$$-\sum_i \log\left[L(\mathbf{p} \mid O_i)\right] - \log\left[\pi(\mathbf{p})\right]$$

where π is the joint prior density of the parameters **p**.

In this assessment, uninformative uniform priors were used for all parameters.

Likelihoods for mark-recapture observations

Symbols used in likelihood equations are presented in Table 2-5.

Table 2-5: Symbols used in likelihood equations.

Symbol	Comment
b	unique tag code
$y_{b,\text{tag}}$	The year the b^{th} sea lion was tagged
$y_{b,\text{last}}$	last year that the b^{th} sea lion was observed
O_{by}	observed state for the b^{th} sea lion in year y
L_{by}	likelihood of the observation in year y given the observation in year y–1
t_{trans}	time within a year that the state of a sea lion is observed
X_{iyj}	the probability that a sea lion in stage i in year y will be alive and in stage j in the following year
$s_{\text{tot},ity}$,	survival of a sea lion during time step t in stage i in year y, includes fishery morality, if used.
p	the proportion of that mortality which had occurred before an observation in a time step. Thus, we have subscripts like $n_{ity;p}$, to denote the number of individuals in the ith class at the time of the observation. For survival, we have $s_{\text{tot},ity;p} = 1 - p + ps_{\text{tot},ity}$.
$r_{j,y}$	resight probability, the probability of seeing a tagged individual in year y, given that it is alive and in the ith partition class
P_{biy}	the probability, given the observations on the sea lion with tag number b up to and including year y, that this sea lion is in non-composite stage i
$Nstage$	The number of stages

Mark recapture observations were inputted as a series of observations of individual tagged sea lions, including for each sea lion: the tag number b (a unique sea lion number), the year tagged $y_{b,\text{tag}}$, the last year of observation $y_{b,\text{last}}$, and the 'state' of the sea lion O_{by} in each year from $y_{b,\text{tag}}$ to $y_{b,\text{last}}$, where the 'state' indicates whether the sea lion was observed and, if so, which class of the partition the sea lion was in.

The negative log-likelihood for the sea lion with tag number b is given by $-\Sigma_y \log(L_{by})$, where the summation is over $y_{b,tag} < y \le y_{b,last}$ and L_{by} is the likelihood of the observation in year y given the observation in year y–1. The likelihood calculation is a generalization of that used in the Cormack-Jolly-Seber model (Cormack 1964). Specifically, when the model partition is of size 1 (so the mark-recapture observations are simply presence/absence) the calculated likelihood is exactly the same as in the Cormack-Jolly-Seber model. SeaBird generalizes this likelihood by allowing multi-state observations (partition size greater than 1) and uncertainty about state (as expressed in composite observations).

Let X_{iyj} be the probability that a sea lion in stage i in year y will be alive and in stage j in the following year. This may be calculated by multiplying the overall survivals ($s_{\text{tot},ity}$) for each time step between the observations together with the transition probability. The equation for this depends on the relationship between the time step, t, for the mark-recapture observations, and that for the transition process, t_{trans}:

$$X_{iyj} = \begin{cases} \dfrac{s_{\text{tot},ity}}{s_{\text{tot},ity;p}} \left[\prod_{t'>t} s_{\text{tot},it'y} \right] \left[\prod_{t' \le t_{trans}} s_{\text{tot},it',y+1} \right] \left[\prod_{t_{trans}<t'<t} s_{\text{tot},jt',y+1} \right] s_{\text{tot},jt,y+1;p} T_{y+1,ij} & \text{if } t > t_{trans} \\ \dfrac{s_{\text{tot},ity}}{s_{\text{tot},ity;p}} \left[\prod_{t<t' \le t_{trans}} s_{\text{tot},it'y} \right] \left[\prod_{t'>t_{trans}} s_{\text{tot},jt'y} \right] \left[\prod_{t'<t} s_{\text{tot},jt',y+1} \right] s_{\text{tot},jt,y+1;p} T_{yij} & \text{if } t \le t_{trans} \end{cases}$$

where we use the convention that 'empty' products are equal to 1 (e.g., the first product in the upper formula will be empty if t is the last time step).

To calculate the likelihoods L_{by}, we needed to define P_{biy} to be the probability, given the observations of the sea lion with tag number b up to and including year y, that this sea lion was in a non-composite stage i in that year. If this sea lion was observed in non-composite stage j in year y, then

$$P_{biy} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \ne j \end{cases}$$

Otherwise, P_{biy} was calculated recursively as follows. If the observed stage at tagging (i.e., in year $y = y_{b,tag}$) was composite then

$$P_{biy} = \begin{cases} \dfrac{n_{ity;p} r_{iy}}{\sum_{i' \in O_{by}} n_{i'ty;p} r_{i'y}} & \text{if } i \in O_{by} \\ 0 & \text{if } i \notin O_{by} \end{cases}$$

where $n_{ity;p}$ are the numbers of sea lions at the time of the observations.

If the observed stage in year y+1 (i.e., $O_{b,y+1}$) is composite, or ≤ 0, then

$$P_{bj,y+1} = \begin{cases} \dfrac{\sum_{i \in O_{by}} P_{biy} X_{iyj} r_{j,y+1}}{\sum_{i \in O_{by}} P_{biy} \sum_{j' \in O_{b,y+1}} X_{iyj'} r_{j',y+1}} & \text{if } O_{b,y+1} > 0 \text{ and } j \in O_{b,y+1} \\ 0 & \text{if } O_{b,y+1} > 0 \text{ and } j \notin O_{b,y+1} \\ \dfrac{\sum_{i \in O_{by}} P_{biy} X_{iyj} \left(1 - r_{j,y+1}\right)}{1 - \sum_{i \in O_{by}} P_{biy} \sum_{j'} X_{iyj'} r_{j',y+1}} & \text{if } O_{b,y+1} = 0 \\ \sum_{i \in O_{by}} P_{biy} X_{iyj} & \text{if } O_{b,y+1} = -1 \end{cases}$$

where, for $O_{by} \le 0$ the notation $\sum_{i \in O_{by}}$ implies a sum over all non-composite stages (i.e., from 1 to Nstage), as does $\sum_{j'}$.

The likelihoods are calculated as

$$L_{b,y+1} = \begin{cases} \sum_{i \in O_{by}} P_{biy} \sum_{j \in O_{b,y+1}} X_{iyj} r_{j,y+1} & \text{if } O_{b,y+1} > 0 \\ \left(1 - \sum_i P_{biy}\right) + \sum_{i \in O_{by}} P_{biy} \left[1 - \sum_j X_{iyj} r_{j,y+1}\right] & \text{if } O_{b,y+1} = 0 \\ 1 & \text{if } O_{b,y+1} = -1 \end{cases}$$

The total log-likelihood associated with a tagged sea lion depends very little, if at all, on the numbers in the partition. These numbers enter the likelihood calculation for a tagged sea lion only if the initial observation, $O_{by_{b,band}}$, is a composite stage, in which case $P_{biy_{b,band}}$ depends on the number of partitions.

Likelihoods for absolute abundance, by-catch or parameter observations

For these observations, the likelihood is a formula involving the observation, *O*, and the population model's expected value, *E*, for the observation. The form of the formula depends on the error distribution assumed for the observation (Table 2-6).

Table 2-6: Formulae for calculating negative-log likelihoods for different error distributions. C.V. is denoted by "c", standard deviation by "s", and the robustification constant by "r".

Error distribution	Parameter(s)	Negative-log likelihood
normal	c	$\log(cE) + 0.5[(O-E)/(cE)]^2$
normal-by-stdev	s	$\log(s) + 0.5[(O-E)/s]^2$
lognormal	c[1]	$\log(\sigma) + 0.5[0.5\sigma + \log(O/E)/\sigma]^2$
normal-log	c[1]	$\log(\sigma) + 0.5[\log(O/E)/\sigma]^2$
robustified-lognormal	c[1], r	$\log(\sigma) - \log\left(\exp\left[-0.5\left(\frac{\log(O/E)}{\sigma} + \frac{\sigma}{2}\right)^2\right] + r\right)$

[1]In the likelihood, $\sigma = [\log(1+c^2)]^{0.5}$

Likelihoods for age distribution observations

Age distributions were fitted using a likelihood based on the multinomial distribution.

Let ***O*** be a vector of observations of proportions-at-age for a single year that sum to 1; let ***E*** be the corresponding fitted values; let *N* be the "effective sample size" parameter. Then the multinomial likelihood for that year, which are expressed on the objective-function scale of -log(*L*), is

$$-\log(L) = -\log(N!) + \sum_i \left[\log\left((NO_i)!\right) - NO_i \log\left(Z(E_i, r)\right)\right]$$

where $Z(x,r)$ is a robustifying function with parameter $r>0$ (to prevent division by zero errors), defined as

$$Z(x,r) = \begin{cases} x \text{ where } x \geq r \\ r/(2 - x/r) \text{ otherwise} \end{cases}$$

Here, r was set to 0 so $Z(x,r) = x$. N was set to 1000 for observations from 1999-2001 data and to 200 for 1998 observations.

2.2.4 Functional forms

Age-at-first-pupping

We adopted the functional form for the probability of first pupping at age as used by Francis & Sagar (2012). An individual that was a juvenile at age a-1 ($4 \le a \le 8$), and survived to age a, either pupped for the first time at age a, with probability $\Pr B1st_a$, or remained immature, where

$$logit(PrB1st_a) = logit(Pr1st_{a-1}) + (a-4)oddsmult$$

where

$$logit(PrB1st_a) = log\left(\frac{PrB1st_a}{1-PrB1st_a}\right)$$

Survival

We investigated the functional form for mortality rate as suggested by Gilbert & Chilvers (2008). He defined mortality (m) as a smooth, U-shaped function of age that gives the probability that a female will die in the year after achieving a given age, where μ_1 is the minimum function value (mortality rate), $0 < \mu_1 < 0.3$, μ_2 is the age at which the minimum is achieved, $0 < \mu_2 < 8$, μ_3 is the function value at age 0, $0 < \mu_3 < 0.8$, and μ_4 is the function value at age 20, $0 < \mu_4 < 0.8$. The mortality rate depends on the parameter vector $\underset{\sim}{\mu}$,

$$\mathrm{m}(a \mid \underset{\sim}{\mu}) = \begin{cases} \mu_1 \left(\frac{\mu_3}{\mu_1}\right)^{\left(\frac{a-\mu_2}{0-\mu_2}\right)} & a \le \mu_2 \\ \mu_1 \left(\frac{\mu_4}{\mu_1}\right)^{\left(\frac{a-\mu_2}{20-\mu_2}\right)} & a > \mu_2 \end{cases}$$

The function has a minimum value of μ_1 at age $a = \mu_2$, takes the value μ_3 at $a = 0$ and μ_4 at $a = 20$.

μ_2 is an integer and so cannot be estimated in the usual way. We investigated the model fit for a number of values between 0 and 8, and choose $\mu_2 = 3$ based on log-likelihood.

Pupping rate

Gilbert (2008) also proposed a functional form for pupping rate, which is a smooth, domed function of age that gives the probability that a high-fecundity cow will bear a pup in a given season. The function is determined by a vector of parameters $\underset{\sim}{\beta}$, where β1 is the maximum value of the function, $0.4 < \beta1 < 0.95$, β2 is the age at which the maximum is achieved, $8 < \beta2 < 14$, β3 and β4 are the ages at which the left and right-hand limbs of the function fall to half the maximum, respectively, $4 < \beta3 < 8$ and $\beta4 > 14$.

$$\mathrm{b}(a \mid \underset{\sim}{\beta}) = \begin{cases} \beta_1 2^{-\left(\frac{a-\beta_2}{\beta_3-\beta_2}\right)^2} & a \le \beta_2 \\ \beta_1 2^{-\left(\frac{a-\beta_2}{\beta_4-\beta_2}\right)^2} & a > \beta_2 \end{cases}$$

The function has a maximum value of β_1 at $a = \beta_2$, takes the value $0.5\beta_1$ at $a = \beta_3$ on the left and at $a = \beta_4$ on the right. We investigated a variation of this functional form where we assumed the pupping rate is of a constant value (β_1) between age 4 and 14, then declines to half of this value at $a = \beta_4$. This simplified version involves only two parameters.

2.2.5 Model development and implementation

Due to the inherent flexibility of modelling with SeaBird a wide array of model configurations could be developed. We adopted a sequential model optimisation process in which the most parsimonious parameterisation (lowest Akaike information criterion (AIC) – a likelihood based measure of goodness-of-fit.) was sought for one demographic rate (e.g. survival) before moving on to the next (e.g. resighting probability). Thus for the Sandy Bay population, the model optimisation proceeded in the following order:

1. An initial **exploration of age, cohort and year effects** on survival, pupping rates and annual resighting probability (model runs 1-3):

   - Age effects on survival, pupping and resighting probability were explored using different functional forms and step functions to find the most parsimonious parameterisation with respect to age. All parameter estimates were year invariant in this modelling step.
   - Cohort effects were also explored with year-invariant estimates, though purely on an investigative basis and the results obtained had no bearing on the model optimisation process[1].
   - Year effects were also explored on an investigative basis, with separate estimates of survival, pupping and resighting probability for each year for which the data were informative. Different parameterisation of year effects (e.g. year-invariant or all varying) were subsequently explored in more detail in the next phases of model optimisation.

2. A **sequential model optimisation process** was used to identify the most parsimonious parameterisation of (in this order) survival (model run 4), resighting probability (model run 5), pupping probability (model run 6) then age-at-first-pupping (model runs 7). This considered:

   - Year-invariant versus all year-varying estimates;
   - Estimates for different demographic groupings (e.g. age, or pupping status).

   This concluded the model optimisation process with regards to parameterisation. The most parsimonious model parameterisation (run 7) was then taken forward to the next model development phase.

3. Survival estimates were adjusted to account for pups that were reported to have died prior to tagging through modification of the mark-recapture observations to include a

[1] A limited assessment of cohort effects was achieved using cohort subsets of mark-recapture observations. For each cohort (birth year), the data subset comprised all females tagged as pups in that year and all resighting observations for those individuals in subsequent years, i.e., a separate model run was made for each cohort. As such, cohort effects were not truly separated from year effects.

proportional number of "phantom" tagged pups that were not observed again in subsequent years. The model configuration was not altered from that of model run 7.

4. Markov Chain Monte Carlo (MCMC) samples were then generated using the optimal model configuration[2] to estimate the degree of uncertainty associated with parameter estimates (95% confidence intervals reported). A chain length of 250,000 was generated, with samples taken every 500 iterations, giving a total of 500 samples (no burn-in).

5. A series of model validation steps were then undertaken:

- The MCMC samples were used to assess the degree of correlation between parameter estimates.
- Posterior distributions of MCMC estimates were analysed to assess the identifiability of model parameters.
- An analysis was conducted to identify the most parsimonious year blocks (or break points) for key demographic parameters. This had the aims of identifying years where changes in demographic rates may have occurred and estimating parameter values for the resulting year blocks.
- A retrospective analysis was conducted to assess the effect of the number of resighting years on parameter estimates, e.g. to determine how many years of resighting effort is normally required before estimates are stabilised (model run 10).
- Tag frequencies associated with each observation were used to simultaneously estimate survival and tag loss (these are otherwise confounded). Year-invariant estimates of tag loss at age0 and age1+ were generated along with separate survival estimates (model run 11).
- The model was fitted to pup census observations (1990-2012) and demographic rates estimated simultaneously with tag loss rate (model run 12).
- The model was fit to age distribution observations from 1998-2001 (Childerhouse et al., 2010a) (model run 13).

Model configurations for each model run are summarised in Table 2-7. Note that all estimates of survival were confounded with tag loss when they were obtained from models that did not estimate tag loss rate simultaneously with survival (all model except runs 11 and 12). Plots of survival estimates have been labelled accordingly for these models.

Mark recapture observations for individuals tagged as pups and resighted at Dundas were used to obtain annual age-specific point estimates of survival for this population (model run 9). The same parameterisation as model run 8 was used except that pupping rate and age-at-first-pupping parameters were not estimated. MCMC samples were then generated as for the Sandy Bay population, described above.

[2] Minor modifications to the configuration of model run 7 were made subsequent to this step and a new set of MCMC parameter estimates were generated with this parameterisation, run 8. These modifications to the model parameterisation are described in the results section.

Table 2-7: Model configurations used in this assessment. "MR" - tag-resighting data, "PP" - pup production, "AD" - age distribution. Three different model partition types used. Mark-recapture observations from Sandy Bay "SB", or Dundas "DD".

Modelling objective	Run	Model	Observations	Partitioning	Tag loss parameters	Phantom tags	Year-varying parameters	Area	MCMC run
Explore age, cohort and year effects; identify initial model parameterisation	1	Age-effects	MR	I	N	N	N	SB	N
	2	Cohort-effects	MR	I	N	N	N	SB	N
	3	Year-effects	MR	I	N	N	Y	SB	N
Sequentially determine optimal parameterisations of survival, resighting, pupping & age-at-first-pupping	4a-m	Survival optimisation	MR	I	N	N	Y	SB	N
	5a-m	Resighting optimisation	MR	I	N	N	Y	SB	N
	6a-d	Pupping optimisation	MR	I	N	N	Y	SB	N
	7	Age-at-first-pupping optimisation	MR	I	N	N	Y	SB	N
Produce "optimal model" for MCMC runs	8	Optimal model Sandy Bay	MR	I	N	Y	Y	SB	Y
	9	Optimal model Dundas	MR	III	N	Y	Y	DD	Y
Model validation runs	10	Retrospective analysis	MR	I	N	Y	Y	SB	N
	11	Tag loss model	MR	II	Y	Y	Y	SB	N
	12	Fit to pup counts	MR, PP	II	Y	Y	Y	SB	N
	13	Fit to age distribution	MR, AD	I	N	Y	Y	SB	N

3 Results

3.1 Demographic assessment of females at Sandy Bay

3.1.1 Exploratory analysis of age, cohort and year effects on demographic rate estimates

An exploratory assessment of age, cohort and year effects on demographic rate estimates was conducted to inform an initial model parameterisation for females at Sandy Bay (model runs 1-3). The parameterisation of each model used in this analysis is described in Appendix B (Table 2-7). Estimates of annual resighting probability were very low at ages 1 and 2 (0.07 & 0.12, respectively). Of individuals that had not previously pupped, peak resighting probability was at age 4 (0.62), with a continuous decline to age 7 (0.23). The estimated probability of resighting non-puppers was similar to that of immature animals aged 3-6 (0.52 and 0.42-0.62, respectively). The annual resighting probability of puppers was high (0.95) (Figure 3-1).

Strong age effects on survival were identified. Estimates increased up to age 2 (0.52, 0.68 and 0.91 for ages 0, 1 and 2, respectively) and peaked between ages 2-5 (ranged from 0.91-0.94), then declined to age 6 and remained relatively constant up to age 14 (ranging from 0.81-0.90). Estimates of survival at ages 15+ were highly variable with age (ranging from 0.24-0.92) and mark-recapture observations were probably not sufficiently informative to provide precise age-specific estimates for these older individuals (Figure B-2) (Figure 3-1).

The estimated probability of pupping was consistently high at ages 7-12 (ranging from 0.70-0.76), with peak pupping rate between ages 9-11 (ranging from 0.75-0.76). With regards to the probability of non-puppers pupping, there was no obvious trend with respect to increasing age, though there was a generally reduced probability of pupping (ranging from 0.19-0.61 across ages 7-12) when compared with estimates of individuals that pupped in the previous year (Figure 3-1).

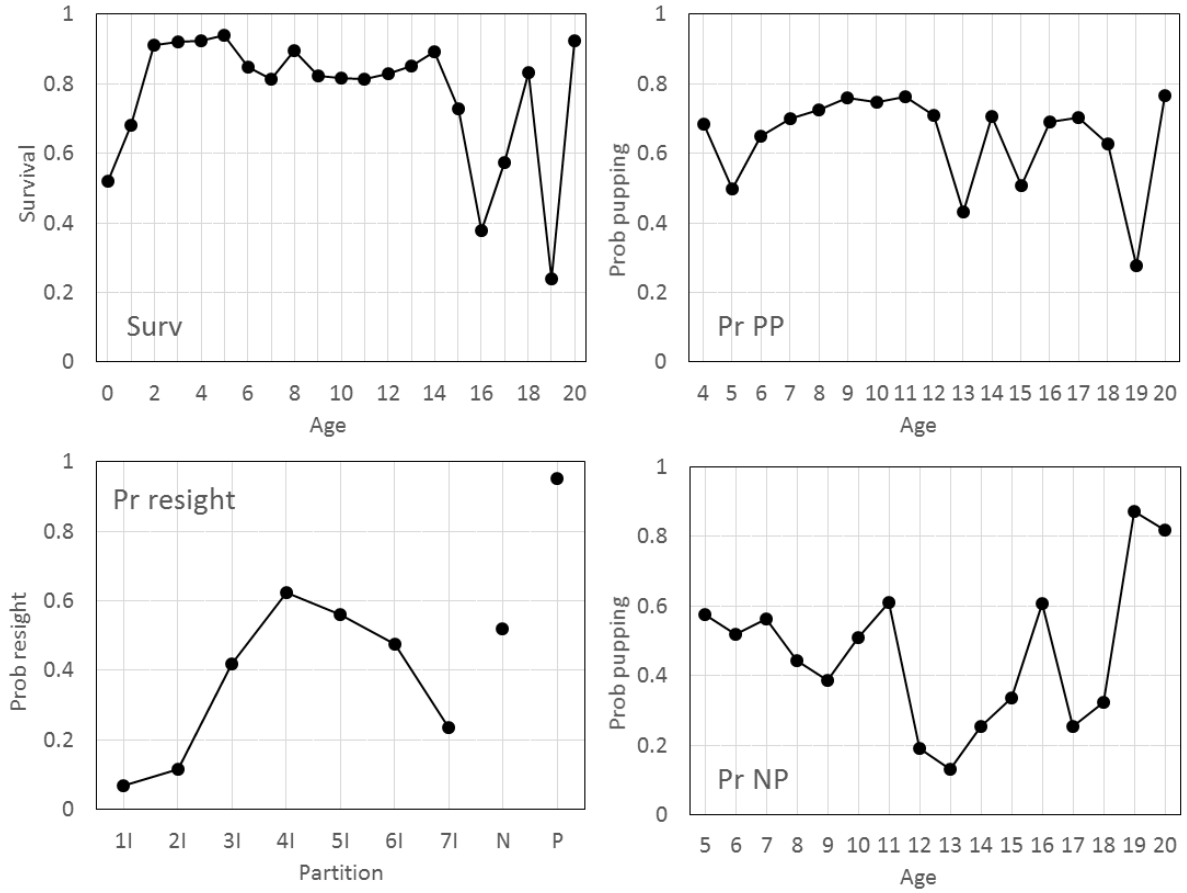

Figure 3-1: Parameter estimates for model exploring age-effects on survival, resighting probability and probability of pupping of females at Sandy Bay (model run 1).

Cohort effects were not separated from year effects, though the age classes for some demographic parameters were sufficiently broad (e.g. survival at ages 6-14) that some of the variation in estimates obtained was likely to have resulted from cohort effects.

For a given cohort, survival estimates at ages 0 and 1 were negatively correlated (a consequence of low resighting probability at ages 1 and 2) (Figure B-3). Multiplying these estimates revealed strong cohort effects on survival up to age 2 (range of 0.55-0.64 for cohorts born 1990-1993 and 0.04-0.55 for cohorts born 1998-2010) (Figure B-3). Variation in survival at ages 2-5 was minimal comparing cohorts, with the exception of the 1998 cohort for which estimated survival was anomalously low (0.77 for the 1998 cohort, compared a range of 0.85-1.00 for all other cohort estimates).

Relatively high estimates of survival were obtained for all age classes (age 0, 1, 2-5 and 6-14) for cohorts born in years 1990-1993. Survival at age 6-14 of cohorts born 1998-2005 was generally low (range of 0.62-0.92) relative to 1990-1993 cohorts (range of 0.82-0.87). The estimation of survival at age 15+ was informed only by observations of cohorts born 1990-1993. Cohorts born from 1998 onwards were not informative and so cohort effects were not explored for this parameter (*See* Figure B-2).

Cohorts born after 2005 were too young in the last year of resighting effort used in this analysis to be sufficiently informative for pupping rate parameters (maximum age of 6 in 2012). There did not appear to be any large cohort effects on estimates of pupping probability for cohorts born prior to

this year. The lowest estimates of puppers pupping were for cohorts born in 1999 and 2000 (0.56 and 0.57, respectively, compared with 0.61-0.80 for all other cohorts born 1990-2005) (*See* Figure B-5).

Strong year effects were observed on estimates of survival for all age classes assessed (*See* Figure B-6) and are discussed in more detail in the analysis of MCMC estimates (Section 3.1.3). Estimates for ages 0 and 1, were for single cohorts within a particular year and so trends observed in cohort effects may also be considered as cumulative year effects on survival during the first two years of life, i.e. high estimates of survival up to age 2 in years 1990-1994 and comparatively low survival up to age 2 in years 2005-2011. The 2007 estimate of survival at age 6-14 was low relative to all other years for which estimates were obtained (0.70 in 2007, compared with a range of 0.80-0.90 for all other years from 1998-2011) (*See* Figure B-3).

Model estimates indicated strong year effects on the probability of puppers and non-puppers pupping in the following year, with low estimates regardless of breeding status in 2004 and 2005 (corresponding with pupping in years 2005 and 2006) (*See* Figure B-8). Estimates of non-puppers pupping in 2008, 2009 and 2010 were reduced when the resighting probability of puppers was fixed to 1 rather than estimated by the model (anomalously high estimates of resighting probability of non-puppers were obtained when the probability of puppers pupping was not fixed to 1; *See* Figure B-7). Fixing the resighting probability of puppers had a minimal effect on estimates of the probability of puppers pupping in the next year.

3.1.2 Model development

With the exception of age-at-first-pupping, none of the functional forms described in Section 2.2.4 were found to reduce AIC and, so, were not carried forward to the next stage of model development. Model run 7 had the lowest AIC of any model parameterisation (comparing model all model runs 4-7) (Table B-2). With this model parameterisation, good fits to tag resighting observations were generally observed for all cohorts and across all resighting years, corresponding to the full range of ages from 1-20 (*See* Figure B-9).

At this stage of model development, phantom tags were added to mark recapture observations for cohorts born 1998-2011, to adjust for pups that had died prior to the date of tagging in those years (Table 2-1). The inclusion of phantom tags had a minimal effect on cohort survival to age 2 (*See* Figure B-10). As expected, phantom tags had the greatest effect on estimates of survival to age 2 of cohorts born in years 2002 and 2003 (0.30 and 0.47 in 2002 and 2003 with phantom tags and 0.37 and 0.57 for cohorts 2002 and 2003 without phantom tags), when pup mortality rates prior to tagging were greatest (Table 2-1). Subsequent to this step, phantom tags were then added to the mark recapture observations of cohorts born in years 1990-1993.

Phantom tags were included in model runs used to generate initial MCMC samples of all estimated parameters, with the model parameterisation as run 7. These samples were then used to conduct an assessment of the degree of correlation between all estimated parameters. This analysis highlighted a high degree of correlation between the two age-at-first-pupping parameters, which would be expected given that they define a functional form (*See* Figure B-31). Also weak negative correlations between survival at age 2-5 in a year and resighting probability at age 4-5 in year+1; and survival at age 6-14 in a year and the resighting probability of non-puppers in year+1 (Figure B-29).

Parameters for the annual resighting probability of immature individuals at ages 6 and 7 (most years) and annual age-at-first-pupping parameters in years 1998-2001 were found to be weakly identifiable. Thus appropriate modifications were made to the parameterisation, making resighting probability

parameters of immature individuals at age 6 and 7 year-invariant; age-at-first-pupping parameters for years 1998-2001 were estimated for a single year block and these estimates were omitted from the results. This revised "optimal" model parameterisation (model run 8) was then used to generate the final MCMC estimates for all parameters.

3.1.3 MCMC parameter estimates

The assessment of parameter correlation highlighted a high degree of autocorrelation in the estimation of survival at ages 0 and 1 (*See* Figure B-30), most probably due to low resighting probability at ages 1 and 2 (*See* Figure B-1). Thus we presented estimates of cohort survival up to age 2 (Survival at 0 * Survival at 1). The resultant posterior distributions of this rate indicate that it was strongly identifiable for all cohorts born from 1998-2010 (*See* Figure B-19) though correlation with survival at age 2-5 in the early 1990s (*See* Figure B-30) (as a result of not using resighting effort prior to 1998) resulted in weakly identifiable survival to age 2 for cohorts 1990-1993. This was addressed by presenting estimates of survival up to age 5 for all cohorts with sufficient years of resighting effort (Figure 3-2).

The median MCMC estimates and associated 95% confidence intervals for parameters estimates in model run 8 are presented in Table 3-1. Relatively high survival estimates were obtained to age 2 of cohorts born 1990-1993 (medians ranged from 0.49 to 0.59) and low survival estimates of cohorts born from 2005-2010 (medians ranged from 0.05 to 0.30) (Figure 3-2). Relatively strong estimates of survival to age 5 were obtained for cohorts born 1991-1993, though survival of the 1990 cohort was no stronger than cohorts born from 1990-2007 (Figure 3-2). Very low estimates of cohort survival to age 5 were obtained for cohorts born in 1998 and 2008 - these anomalous estimates can at least partly be explained by high flipper-tag failure rates in these years (Appendix B and Louise Chilvers unpub dat.).

Table 3-1: Demographic parameter estimates to be carried forward to the correlative modelling phase of the project. Median MCMC estimates from model configured as model run 8; estimates used may change depending on further model development as described in this report. Parameter notation is <demographic rate><age range><year>, where "Surv" are estimates of survival to year+1 (confounded with tag loss); "Mat" are maturation parameters 1 and 2; "NP" and "PP" are estimates of puppers and non-puppers pupping in year+1.

Parameter	Value	Parameter	Value
Surv 0_1990 * Surv 1_1991	0.57 (0.27 - 0.82)	Surv 6_14_1998	0.95 (0.80 - 0.99)
Surv 0_1991 * Surv 1_1992	0.59 (0.41 - 0.82)	Surv 6_14_1999	0.89 (0.81 - 0.94)
Surv 0_1992 * Surv 1_1993	0.62 (0.45 - 0.83)	Surv 6_14_2000	0.80 (0.73 - 0.85)
Surv 0_1993 * Surv 1_1994	0.49 (0.39 - 0.69)	Surv 6_14_2001	0.90 (0.83 - 0.94)
Surv 0_1998 * Surv 1_1999	0.14 (0.10 - 0.19)	Surv 6_14_2002	0.80 (0.73 - 0.85)
Surv 0_1999 * Surv 1_2000	0.40 (0.32 - 0.50)	Surv 6_14_2003	0.87 (0.81 - 0.91)
Surv 0_2000 * Surv 1_2001	0.23 (0.16 - 0.30)	Surv 6_14_2004	0.80 (0.72 - 0.85)
Surv 0_2001 * Surv 1_2002	0.43 (0.35 - 0.48)	Surv 6_14_2005	0.90 (0.81 - 0.96)
Surv 0_2002 * Surv 1_2003	0.29 (0.23 - 0.34)	Surv 6_14_2006	0.80 (0.73 - 0.86)
Surv 0_2003 * Surv 1_2004	0.46 (0.39 - 0.52)	Surv 6_14_2007	0.66 (0.58 - 0.71)
Surv 0_2004 * Surv 1_2005	0.39 (0.31 - 0.46)	Surv 6_14_2008	0.84 (0.75 - 0.91)
Surv 0_2005 * Surv 1_2006	0.19 (0.14 - 0.24)	Surv 6_14_2009	0.80 (0.70 - 0.85)
Surv 0_2006 * Surv 1_2007	0.28 (0.20 - 0.33)	Surv 6_14_2010	0.86 (0.76 - 0.92)
Surv 0_2007 * Surv 1_2008	0.29 (0.22 - 0.34)	Surv 6_14_2011	0.77 (0.63 - 0.93)
Surv 0_2008 * Surv 1_2009	0.05 (0.03 - 0.07)		
Surv 0_2009 * Surv 1_2010	0.30 (0.22 - 0.40)	Surv 15+	0.59 (0.50 - 0.64)
Surv 0_2010 * Surv 1_2011	0.21 (0.08 - 0.35)		
Surv 2_5_1992	0.72 (0.43 - 0.97)		
Surv 2_5_1993	0.80 (0.52 - 0.97)		
Surv 2_5_1998	0.84 (0.64 - 0.97)		
Surv 2_5_1999	0.95 (0.84 - 0.99)		
Surv 2_5_2000	0.89 (0.72 - 0.96)		

Parameter	Value	Parameter	Value
Surv 2_5_2001	0.71 (0.59 - 0.81)		
Surv 2_5_2002	0.87 (0.74 - 0.96)		
Surv 2_5_2003	0.83 (0.71 - 0.89)		
Surv 2_5_2004	0.98 (0.92 - 1.00)		
Surv 2_5_2005	0.96 (0.88 - 0.99)		
Surv 2_5_2006	0.84 (0.77 - 0.89)		
Surv 2_5_2007	0.90 (0.81 - 0.94)		
Surv 2_5_2008	0.87 (0.78 - 0.92)		
Surv 2_5_2009	0.80 (0.71 - 0.87)		
Surv 2_5_2010	0.96 (0.90 - 0.99)		
Surv 2_5_2011	0.78 (0.66 - 0.88)		
Mat_1_2001	0.12 (0.07 - 0.17)	NP_1999	0.39 (0.09 - 0.58)
Mat_1_2002	0.02 (0.01 - 0.05)	NP_2000	0.50 (0.38 - 0.60)
Mat_1_2003	0.16 (0.07 - 0.25)	NP_2001	0.47 (0.34 - 0.56)
Mat_1_2004	0.08 (0.04 - 0.12)	NP_2002	0.40 (0.27 - 0.53)
Mat_1_2005	0.05 (0.02 - 0.08)	NP_2003	0.56 (0.44 - 0.63)
Mat_1_2006	0.09 (0.05 - 0.12)	NP_2004	0.46 (0.32 - 0.57)
Mat_1_2007	0.11 (0.06 - 0.15)	NP_2005	0.31 (0.14 - 0.45)
Mat_1_2008	0.12 (0.06 - 0.19)	NP_2006	0.24 (0.15 - 0.32)
Mat_1_2009	0.11 (0.05 - 0.16)	NP_2007	0.29 (0.17 - 0.37)
Mat_1_2010	0.34 (0.18 - 0.46)	NP_2008	0.45 (0.33 - 0.57)
Mat_1_2011	0.14 (0.04 - 0.22)	NP_2009	0.46 (0.27 - 0.59)
		NP_2010	0.50 (0.39 - 0.59)
Mat_2_2001	1.61 (1.29 - 1.91)	NP_2011	0.55 (0.39 - 0.66)
Mat_2_2002	3.35 (0.95 - 5.75)		
Mat_2_2003	1.72 (0.87 - 2.88)	PP_1999	0.18 (0.02 - 0.37)
Mat_2_2004	1.93 (1.20 - 2.60)	PP_2000	0.67 (0.53 - 0.77)
Mat_2_2005	1.72 (1.09 - 2.36)	PP_2001	0.83 (0.75 - 0.88)
Mat_2_2006	1.50 (1.10 - 1.86)	PP_2002	0.66 (0.57 - 0.73)
Mat_2_2007	1.82 (1.31 - 2.40)	PP_2003	0.81 (0.70 - 0.87)
Mat_2_2008	1.26 (0.91 - 1.59)	PP_2004	0.83 (0.72 - 0.89)
Mat_2_2009	1.72 (1.31 - 2.25)	PP_2005	0.44 (0.33 - 0.52)
Mat_2_2010	0.96 (0.68 - 1.29)	PP_2006	0.42 (0.29 - 0.52)
Mat_2_2011	2.29 (1.39 - 3.95)	PP_2007	0.75 (0.63 - 0.87)
		PP_2008	0.75 (0.64 - 0.81)
		PP_2009	0.47 (0.38 - 0.54)
		PP_2010	0.77 (0.68 - 0.84)
		PP_2011	0.71 (0.60 - 0.76)

The greatest estimates of survival at age 6-14 were obtained for years 1998, 1999, 2001 and 2005 (medians of 0.95, 0.89, 0.90 and 0.89, respectively). By far the lowest estimate of survival at these ages was obtained for year 2007 (0.66, the next lowest was 0.79 in 2011) (Figure 3-3). A year-invariant value of survival rate was estimated for age 15+ at 0.52 (95% confidence interval = 0.44-0.57).

Estimates of the probability of pupping in year+1 were low in 2004 and 2005 relative to other years, regardless of pupping status (0.44 and 0.42 for puppers and 0.30 and 0.24 for non-puppers in 2004 and 2005, respectively; Figure 3-4). The 95% confidence intervals associated with estimates of the probability of puppers pupping in years 2004, 2005 and 2008 did not overlap with those of estimates obtained for any other year from 2000-2011. The relatively broad confidence intervals associated with estimates of non-puppers pupping indicated a reduced degree of precision of pupping rate estimates for this demographic grouping (Figure 3-4). There was also quite a high degree of variability around estimates of age-at-first-pupping parameters – these did not vary much with year, with the exception of Pr$B1st_a$ (the proportion of individuals at age 3 that pupped in yr+1) for which an anomalously high estimate was obtained for the year 2010 (0.32, 95% CI = 0.17-0.46); the second highest estimate was obtained for the year 2003 (0.17, 95% CI = 0.08-0.27) (*See* Figure B-15).

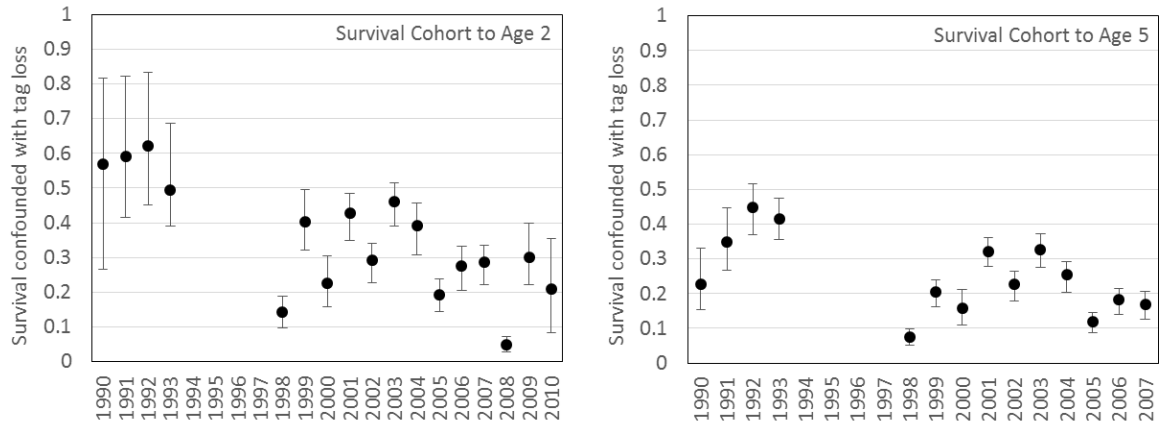

Figure 3-2: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

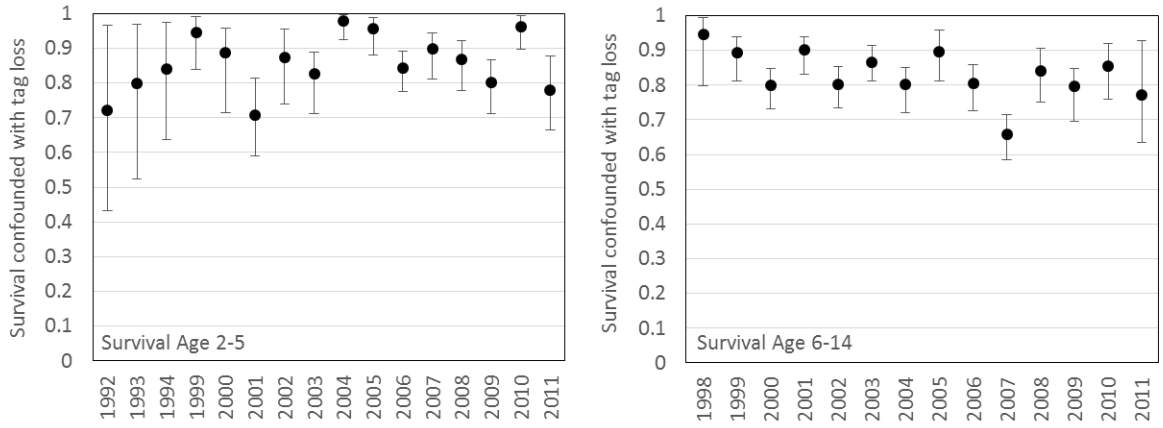

Figure 3-3: MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

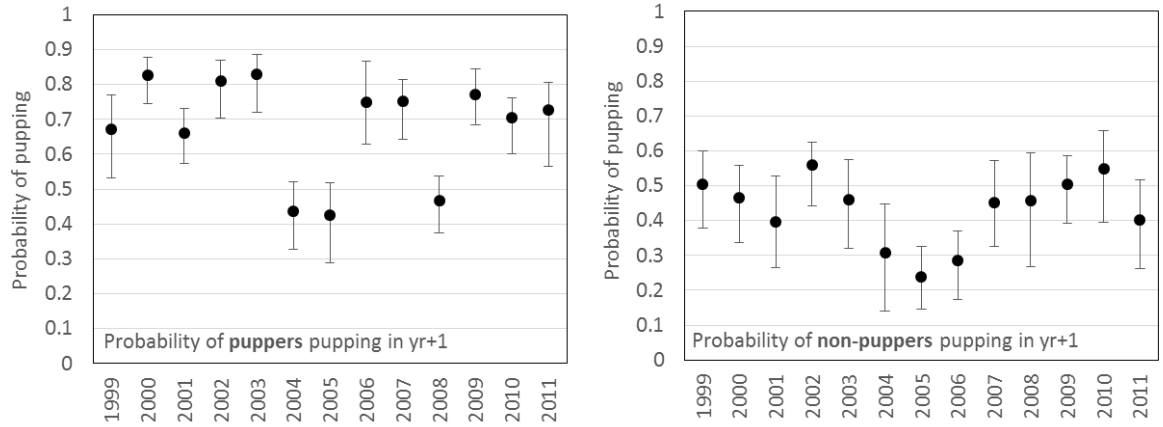

Figure 3-4: MCMC estimates of pupping probability of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

3.1.4 Additional model validation

Breakpoint analysis

An analysis was conducted to year groupings in the time series of demographic parameter estimates. This had the objectives of identifying year break points after which demographic rate estimates were different and to estimate demographic parameter values for the different year groups. The most parsimonious year groups for survival up to age 2 were 1990-2005 and 2006-2010. The second of these groups was further subdivided to create the year groups 1990-2005, 2006-2007, 2008 and 2009-2010 – for which the estimates of survival to age 2 were 0.42, 0.26, 0.05 and 0.25, respectively (Figure 5 5). Cohorts 1990-1993 were not separated from those of 1998-2004 despite high survival estimates for these cohorts to age 2, possibly because estimation of survival to age 2 was confounded with survival at age 2-5 in the period before consistent resighting effort prior to 1999. Four year groupings were also identified in survival at age 6-14: 1998-1999, 2000-2005, 2006-2007 and 2008-2011 – for which the estimates were 0.92, 0.84, 0.73 and 0.83, respectively (Figure 3-5).

Three year groupings were identified in pupping rate parameters (for which the same year groupings were simultaneously applied to the probability of puppers and non-puppers pupping in year+1). These were: 1999-2003, 2004-2006 and 2007-2011, for which the estimates were 0.77, 0.43 and 0.68 respectively for puppers pupping; and 0.48, 0.24 and 0.42 respectively for non-puppers pupping (Figure 3-6). All additional year breaks increased AIC and so were not retained. Only two year groupings were identified in the two age-at-first-pupping parameters (for which the same year groupings were trialled simultaneously). These were 2001-2009 and 2010-2011, for which the associated estimates were 0.09 and 0.27 for the proportion of individuals at age 3 pupping in the next year (Pr$B1st_a$)and 1.69 and 1.44 for the odds multiplier (*oddsmult*) (Figure 3-7).

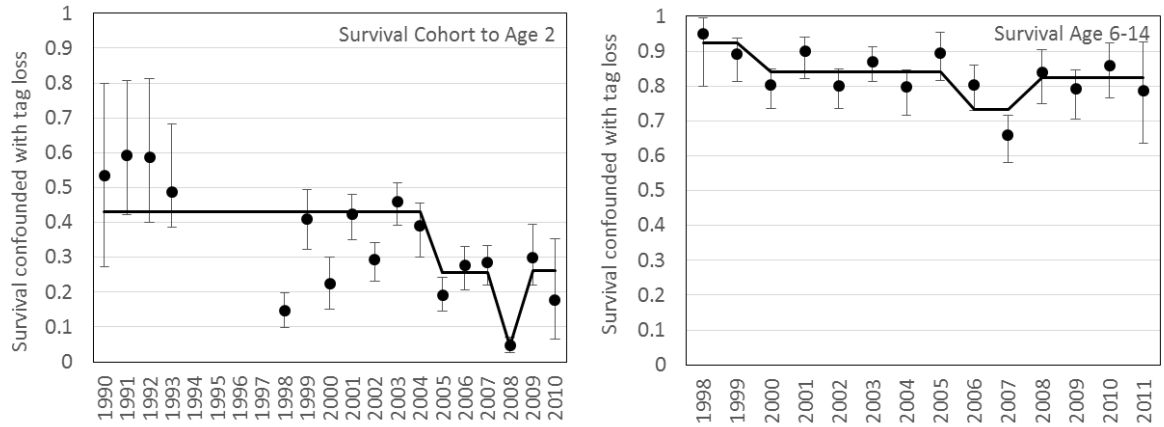

Figure 3-5: Year group estimates from the breakpoint analysis and MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

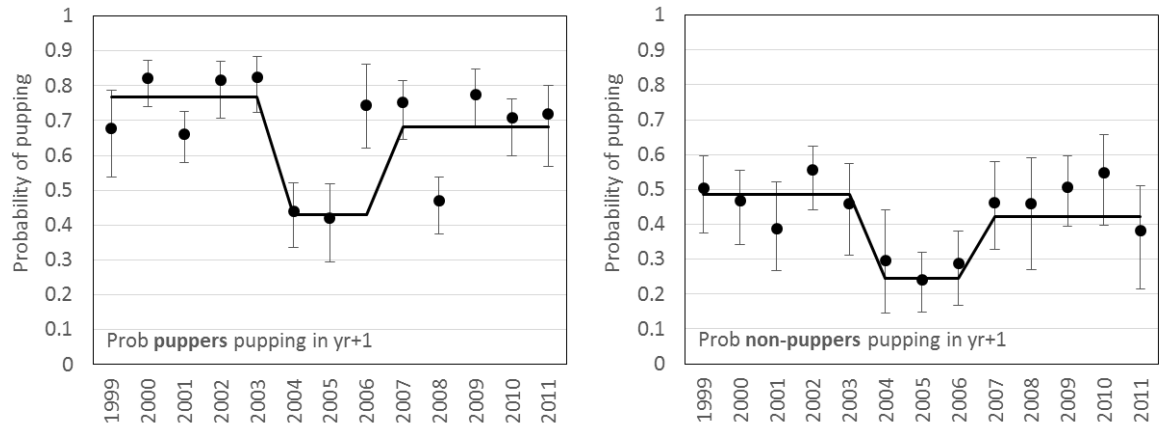

Figure 3-6: Year group estimates from the breakpoint analysis and; MCMC estimates of probability of puppers pupping in year +1 (left) and non-puppers pupping in year+1 (right) of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

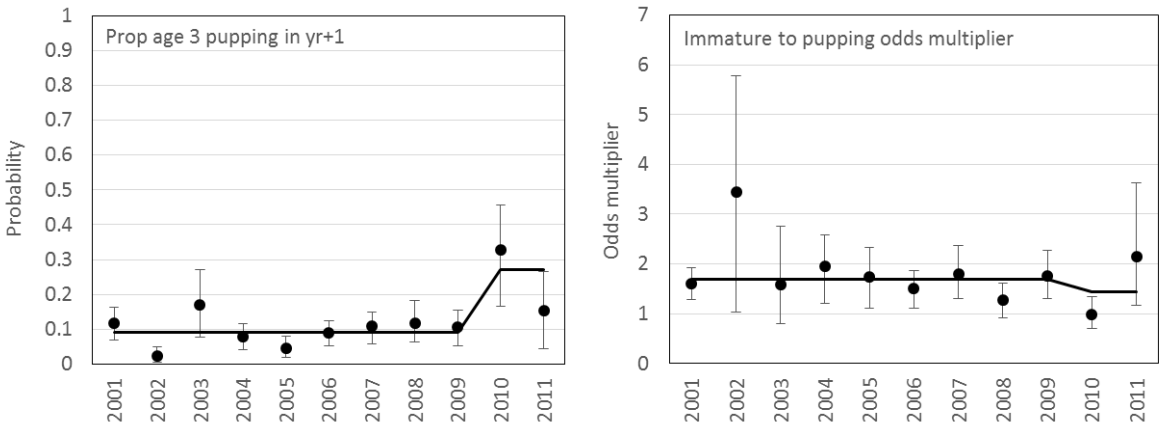

Figure 3-7: Year group estimates from the breakpoint analysis and MCMC estimates of age-at-first-pupping parameters $\Pr B1st_a$ (left) and *oddsmult* (right) of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

Retrospective analysis

A retrospective analysis was conducted with model parameterisation as model run 7, in which the latest year of observations was sequentially removed prior to parameter estimation, to assess model bias in the estimation of demographic parameters. This analysis indicated that there was a negative bias in model estimates of survival at age 0 (s0). Estimates tended to stabilise after 4 years of resighting effort (*See* Figure B-35), presumably in response to the increase in resighting effort at breeding ages (Figure 3-1). The retrospective analysis also indicated a positive model bias in the estimation of resighting probability of non-puppers and the probability of non-puppers pupping and these estimates also appeared to stabilise after 3-4 years of collecting additional observations. There was no evidence for model bias in the estimation of survival at age 6-14 or the probability of puppers pupping associated with the number of years for which observations were used (*See* Figure B-36).

Estimation of tag loss rate & models fit to pup census observations

Tag loss rates were estimated in two models: one fitted to mark-recapture observations only and an integrated assessment model simultaneously fitted to mark-recapture and pup census observations. Two tag loss parameters were estimated: – the probability of losing a tag in the first year after tagging; and the probability of losing a tag at age 1+. Slightly lower tag loss parameter estimates were obtained from the model fitted to mark-recapture observations only (model run 11), 0.085 for tag loss at age 0 and 0. 049 for tag loss at age 1+; compared with 0.103 for age 0 and 0.063 for age 1+ for the model run also fitted to pup census observations (model run 12). In both these model runs the annual probability of losing both tags (in a single year) was calculated as the square of the probability of losing a single tag at each respective age and was thus: 0.007 at age 0 and 0.002 at age 1+ for the model fitted only to mark recapture observations, and increased to 0.011 at age 0 and 0.004 at age 1+ for the model also fitted to pup census observations. Estimates of tag loss rates are summarised alongside those of other demographic assessments of NZ sea lions at the Auckland Islands (Table 3-2).

Table 3-2: Annual tag loss rates estimates for females at Sandy Bay (model run 11) compared with estimates from other assessments. Model configurations of other assessments summarised in Table B-2.

Assessment	Parameter	Value	Comments
This assessment	Age 0; 2tags > 0tag	0.007	Separate tag loss probability for individuals ages 0 and 1+. Probability of losing two tags in the same year taken as the square of the probability of losing a single tag. Tag loss probabilities were assumed constant with respect to year.
	Age 1+; 2tags > 0tag	0.002	
	Age 0; 2tags > 1tag	0.156	
	Age 1+; 2tags > 1tag	0.093	
	Age 0; 1tags > 0tag	0.085	
	Age 1+; 1tags > 0tag	0.049	
Chilvers & Mackenzie (2010)	Age 0; 2tags > 0tag	0.10	Tag loss estimates use observations based on resightings of brands and PIT tags. Independent estimates for losing both tags in a single year. Tag loss probabilities were assumed constant with respect to year.
	Age 1+; 2tags > 0tag	0.01	
	Age 0; 2tags > 1tag	0.21	
	Age 1+; 2tags > 1tag	0.13	
	Age 0; 1tag > 0tag	0.13	
	Age 1+; 1tag > 0tag	0.13	
Mackenzie (2012)	2tags > 0tag	0.04	Tag loss estimates use observations based on resightings of brands and PIT tags. Tag loss probabilities were assumed constant with respect to animal age and year.
	2tag > 1tag	0.14	
	1tag > 0tag	0.11	

As expected, slightly increased estimates of survival parameters were obtained from models that also estimated tag loss rate across all years. The increase in survival estimates was approximately similar to the annual tag loss rate at the corresponding age. For example, with the model fitted to mark-recapture observations only, survival estimates at age 0 were 0.08 greater than those obtained using the same model parameterisation (model run 7) and survival estimates at age 6-14 were on average 0.05 greater when averaged across all years. This compares with estimated tag loss rates of 0.085 and 0. 049 at ages 0 and 1+ from the same model.

Good fits were obtained with pup census observations (model run 12) (*See* Figure B-38). Fitting to pup census produced generally increased estimates of survival at age 6-14 and reduced inter-annual variation in estimates of pupping rate, for puppers and non-puppers (*See* Figure B-39).

Models fits to age distribution observations

Good model fits were also obtained with age distribution observations (model run 13) (*See* Figure B-40). Fitting to age distribution observations had a minor effect on estimates of survival at age 0, with high survival of pups born in 1990-93 and low estimate for pups born in 1994-1997 (*See* Figure B-41), years for which there was no tagging program to inform to inform the estimation of survival. Age distribution observations were uninformative for all other parameters estimated in this model run and had an extremely small effect on estimates obtained.

3.2 Demographic assessment of females at Dundas

Mark recapture observations of females at Dundas were not sufficient to inform the estimation of pupping rate and age-at-first-pupping parameters, though reasonably precise estimates of survival at age were obtained despite the greatly reduced number of days in which resighting effort was conducted each year (< 10 days) relative to Sandy Bay (>30 days).

As with the Sandy Bay model there was a strong negative correlation between estimates of survival at age 0 and 1 (*See* Figure B-30), which was dealt with by using the MCMC samples to calculate cohort survival to age 2 (and to age 5, to account for not using resighting effort prior to 1998). The parameter correlation analysis also indicated some issues with the estimation of survival at age 6-14, which appeared to be increasingly negatively correlated with the probability of resighting individuals at age 8+ in years after 2005 (*See* Figure B-29). Thus there may be model bias in the estimation of adult survival at Dundas, as configured, that would be considered when viewing the time series of survival estimates for this demographic grouping.

As with Sandy Bay, estimates of survival up to age 2 were greatest in cohorts born in the early 1990s (Figure 3-8, pups only tagged in 1991 and 1992 at Dundas), though were low for cohorts born 1998-2004 relative to survival estimates for the Sandy Bay population (Figure 3-9). Model estimates indicate that cohorts born after 2003 may have had slightly improved survival up to age 2 relative to those born 1999-2002 (Figure 3-8). However, low estimates were again obtained for the 1998 and 2008 cohorts, for which high rates of tag failure are suspected. Estimates of survival at age 6-14 for the Dundas population were slightly different to those obtained for Sandy Bay; they were relatively high at Dundas from 1999-2003 (range 0.88-0.97) and very low in 2004-2005, 2007 and 2011 (range 0.61-0.73) (Figure 3-10). Posterior distributions of all model parameters are shown in Appendix B.

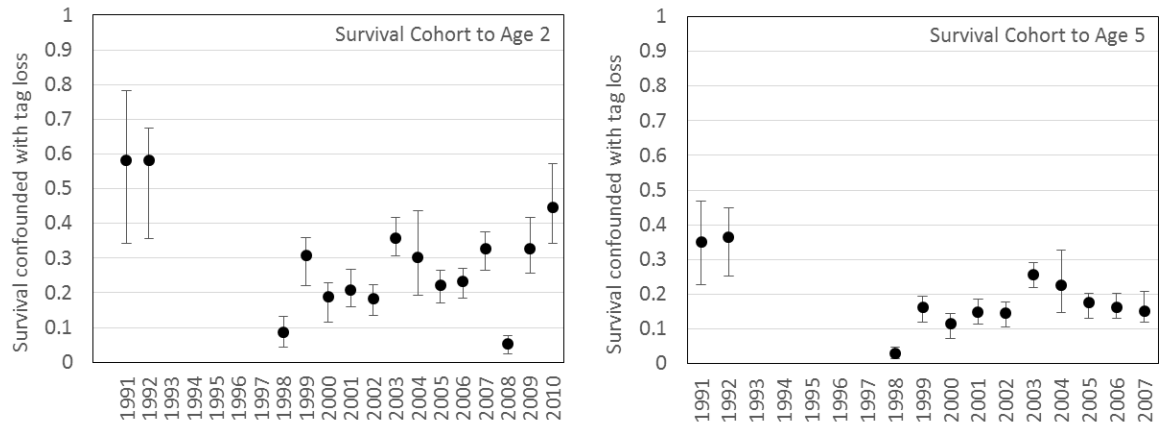

Figure 3-8: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Dundas (model run 9). Points are median estimates, bars are 95% confidence intervals.

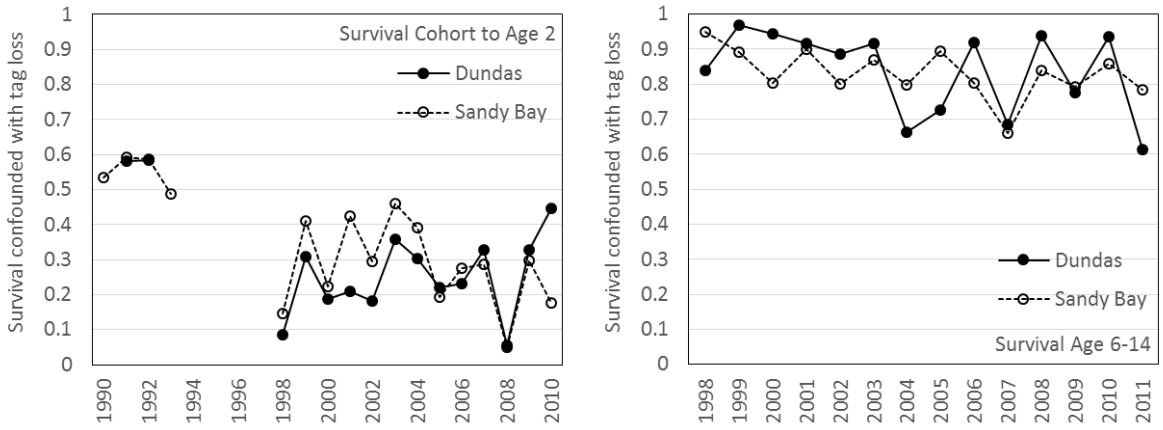

Figure 3-9: Comparison of MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay and Dundas (model runs 8 and 9).

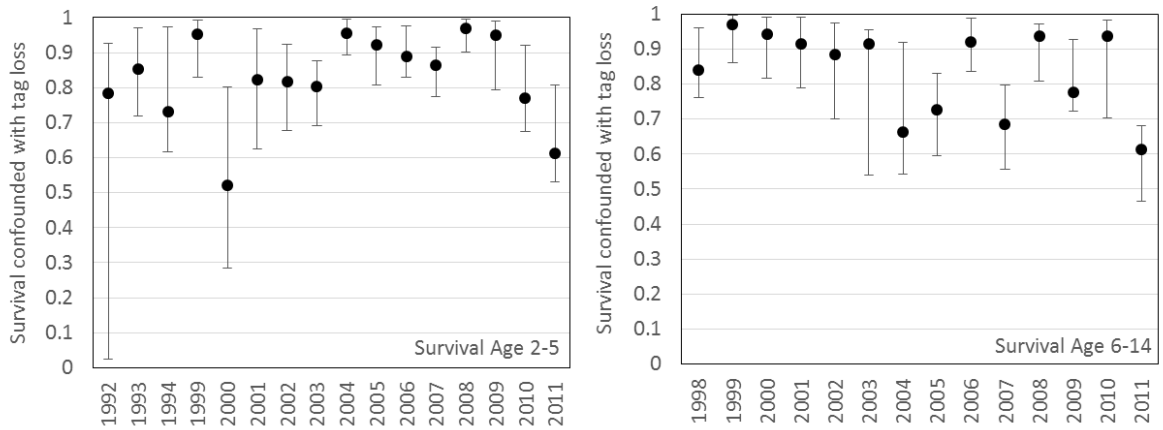

Figure 3-10: MCMC estimates of age-specific survival of female NZ sea lions at Dundas (model run 9). Points are median estimates, bars are 95% confidence intervals.

4 Discussion

4.1 Model configuration, observations and parameter estimation

A number of different model configurations/parameterisations were trialled, including: three different partition types (e.g. to accommodate observations of breeding status or number of tags), variation in parameters estimated (e.g. tag loss rate or age-at-first-pupping parameters were not estimated by some models) and variation in the way that parameters were estimated with respect to age and year (e.g. step functions versus functional forms or year-invariant parameter estimation). In addition, there were a number of fundamental differences in model configurations used here relative to previous demographic assessments, which may affect differences in the parameter estimates obtained given the same set of observations (summarised in Table 4-1).

With respect to survival, in this assessment an interaction model was used to estimate discrete annual survival probabilities for different age groupings (ages 0, 1, 2-5, 6-14 and 15+), which in the optimal model (model run 8) were year-varying for all groupings except for age15+. MacKenzie (2012) and Chilvers & MacKenzie (2010) used a model with additive age and year effects on survival, i.e., a fixed age pattern. Thus for a given year, age-specific estimates were not independent of each other (survival of ages 0-3 will have been influenced by observations of 4-14 and 15+ aged individuals). Gilbert and Chilvers (2008) estimated cohort specific survival for pups to age 1 (could also be considered to be a year effect) and a functional form (again a fixed pattern) for all other ages with year-invariant parameters (Table 4-1).

With respect to pupping rate, we estimated maturation parameters using a functional form, which gave the probability of immature individuals between ages 3 and 7 pupping in the following year. This meant that pupping rate could be estimated separately for individuals that were known to be reproductively mature and will have led to the estimation of different pupping rate values from those reported by MacKenzie (2012).

With respect to the observations models were fitted to, there were several differences comparing this and previous assessments. For example, Mackenzie (2012) used a different area subset of mark-recapture observations including all observations at Enderby, which include the Southeast Point colony (we used observations from Sandy Bay only); a different time series of observations including all flipper-tagged from 1998-2011 (we used all flipper-tagged 1990-1993 and 1998-2011); and observations of different marking types including PIT-tagged and branded individuals as well as flipper-tagged as pups (e.g. we only used flipper-tagged individuals) (Table 4-1). Observations of these individuals have been used in previous demographic assessments to obtain more accurate estimates of tag loss, including independent estimation of the probability of losing both tags in a single year. Where tag loss rates were underestimated, this will have consequences for the estimates of survival obtained.

In this assessment the parameterisation of survival (with respect to age and year) was optimised prior to resighting effort, then pupping rate parameters, then age-at-first-pupping. The order in which the parameters were optimised may have affected the final model structure that was obtained, though we did not explore the effects of optimising them in a different order.

Table 4-1: Summary of model configurations used in demographic assessments of NZ sea lions at the Auckland Islands.

Assessment	Colony and years of mark-recapture observations	Tag type	Survival	Resighting probability	Tag loss	Maturation at age	Pupping rate
This assessment	Females; Sandy Bay & Dundas; marked 1990-1993 & 1998-2011; resighting 1999-2012	Tagged pups, excluding branded pups and resighting where only a PIT tag ID was recorded	Independent estimates for each demographic grouping; survival functional form explored (as Gilbert & Chilvers 2008).	Annual resighting probability; independent estimates for each demographic grouping	Year-invariant; assumed can only lose 1 tag each year; 2 parameters: one for age 0 and another for all other ages	Two parameters give probability of pupping for first time at ages 4-7; year-varying	Separate estimates of pupping for females that did or didn't pup in the previous year; dome-shaped functional form explored (as Gilbert & Chilvers 2008) though not optimal
Breen et al., 2013	Females; Auckland Islands; marked 1987, 1990-93 & 1998-2004; resighting 1998-2007.	Tagged and branded as pups and adults	Annual survival at specified ages with survival at intermediate ages determined through linear interpolation. Density dependent pup survival.	Year-invariant with separate estimates for breeding and non-breeding females tagged as pups and non-breeding females that were branded	Not estimated	Implicitly incorporated in to age specific pupping rate	Age specific pupping rate. Functional form given by age at 50% maturity
Childerhouse *et al*., 2010b	Females; Sandy Bay; marked [not specified]; resighting 1999-2005.	Tagged as pups and branded as pups and adults	Not estimated	Not estimated – estimates of pupping rate for all individuals for which pupping status was confirmed and also for an additional dataset including individuals not seen though known to be alive (assumed to be non-puppers)	Not estimated	Implicitly incorporated in to age specific pupping rate	Estimated as a domed function of age with five parameters

Table 4-1: Continued

Assessment	Colony and years of mark-recapture observations	Tag type	Survival	Resighting probability	Tag loss	Maturation at age	Pupping rate
Chilvers & MacKenzie 2010	Males and females; Sandy Bay; marked 1990-1993 & 1998-2005; resighting 1999-2006	Tagged and branded pups; including resighting where only a PIT tag ID was recorded	Multiplier related estimates for each age grouping	Annual resighting probability, with separate estimates for individuals with 1 or 2 flipper tags and by age group.	Year-invariant; separate estimates for losing both tags or just one tag; 2 parameters: one for age0 and another for all other ages.	Not estimated	Not estimated
Chilvers et al., 2010	Females; Sandy Bay; marked 2000; resighted 2001-2005	Branded as adults	Estimated as a domed function of age with four parameters; year-invariant	Year-invariant estimates for different demographic groupings relating to pupping status and survival of pup	Not applicable to branded individuals	Implicitly incorporated into functional form of pupping rate at age	Estimated as a domed function of age with five parameters; separate estimates depending on pupping status and survival of pup in the previous year
Gilbert & Chilvers, 2008	Females; Enderby; marked 1987 & 1990-1993 & 1998-2003; resighting 2000-2007	Tagged and branded pups	Estimated first years survival for each cohort, then a functional form across all other ages with year-invariant estimation	Multipliers gave observation frequencies for different demographic groupings (not estimated independently)	Not estimated separately of survival	Implicitly incorporated into functional form of pupping rate at age	Estimated as a domed function of age with five parameters; separate estimation for each cohort; no separate estimation based on pupping status in previous year
MacKenzie, 2011	Females; Enderby (Sandy Bay and SE Point); marked 1990-1993 & 1998-2005; resighting 1999-2010	Tagged and branded pups; including resighting where only a PIT tag ID was recorded	Multiplier related estimates for each age grouping	Daily resighting probability estimated for PIT-tagged, branded and flipper tagged individuals; ages 0-3 and 4+. Converted to annual resighting probability.	Year-invariant; separate estimates for losing both tags or just one tag.	Not estimated	Separate estimates of pupping for females that did or didn't pup in year+1

4.2 Age and cohort effects on demographic rate estimates

Age effects on survival, resighting probability and pupping rate were assessed with a model with year-invariant parameters. Survival estimates were greatest for ages 2-5 and declined at later ages. The apparent step-down in survival post age 5 may relate to the increased energetic costs and other constraints relating to the onset of reproduction. The peak in pupping rate occurred at ages 9-11, though was relatively high at all ages from 7-12. Individuals ages 1 and 2 had a very low probability of resighting (<15% in a year). Also non-pupping animals had a much lower probability of being resighted relative to females confirmed to have pupped.

There appear to be cohort effects on survival at ages 6-14, with greater estimates for animals born in 1990-1993. There are also likely to be strong cohort effects on survival at ages 0 and 1 and these are discussed in relation to year effects on survival, below.

4.3 Estimation of pupping-related parameters

The proportion of individuals at age ascribed to each reproductive status in a year (i.e., immature, pupper or non-pupper) was calculated from estimated age-at-first-pupping and annual pupping rate parameters. These parameters were not estimated for the Dundas population for which there were too few individuals with confirmed pupping status each year to inform their estimation.

Age-at-first-pupping was represented by a functional form with two parameters: a first parameter which gave the proportion of 3 year olds that produce at pup at age 4; and a second parameter that gave the rate at which this proportion increased at subsequent ages up to age 8 when all individuals were assumed to be reproductively mature (these are strongly negatively correlated, *See* Figure B-31). The breakpoint analysis indicated that the estimated proportion of individuals pupping at age 4 was high in 2011 (Figure 3-7). Model estimates indicated that in a number of years (particularly 2001-2009) a large proportion of females had not pupped by age 8 (*See* Figure B-16). In the model using model partitioning I, all individuals >age 8 were assumed to be reproductively mature and, so, contributed to pupping rate estimates (in this case will have reduced the pupping probability of non-puppers).

A number of years with low pupping rates were identified, including 2002, 2005, 2006 and 2009 (Figure 3-4; pupping rate in these plots relates to pupping events in the following year), which were all identified as years with relatively low pupping rate in the demographic assessment by MacKenzie (2012). These low pupping rate years coincided with years with reduced pup production at Sandy Bay even when accounting for the long-term declining trend (Figure 1-1). Fitting to pup census reduced the variation in pupping rate estimates, because the decline in pup production was not as great as what would be expected from the mark-recapture estimates. This could potentially relate to age of tagged population effects (i.e., pups were not tagged in years 1994-1997 and these may have been good breeders in these years). Alternatively, breeders born at other rookeries of the Auckland Islands, including the much larger colony at Dundas may have bred at Sandy Bay in these years, though we did not assess the prevalence of breeding relocations in this assessment, nor were relocation events accounted for in any of our demographic models.

Previous assessments have highlighted potential cohort effects on pupping rates, obtaining low pupping rate estimates for the cohort born in 1998 (Gilbert & Chilvers 2008). This was related to potential disease effects, given the high rates of pup and adult mortality related to disease in that year. We found no evidence for low reproductive output of this cohort (per living individual at breeding age); an analysis of predicted numbers at age (model run 12) indicated that the pupping

rate of the 1998 cohort was actually relatively good. There are some major differences in model configuration, which may have led to these opposing results. Gilbert & Chilvers (2008) estimated year-invariant survival for age 0 only and a functional form was used to estimate survival at all other ages, with year-invariant parameter estimation. In this assessment (all model runs 7-13), survival was estimated separately for ages 0, 1, 2-5, 6-14 and 15+ and the estimates of survival at age 2-5 for pups born 1998 was the lowest of any cohort (*See* Figure B-2). Thus the model configuration adopted by Gilbert and Chilvers (2008) will have underestimated pre-breeding mortality of this cohort and overestimated the number of non-breeding individuals (which have a low resighting probability). Furthermore, the tag failure rate for this cohort is likely to have been high (*See* Appendix C), and relatively low survival estimates up to age 5 are likely to relate to high tag loss rates for this particular cohort (*See* Figure B-2).

4.4 Estimation of survival

For all models used in this assessment except for runs 11 and 12, tag loss parameters were not estimated and survival rates will be lower than their true values (confounded with tag loss). In models where tag loss rate was estimated, the probability of losing both tags was calculated as the square of the probability of losing a single tag, though it is thought that the rate of losing both tags in a year is greater than the combined probability of losing a single tag in one year and another tag in the next (MacKenzie 2011; Chilvers & MacKenzie 2010). Model estimates of tag loss rate from model run 11 (fitted to mark-recapture only) are generally lower than those obtained from other assessments, with the consequence that estimates of survival from this study will tend to be lower (Table 3-2). This is one of the possible explanations for the increase in survival estimates (at ages 6-14) when fitting to pup census (model run 12), compared with mark-recapture only (e.g. model run 7). Emigration out of each study population would also reduce estimates of survival, though we did not assess the extent to which this occurs or attempt to estimate rates of breeding relocation.

There has been variation in flipper-tag design, application and breakability through time, e.g. round tags were deployed in 1990-1993, button tags in 1998, coffin tags in all other years since 1999. Also tags were reported to have high pull-out rate (indicative of tag failure) in 2008 (Chilvers, pers. comm.). Given that separate year-invariant tag loss probabilities were estimated for age 0 and age 1+, cohort-specific estimates of survival (e.g. to age 2) will be confounded with the yearly deviations in tag loss rate. We did not make use of PIT-tag observations or observations of branded individuals (given differences in resighting probability and added partitions required to accommodate them) and so could not estimate year of tagging effects on tag loss.

Model estimates of survival at ages 0 and 1 indicated relatively strong year effects on survival (e.g. years of high survivorship of pups born in 1990, 1991, 1992 and 1993; low survivorship of pups born in 1998, 2000, 2005 and 2008) and a long-term decline relative to strong cohorts in 1990-1993. These were also identified to be strong cohorts in an ageing study of lactating females in 1998-2001 (Childerhouse et al., 2010a) and we obtained good model fits to age distribution without great alteration in estimates of survival at ages 0 and 1. The model fit to age data also generated low estimates of pup/yearling survival of cohorts 1994-97 for which the tagging data were not informative. At Sandy Bay, pup/yearling survival estimates were particularly low for cohorts 2005-2010. The retrospective analysis indicated that this may partly be explained by a model bias towards underestimation of survival at age 0 in later years, though this would have a minor effect on cohorts born 2005-2007 for estimates were still relatively low. Even so, annual estimates of survival at age 0 were similar to those obtained from an assessment in MARK using the same observations with the

same model configuration and were nearly identical for most years (McMahon & Hindell, 2013; see Appendix E).

There was also inter-annual variation in estimates of survival at Sandy Bay at prime breeding ages (6-14). The lack of consistent resighting effort prior to 1998 meant that there were few estimates during the period of population increase in the mid to late 1990s (Table 1-1). However, estimates for 1998 and 1999 were high relative to most years during the post-1999 period of population decline (1998-1999 was identified as separate grouping in the breakpoint analysis for survival at ages 6-14). As parameterised, adult survival relates to 9 age classes (6-14) relative to only 2 age classes for survival to age 2. As such, small deviations in adult survival parameters would have greater relative consequences for population trajectory, though we have made no attempt to assess which of the decline in pup/yearling survival or adult survival has had a greater effect.

The estimate for 2007 was particularly low and appeared to primarily affect cohorts at first time breeding ages (born 2000, 2001 and 2002; *See* Figure B-9). Factors relating demographic rates to reproductive biology are addressed in the correlative assessment report (Roberts et al., 2014).

Similar year trends in survival at age were obtained for the Dundas population with a much smaller set of mark-recapture observations, though negative correlations with resighting probability suggest that the estimates obtained should be treated with caution. In addition the increase in proportion of pups flipper tagged at Dundas being resighted at Sandy Bay (especially cohorts 2005 and 2006) suggests that migration events may have occurred between these two rookeries. Also models could be configured to estimate survival of Dundas tagged pups from resightings at Sandy Bay (Figure A-3).

4.5 Use of demographic rate estimates in the correlative assessment

In the next project phase, a simple correlative analysis was used to relate demographic estimates to biological, environmental and fishery-related datasets, to inform the identification of environmental drivers of population change. Median values of parameter estimates were used as point estimates. The error distributions associated with demographic parameter estimates were not used in the correlative analysis. As such, relationships identified in the correlative analysis should be taken as indicative and potentially highlighting areas for more thorough assessment.

The demographic rate estimates (age-specific survival and pupping related parameters) from model run 8 (Sandy Bay) were carried forward to the correlative analysis (Roberts et al., 2014). Model run 8 did not estimate tag loss rates, as such the absolute estimates of survival will be lower than the true rates (confounded with tag loss, and migration, potentially). As such the survival time series carried forward to the correlative analysis can be considered a year-varying index of survival, which can be related to year-varying biological, environmental and fishery-related correlates.

Year of tagging effects on tag loss rate are likely to have negatively biased the estimates of survival to age 2 of the 1998 and 2008 cohorts. This was handled by conducting a sensitivity analysis in which estimates for these cohorts were omitted.

The break point analysis indicated that pupping rate and pup survival rates were very different prior to 2005, relative to years after. This was taken as justification for taking year subsets of demographic rates before and after this year when conducting the correlative assessment, where there was a biological justification for doing so.

4.6 The demographic causes of population decline at the Auckland Islands

The prime objective of this assessment was to identify the year-varying demographic rates that have caused the observed decline in pup production at the Auckland Islands since the late-1990s. We assumed that demographic factors affecting the female sub-population would have a greater effect on total population trends than those affecting the male population. This assessment focussed on the female component of the population and we do not know how, for example, the survival of males related to that of females.

This assessment focussed on the Sandy Bay population for which a more intensive and consistent time series of mark-recapture observations have been collected. Model estimates indicated a decline in the survival to age 2 since the early 1990s. In addition there is evidence for a decline in the survival of breeding age females since the late 1990s, coincident with the onset of the decline in pup production (comparing survival in 1998-1999 and later years) (Figure 1-1) (Figure 3-3). Unfortunately, there was no consistent resighting effort in years immediately preceding 1998 when pup census estimates had a consistent increasing trend. A more thorough assessment of tag loss rates and between-colony relocations may be required to obtain estimates of survival that would be suitably robust for explaining population trends. NZ sea lions are known to exhibit strong natal fidelity in the selection of breeding site and we did not explore potential relocation effects on demographic rate estimates, or the prevalence with which breeding relocations have occurred between rookeries at the Auckland Islands.

In addition, estimates of pupping rate are low for a pinniped species (as identified in previous assessments, e.g. Childerhouse et al., 2010b) and we found evidence for years with very low pupping rate, which would also compromise the long-term productivity of this population.

The basic model configuration developed to assess the Sandy Bay population was also used to obtain preliminary estimates of age dependent survival at Dundas. Issues were identified with correlations between key model parameters (e.g. survival and resighting probability of breeding age females). Even so, there were similarities comparing the basic time trends of survival at age for the Sandy Bay and Dundas populations.

5 Acknowledgements

We would like to acknowledge the help we received from a number of individuals in developing this assessment, including: Louise Chilvers (DOC/Massey University), Andrew Trites (University of British Columbia) and Mark Hindell (University of Tasmania) relating to reproductive biology, the use of field observations and the development of demographic assessments for NZ sea lions and other pinniped species. We also thank Simon Childerhouse for supplying the raw age data and Daryl MacKenzie (Proteus) and numerous participants of the DOC CSP Technical Working Group for providing many constructive reviews of this analysis. Also Vidette McGregor, Kath Walker, Ian Tuck and Charles Edwards (all NIWA) for reviews of earlier drafts of this manuscript and previous progress reports. We must also acknowledge the hard work of the field researchers at the Auckland Islands, without which our models would have nothing to fit to.

6 References

Baker C.S., Chilvers B.L., Constantine R., Dufresne S., Mattlin R., Van Helden A., Hitchmough R. (2010) Conservation status of New Zealand Marine Mammals (suborders Cetacea and Pinnipedia), 2009. *New Zealand Journal of Marine and Freshwater Research*, 44, 101–115.

Breen P.A., Fu D., Gilbert D.J. (2012) *Sea lion population modelling and management procedure evaluations.* New Zealand Aquatic Environment and Biodiversity Report 2012/xx

Childerhouse S.J., Amey J., Hamer D., McCrone A. (2013) *DRAFT Final report for CSP Project 4426 New Zealand sea lion ground component 2012/13.* Unpublished Report to the Conservation Services Programme, Department of Conservation, Wellington, New Zealand. Version 1.0. 20 p.

Childerhouse S.J., Dawson S.M., Slooten E., Fletcher D.J., Wilkinson I.S. (2010a) Age distribution of lactating New Zealand sea lions: Interannual and intersite variation. *Marine Mammal Science*, *26*: 123-139.

Childerhouse S.J., Dawson S.M., Fletcher D.J., Slooten E., Chilvers B.L. (2010b) Growth and reproduction of female New Zealand sea lions. *Journal of Mammalogy,* 91: 165-176.

Chilvers B.L. (2012) Using life-history traits of New Zealand sea lions, Auckland Islands to clarify potential causes of decline. *Journal of Zoology*, *287*: 240-249.

Chilvers B.L., MacKenzie D.I. (2010) Age- and sex-specific survival estimates incorporating tag loss for New Zealand sea lions *Phocarctos hookeri*. *Journal of Mammalogy*, *91*: 758-767.

Cormack R.M. (1964) Estimates of survival from the sighting of marked animals. *Biometrika*, *51*: 429-438.

Francis R.I.C.C., Sagar P.M. (2012) Modelling the effect of fishing on southern Buller's albatross using a 60-year dataset. *New Zealand Journal of Zoology, 39*:1, 3-17.

Gilbert D.J., Chilvers B.L. (2008) *Final report on New Zealand sea lion pupping rate. POP2006-01.* Objective 3. Analysis from sea lion database to estimate pupping rate and associated parameters.

MacKenzie D.I. (2012) *Estimation of Demographic Parameters for New Zealand Sea Lions Breeding on the Auckland Islands - Final Report: 1997/98-2010/11.* Objective 3: POP2010/1

McMahon C., Hindell M. (2013) Age-specific survival estimates for New Zealand sea lions *Phocarctos hookeri*. Unpublished Report. Institute for Marine and Antarctic Studies, University of Tasmania.

Roberts J., Fu D., Doonan I., Francis R.I.C.C. (2014) New Zealand sea lions – demographic assessment of the cause of decline at the Auckland Islands (POP2012—02): demographic model options – correlative assessment. Report for the NZ Department of Conservation.

Robertson B.C., Chilvers B.L. (2011) The population decline of the New Zealand sea lion *Phocarctos hookeri*: a review of possible causes. *Mammal Review, 41*: 253-275.

White G.C., Burnham K.P. (1999) Program MARK: survival estimation from populations of marked animals. *Bird Study, 46*: 120-139.

Appendix A Summary plots of mark-recapture observations

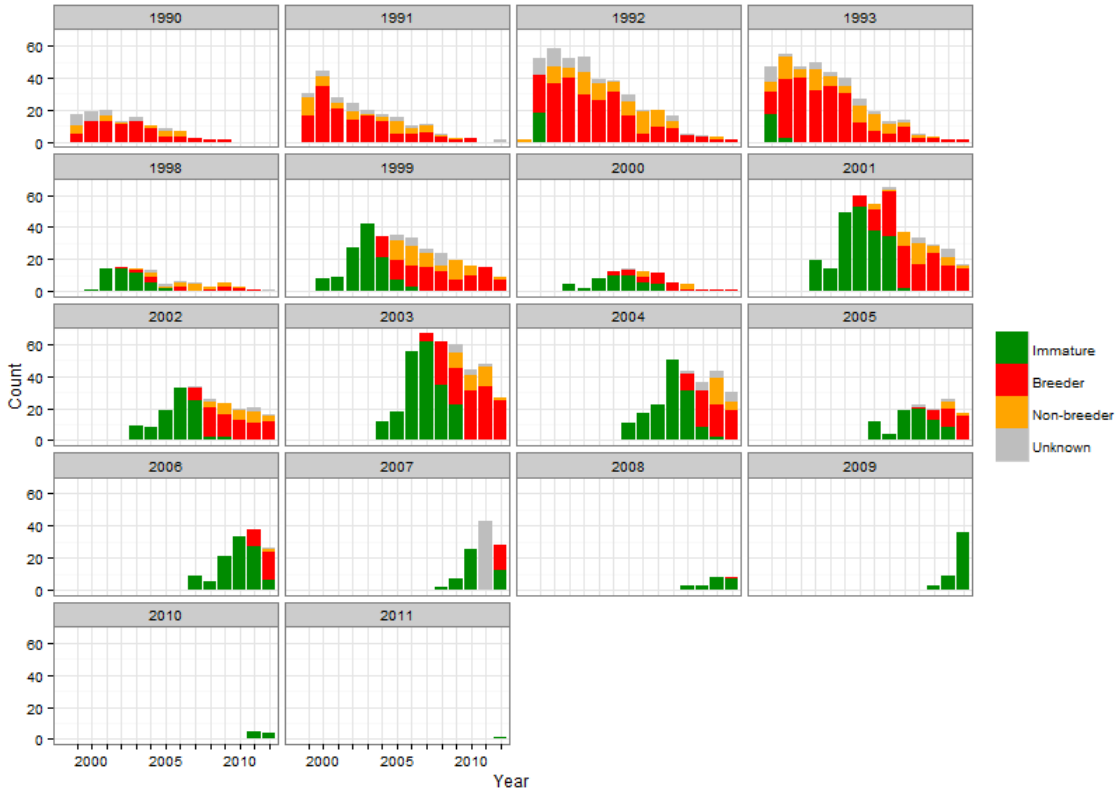

Figure A-1: Summary of mark-resighting observations of female NZ sea lions flipper-tagged as pups at Sandy Bay and resighted at Sandy Bay. Cohort birth year is a banner above each plot, x-axis is the resighting year.

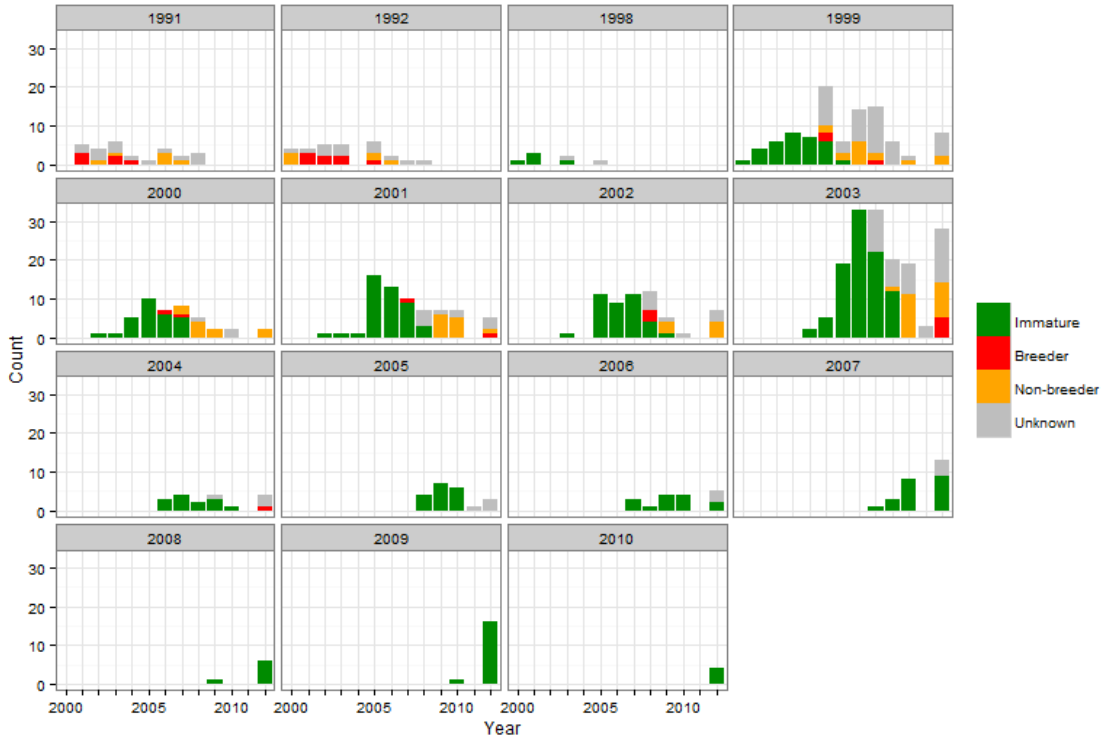

Figure A-2: Summary of mark-resighting observations of female NZ sea lions flipper-tagged as pups at Dundas and resighted at Dundas. Cohort birth year is a banner above each plot, x-axis is the resighting year.

Figure A-3: Summary of mark-resighting observations of female NZ sea lions flipper-tagged as pups at Dundas and resighted at Sandy Bay. Cohort birth year is a banner above each plot, x-axis is the resighting year.

Appendix B Model configuration and estimates

Model configuration

Table B-1: Model configurations used in this assessment; "MR" - tag-resighting data, "PP" - pup production, "AD" - age distribution. Three different model partition types used. Mark-recapture observations from Sandy Bay "SB", or Dundas "DD".

Modelling objective	Run	Model	Observations	Partitioning	Tag loss parameters	Phantom tags	Year-varying parameters	Area	MCMC run
Explore age, cohort and year effects; identify initial model parameterisation	1	Age-effects	MR	I	N	N	N	SB	N
	2	Cohort-effects	MR	I	N	N	N	SB	N
	3	Year-effects	MR	I	N	N	Y	SB	N
Sequentially determine optimal parameterisations of survival, resighting, pupping & age-at-first-pupping	4a-m	Survival optimisation	MR	I	N	N	Y	SB	N
	5a-m	Resighting optimisation	MR	I	N	N	Y	SB	N
	6a-d	Pupping optimisation	MR	I	N	N	Y	SB	N
	7	Age-at-first-pupping optimisation	MR	I	N	N	Y	SB	N
Produce "optimal model" for MCMC runs	8	Optimal model Sandy Bay	MR	I	N	Y	Y	SB	Y
	9	Optimal model Dundas	MR	III	N	Y	Y	DD	Y
Model validation runs	10	Retrospective analysis	MR	I	N	Y	Y	SB	N
	11	Tag loss model	MR	II	Y	Y	Y	SB	N
	12	Fit to pup counts	MR, PP	II	Y	Y	Y	SB	N
	13	Fit to age distribution	MR, AD	I	N	Y	Y	SB	N

Table B-2: Detailed model configuration of all models developed during the model optimisation process. Models in each optimisation stage (3-7) ranked in descending order of AIC (best model at the bottom of those in each optimisation stage); parameters denoted by age groupings (numerals); pupping status ("P" = puppers; "N" = non-puppers); and names of parameters used in functional forms.

Optimisation	Model run	Survival		Resighting probability		Pupping rate		Age at first pupping		Parameter *n*	Delta AIC
		Parameters	Year groupings	Parameters	Year groupings	Parameters	Year groupings	Parameters	Year groupings		
Initial model	3	0, 1, 2-5, 6-14, 15+	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	208	83
Survival	4l	0, 1, 2-5, 6-14, 15+	1 & 15+ year-invariant	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	186	1,030
	4f	0-1, 2-5, 6-14, 15+	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	191	1,027
	4b	u1, u3, u4, max (u3) at age2	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	144	262
	4a	u1, u3, u4, max (u3) at age3	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	145	262
	4c	0, 1, 2, 3, 4, 5, 6-14, 15+	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	243	132
	4g	0, 1, 2-14, 15+	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	194	101
	4d	0, 1, 2, 3-5, 6-14, 15+	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	222	98
	4e	0, 1, 2-4, 5-14, 15+	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	208	98
	4h	0, 1, 2-5, 6+	All year varying	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	201	97
	4j	0, 1, 2-5, 6-14, 15+	6+ year-invariant	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	189	84
	4k	0, 1, 2-5, 6-14, 15+	2-5 & 15+ year-invariant	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	187	82
	4i	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	202	81
	4m	0, 1, 2-5, 6-14, 15+	0 & 15+ year-invariant	1,2,3,4,5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	185	61
Resighting probability	5c	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1,2,3,4-6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	182	879
	5a	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1,2,3,4-7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	175	149
	5k	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	0-7 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	127	121
	5e	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	N year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	166	101
	5g	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	6 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	170	85
	5i	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	3 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	168	83
	5f	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	7 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	170	82
	5h	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	4-5 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	169	78
	5b	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1,2,3,4-5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	192	75
	5d	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	All year varying	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	179	67
	5l	0, 1, 2-5, 6-14, 15+	0 & 15+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	149	63
	5m	0, 1, 2-5, 6-14, 15+	6+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	153	62
	5j	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	4-14 (P), 4-14 (N), 15+ (P), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	166	58
Pupping rate	6c	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	functional form	All year-varying	PrB1sta & oddsmult	All year-invariant	166	63
	6a	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	4+ (P), 4-14 (N), 15+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	159	51
	6d	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	functional form	All year invariant	PrB1sta & oddsmult	All year-invariant	154	46
	6b	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	4+ (P), 4+ (N)	All year-varying	PrB1sta & oddsmult	All year-invariant	152	43
Age at first pupping	7	0, 1, 2-5, 6-14, 15+	15+ year-invariant	1-2,3,4-5,6,7,N	1-2 year-invariant	4+ (P), 4+ (N)	All year-varying	PrB1sta & oddsmult	All year-varying	178	0

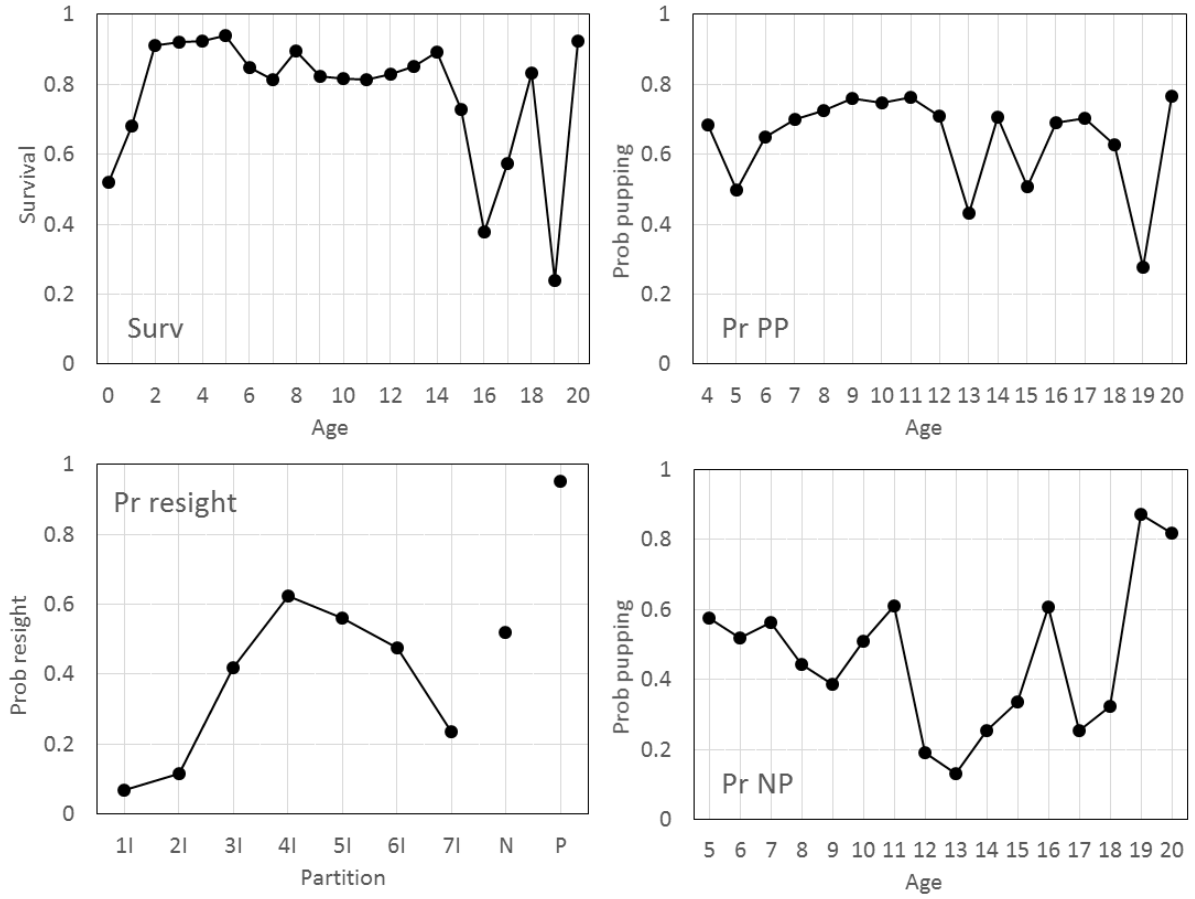

Figure B-1: Estimated parameter values for model exploring age-effects on survival, resighting probability and probability of pupping (model run 1).

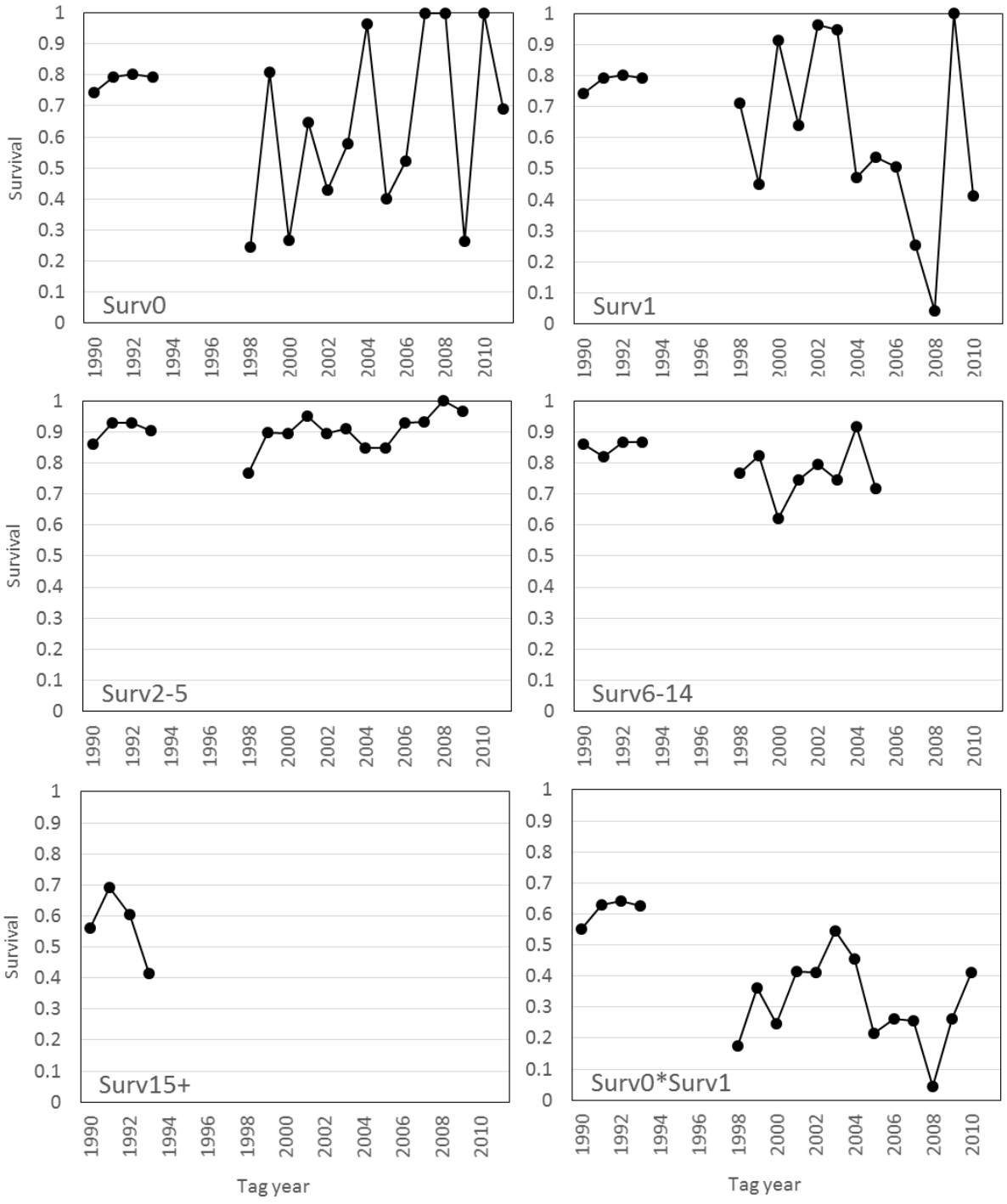

Figure B-2: Model estimates of survival for model exploring cohort-effects on survival, resighting probability and probability of pupping of females at Sandy Bay (model run 2). "Tag year" along y-axis relates to year of tagging as pup or "cohort". Bottom right panel plot gives product of survival across ages 0 and 1.

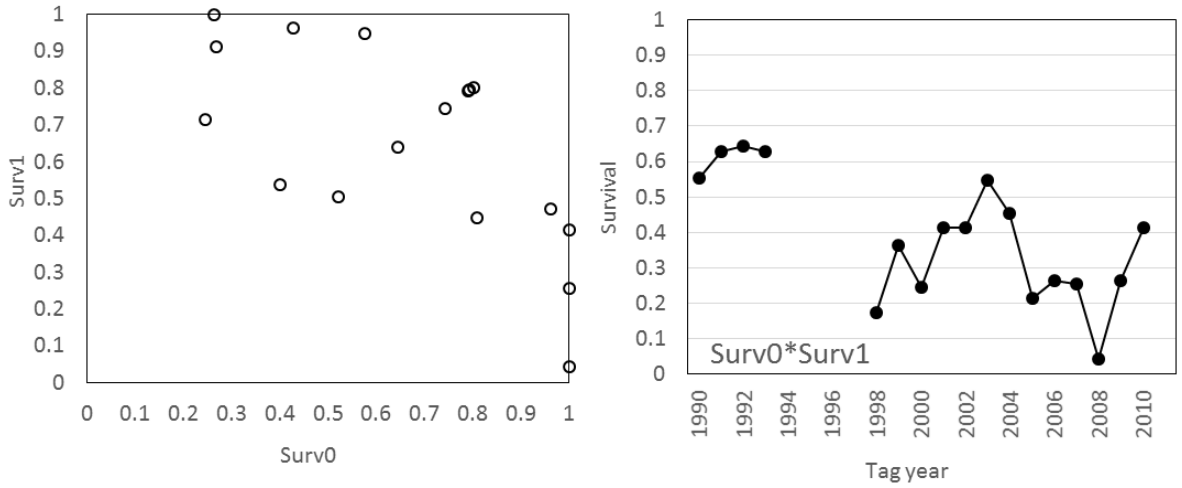

Figure B-3: Scatterplot of model estimates of survival. At age 0 in yr and 1 in yr+1 (left); and cohort survival to age 2 (right) of females at Sandy Bay (model run 2).

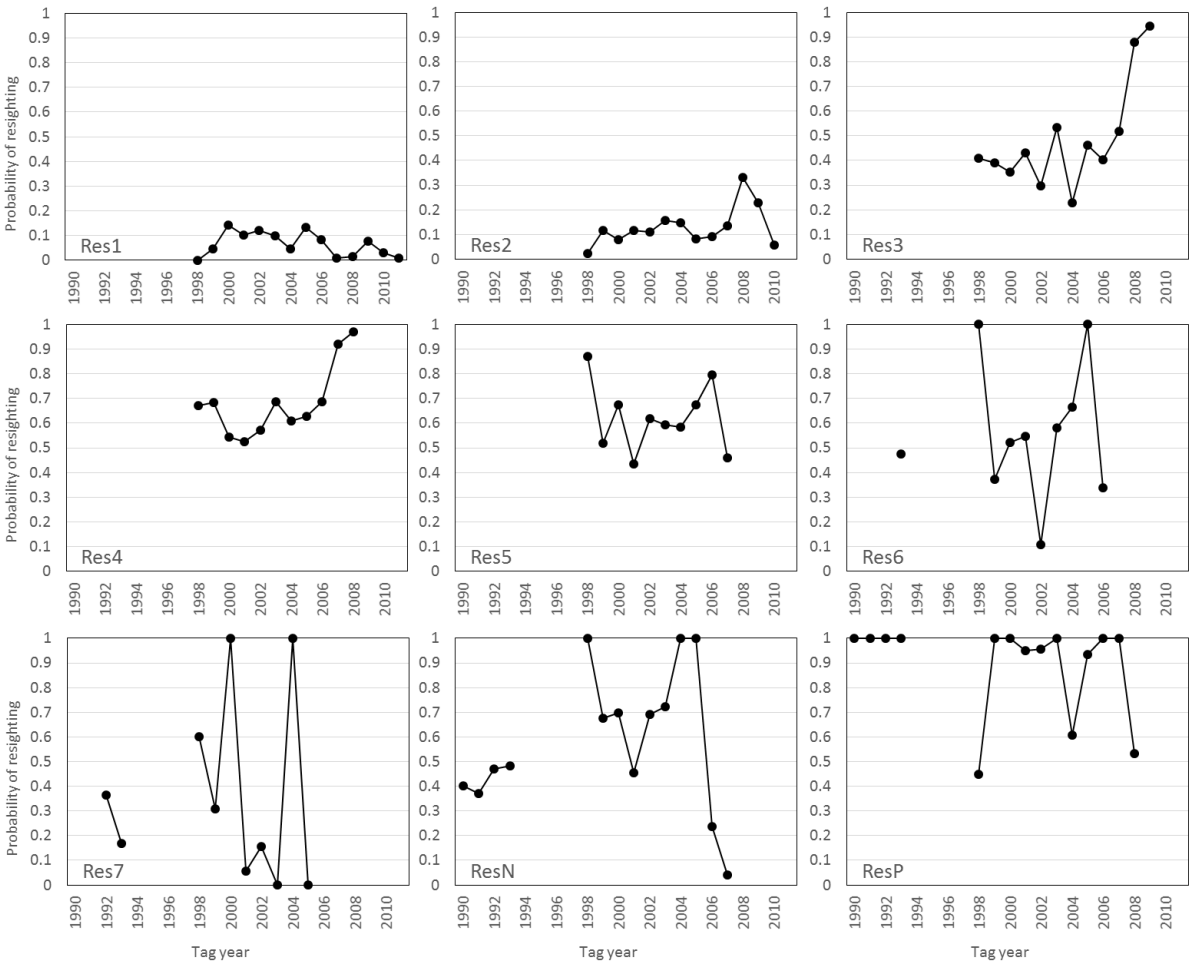

Figure B-4: Model estimates of resighting probability for model exploring cohort-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 2). "Tag year" along y-axis relates to year of tagging as pup or "cohort".

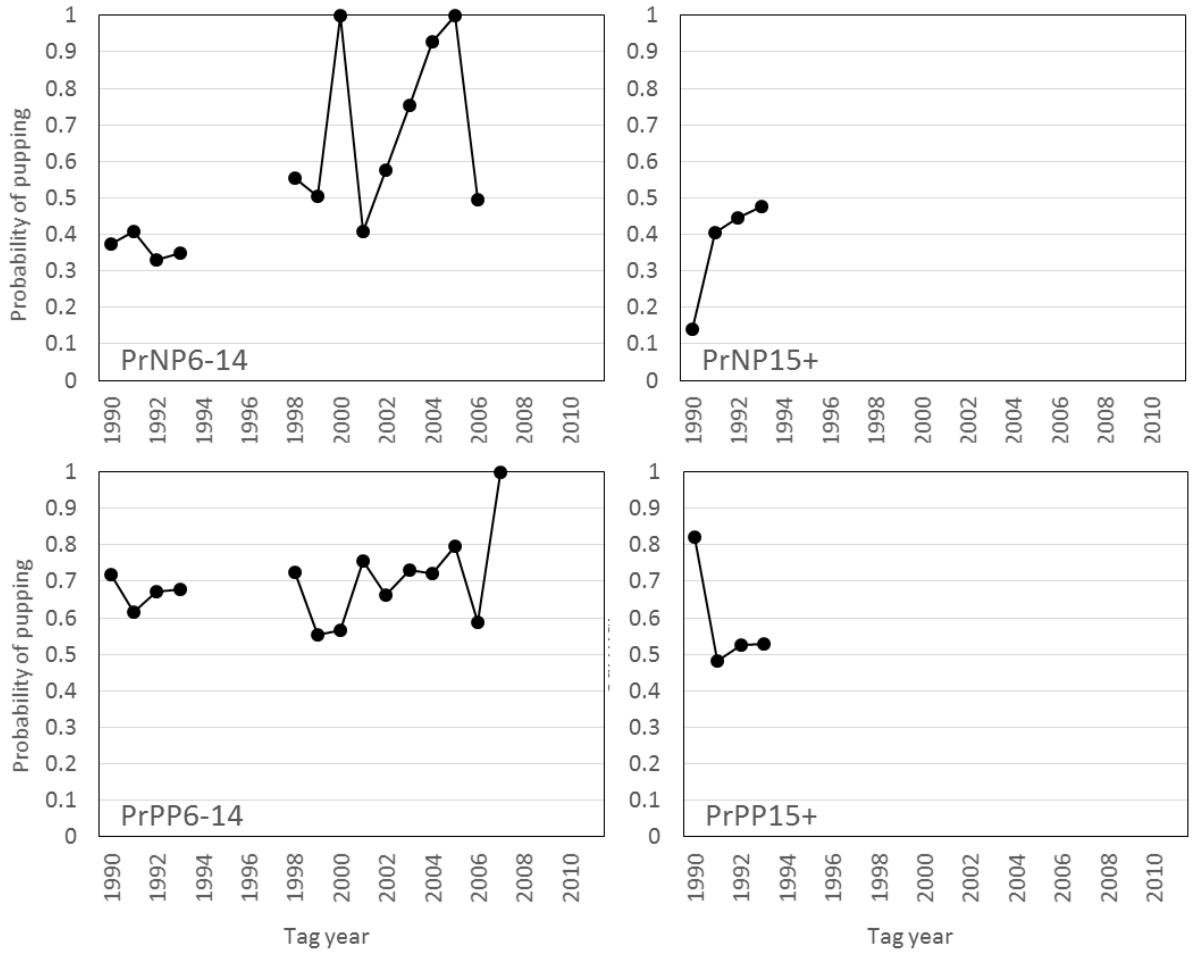

Figure B-5: Model estimates of pupping probability for model exploring cohort-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 2). "Tag year" along y-axis relates to year of tagging as pup or "cohort".

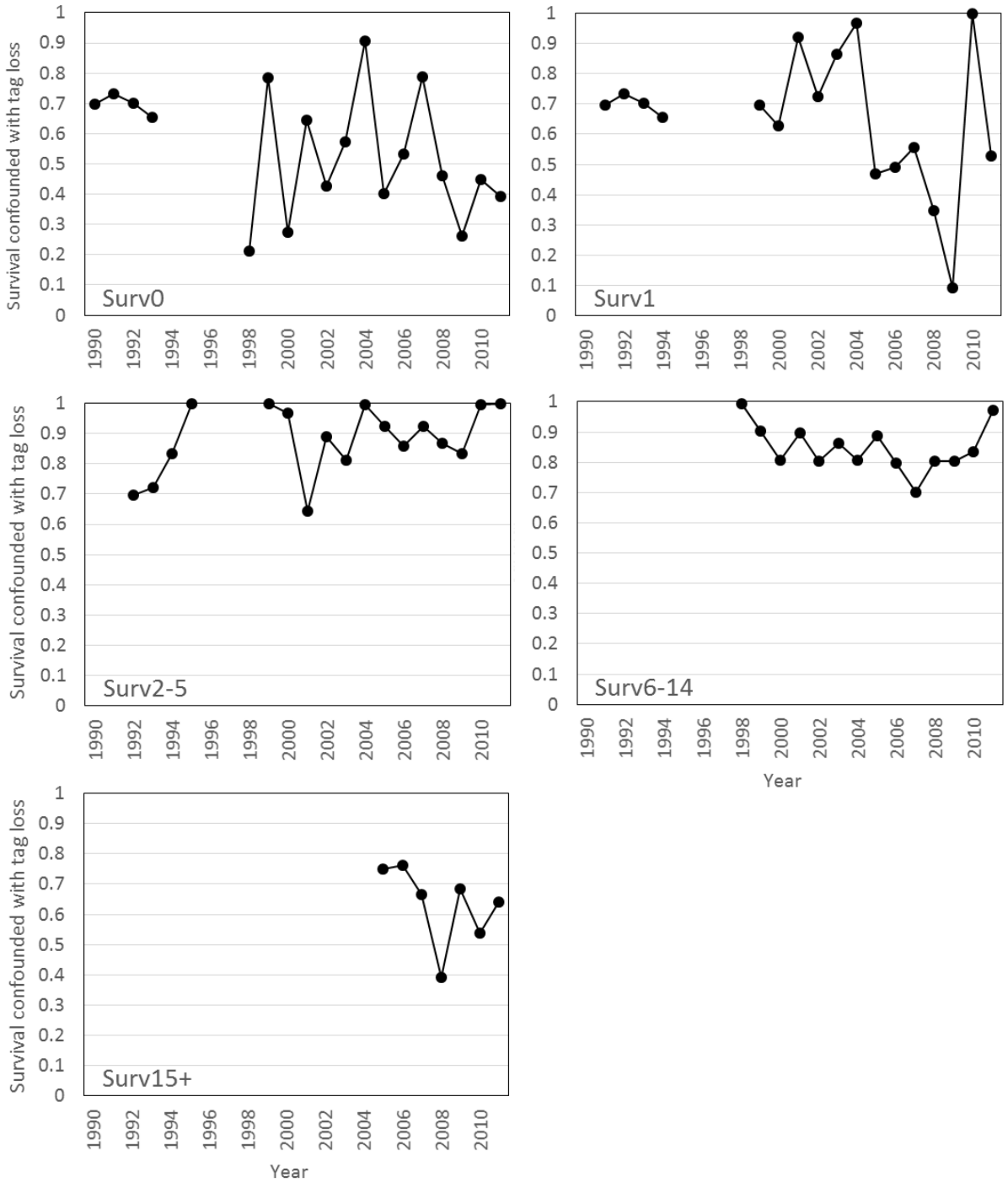

Figure B-6: Model estimates of survival for model exploring year-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 3). "Year" along y-axis relates to survival at year to year+1.

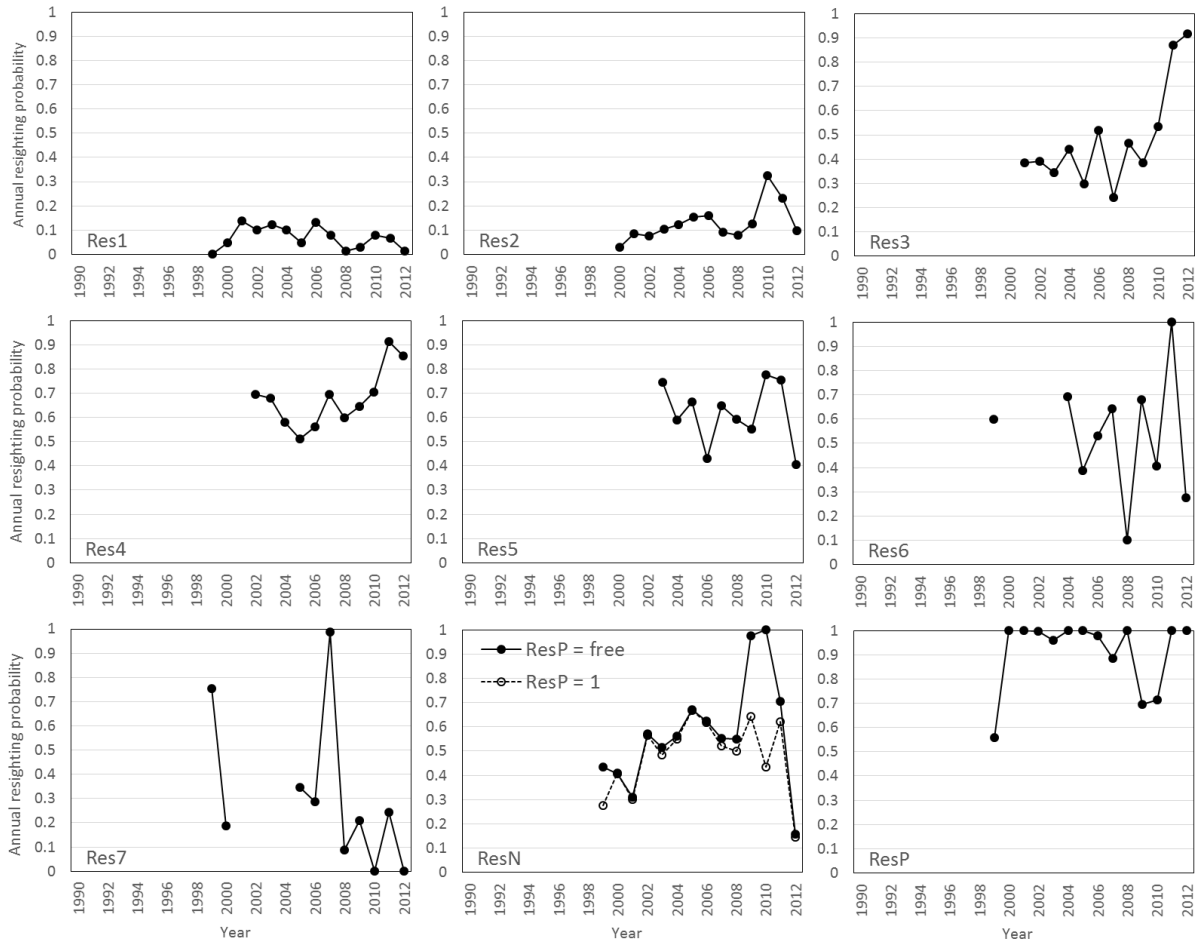

Figure B-7: Model estimates of resighting probability for model exploring year-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 3). "Year" along y-axis relates to survival at year to year+1; black points connected by orange lines are estimates with resighting probability of puppers free; purple points and lines are estimates with probability of puppers pupping constrained to 1.

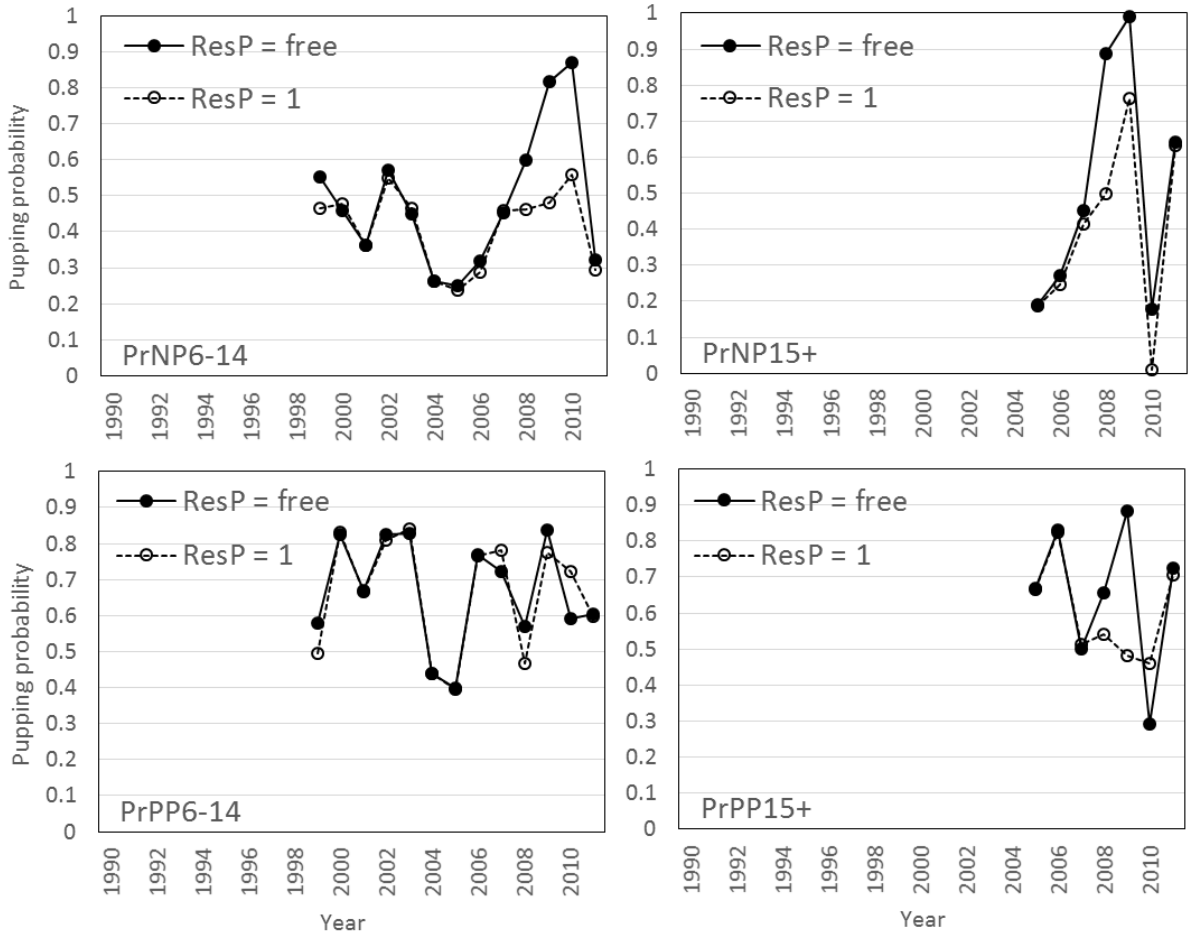

Figure B-8: Model estimates of pupping probability for model exploring year-effects on survival, resighting probability and probability of pupping for females at Sandy Bay (model run 3). "Year" along y-axis relates to survival at year to year+1; black points connected by orange lines are estimates with resighting probability of puppers free; purple points and lines are estimates with probability of puppers pupping constrained to 1.

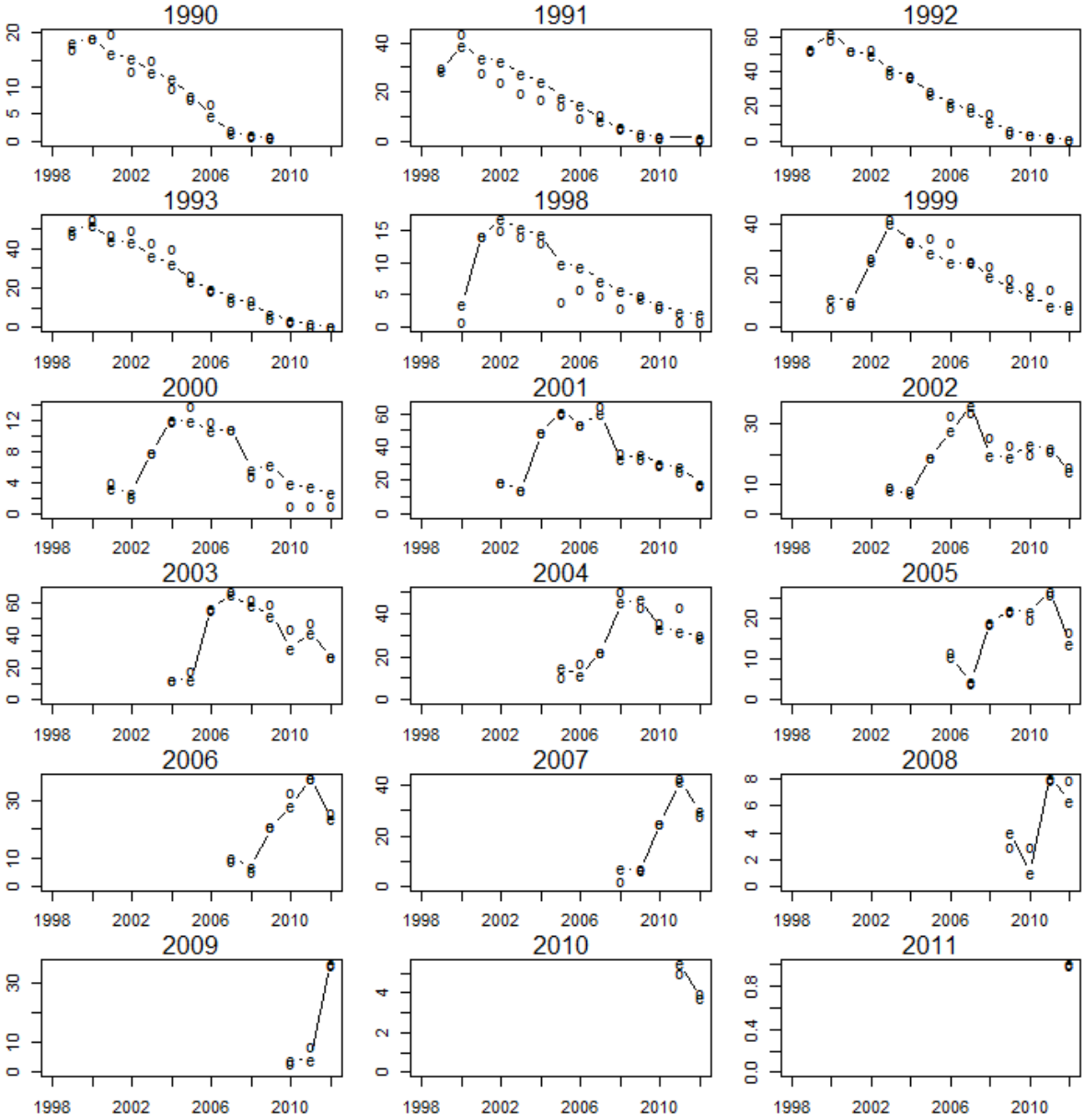

Figure B-9: : Fits of tag resighting frequency by cohort (one plot for each cohort) and year of resighting (y-axis), comparing model estimates ("e") and observed values ("o"). Model run 7 for females at Sandy Bay.

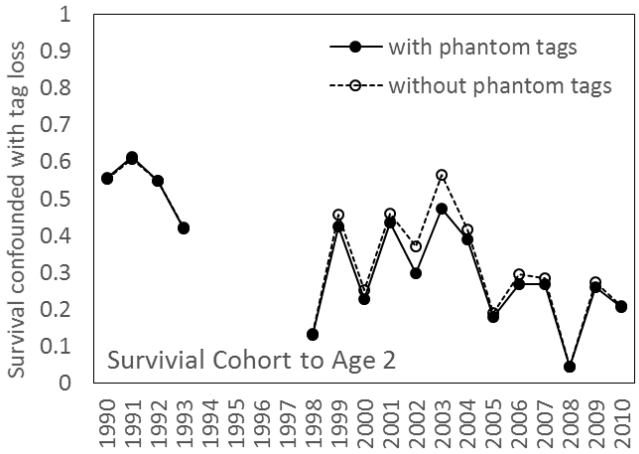

Figure B-10: Effect of inclusion of phantom tags on model estimates of cohort survival to age 2. . Model run 7, females at Sandy Bay.

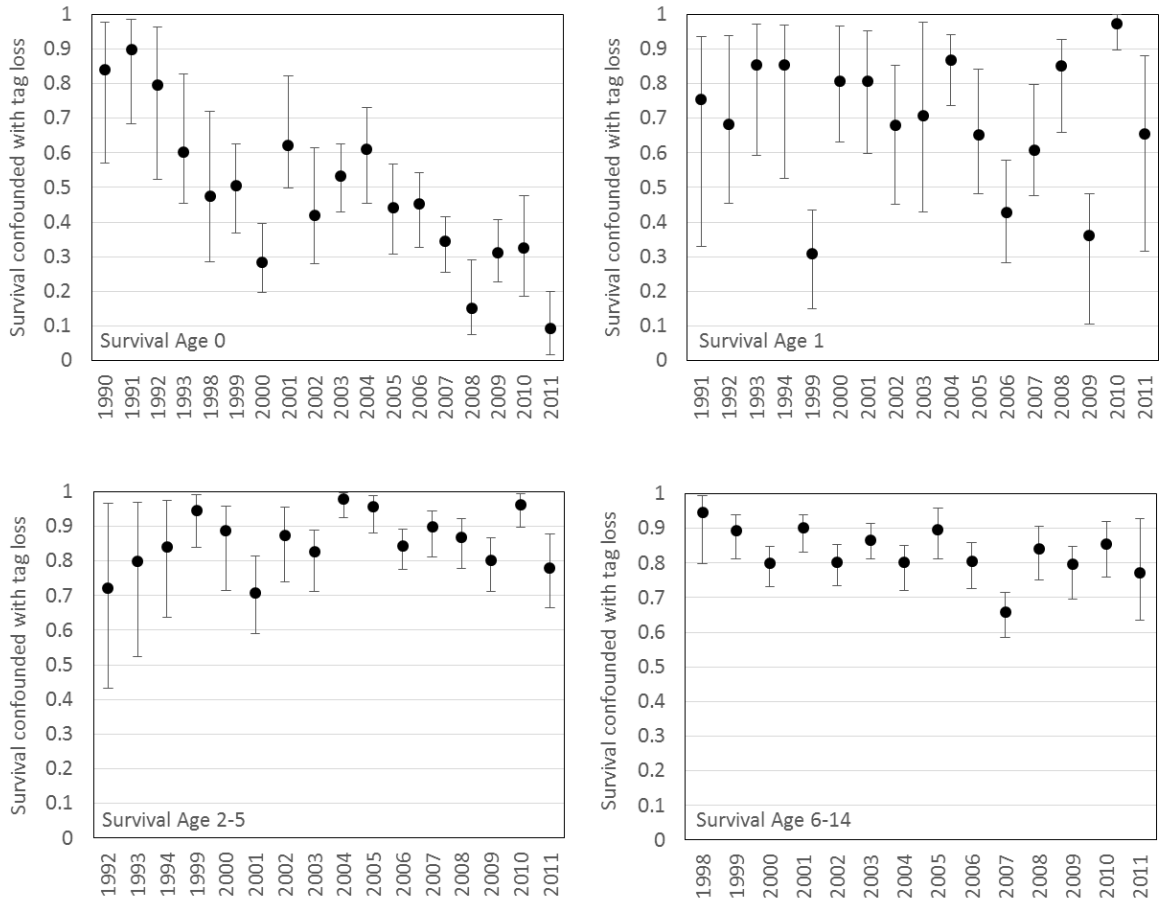

Figure B-11: MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

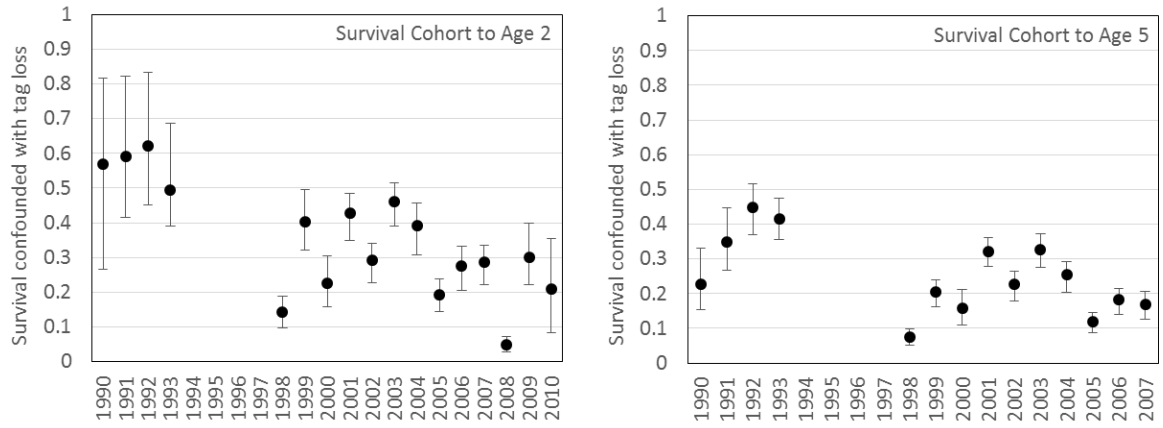

Figure B-12: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

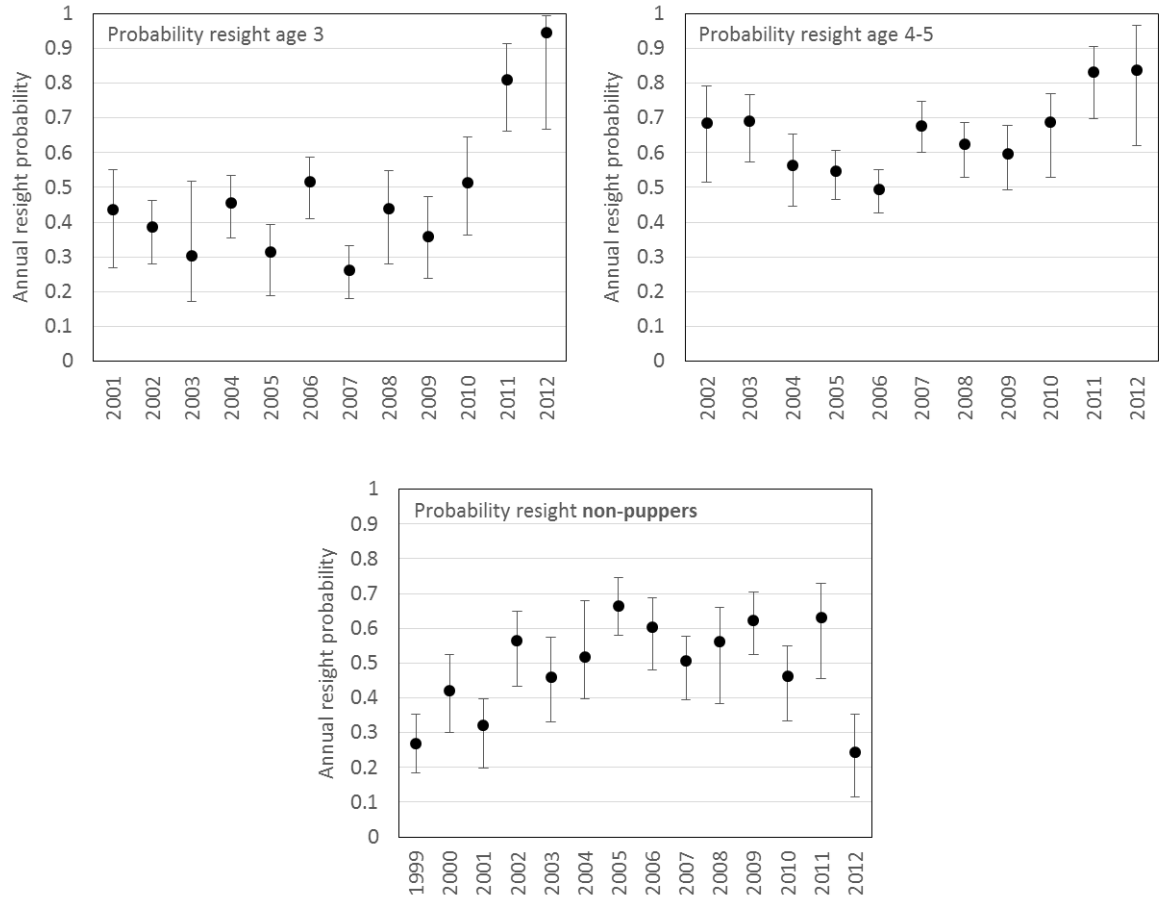

Figure B-13: MCMC estimates of age/status-specific resighting probability of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

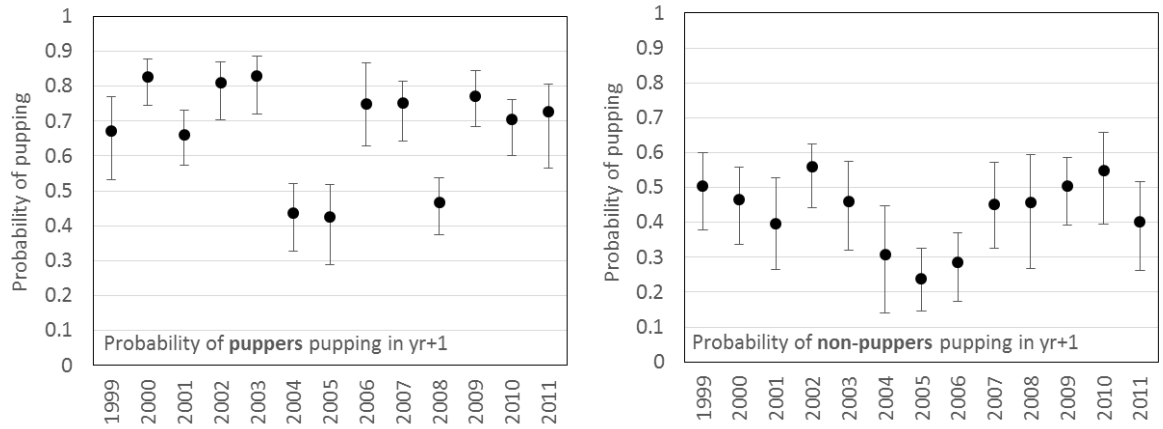

Figure B-14: MCMC estimates of pupping probability of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

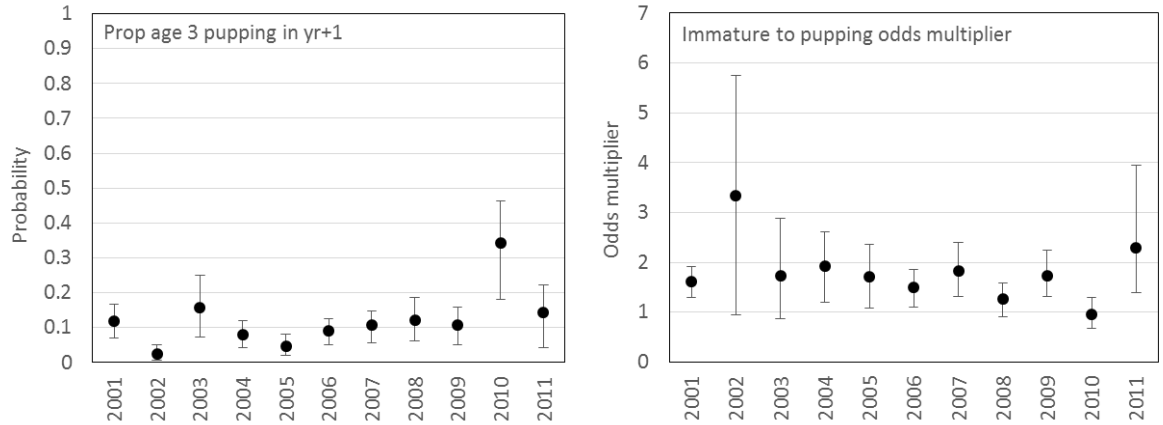

Figure B-15: MCMC estimates of age at maturation parameters $\Pr B1st_a$ (left) and *oddsmult* (right) of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

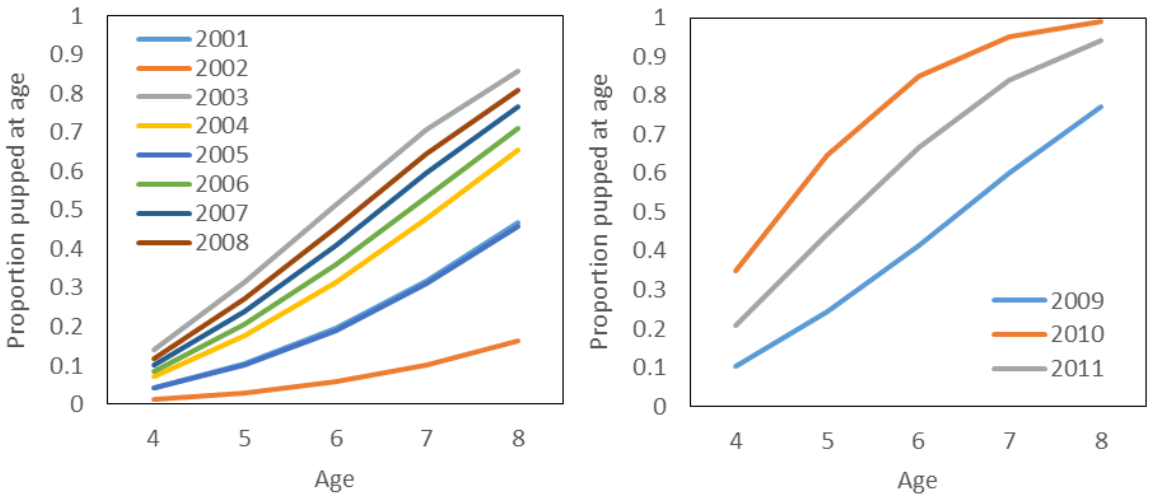

Figure B-16: Cumulative proportion of individuals that will have pupped at age, derived from year-varying estimates of parameters from model run 7. A separate plot is presented for relationships derived from 2001-2008 and 2009-2011 estimates.

Table B-3: Demographic parameter estimates to be carried forward to the correlative modelling phase of the project. Median MCMC estimates from model configured as model run 8; estimates used may change depending on further model development as described in this report. Parameter notation is <demographic rate><age range><year>, where "Surv" are estimates of survival to year+1 (confounded with tag loss); "Mat" are maturation parameters 1 & 2; "NP" and "PP" are estimates of puppers and non-puppers pupping in year+1.

Parameter	Value	Parameter	Value
Surv 0_1990 * Surv 1_1991	0.57 (0.27 - 0.82)	Surv 6_14_1998	0.95 (0.80 - 0.99)
Surv 0_1991 * Surv 1_1992	0.59 (0.41 - 0.82)	Surv 6_14_1999	0.89 (0.81 - 0.94)
Surv 0_1992 * Surv 1_1993	0.62 (0.45 - 0.83)	Surv 6_14_2000	0.80 (0.73 - 0.85)
Surv 0_1993 * Surv 1_1994	0.49 (0.39 - 0.69)	Surv 6_14_2001	0.90 (0.83 - 0.94)
Surv 0_1998 * Surv 1_1999	0.14 (0.10 - 0.19)	Surv 6_14_2002	0.80 (0.73 - 0.85)
Surv 0_1999 * Surv 1_2000	0.40 (0.32 - 0.50)	Surv 6_14_2003	0.87 (0.81 - 0.91)
Surv 0_2000 * Surv 1_2001	0.23 (0.16 - 0.30)	Surv 6_14_2004	0.80 (0.72 - 0.85)
Surv 0_2001 * Surv 1_2002	0.43 (0.35 - 0.48)	Surv 6_14_2005	0.90 (0.81 - 0.96)
Surv 0_2002 * Surv 1_2003	0.29 (0.23 - 0.34)	Surv 6_14_2006	0.80 (0.73 - 0.86)
Surv 0_2003 * Surv 1_2004	0.46 (0.39 - 0.52)	Surv 6_14_2007	0.66 (0.58 - 0.71)
Surv 0_2004 * Surv 1_2005	0.39 (0.31 - 0.46)	Surv 6_14_2008	0.84 (0.75 - 0.91)
Surv 0_2005 * Surv 1_2006	0.19 (0.14 - 0.24)	Surv 6_14_2009	0.80 (0.70 - 0.85)
Surv 0_2006 * Surv 1_2007	0.28 (0.20 - 0.33)	Surv 6_14_2010	0.86 (0.76 - 0.92)
Surv 0_2007 * Surv 1_2008	0.29 (0.22 - 0.34)	Surv 6_14_2011	0.77 (0.63 - 0.93)
Surv 0_2008 * Surv 1_2009	0.05 (0.03 - 0.07)		
Surv 0_2009 * Surv 1_2010	0.30 (0.22 - 0.40)	Surv 15+	0.59 (0.50 - 0.64)
Surv 0_2010 * Surv 1_2011	0.21 (0.08 - 0.35)		
Surv 2_5_1992	0.72 (0.43 - 0.97)		
Surv 2_5_1993	0.80 (0.52 - 0.97)		
Surv 2_5_1998	0.84 (0.64 - 0.97)		
Surv 2_5_1999	0.95 (0.84 - 0.99)		
Surv 2_5_2000	0.89 (0.72 - 0.96)		
Surv 2_5_2001	0.71 (0.59 - 0.81)		
Surv 2_5_2002	0.87 (0.74 - 0.96)		
Surv 2_5_2003	0.83 (0.71 - 0.89)		
Surv 2_5_2004	0.98 (0.92 - 1.00)		
Surv 2_5_2005	0.96 (0.88 - 0.99)		
Surv 2_5_2006	0.84 (0.77 - 0.89)		
Surv 2_5_2007	0.90 (0.81 - 0.94)		
Surv 2_5_2008	0.87 (0.78 - 0.92)		
Surv 2_5_2009	0.80 (0.71 - 0.87)		
Surv 2_5_2010	0.96 (0.90 - 0.99)		
Surv 2_5_2011	0.78 (0.66 - 0.88)		
Mat_1_2001	0.12 (0.07 - 0.17)	NP_1999	0.39 (0.09 - 0.58)
Mat_1_2002	0.02 (0.01 - 0.05)	NP_2000	0.50 (0.38 - 0.60)
Mat_1_2003	0.16 (0.07 - 0.25)	NP_2001	0.47 (0.34 - 0.56)
Mat_1_2004	0.08 (0.04 - 0.12)	NP_2002	0.40 (0.27 - 0.53)
Mat_1_2005	0.05 (0.02 - 0.08)	NP_2003	0.56 (0.44 - 0.63)
Mat_1_2006	0.09 (0.05 - 0.12)	NP_2004	0.46 (0.32 - 0.57)
Mat_1_2007	0.11 (0.06 - 0.15)	NP_2005	0.31 (0.14 - 0.45)
Mat_1_2008	0.12 (0.06 - 0.19)	NP_2006	0.24 (0.15 - 0.32)
Mat_1_2009	0.11 (0.05 - 0.16)	NP_2007	0.29 (0.17 - 0.37)
Mat_1_2010	0.34 (0.18 - 0.46)	NP_2008	0.45 (0.33 - 0.57)
Mat_1_2011	0.14 (0.04 - 0.22)	NP_2009	0.46 (0.27 - 0.59)
		NP_2010	0.50 (0.39 - 0.59)
Mat_2_2001	1.61 (1.29 - 1.91)	NP_2011	0.55 (0.39 - 0.66)
Mat_2_2002	3.35 (0.95 - 5.75)		
Mat_2_2003	1.72 (0.87 - 2.88)	PP_1999	0.18 (0.02 - 0.37)
Mat_2_2004	1.93 (1.20 - 2.60)	PP_2000	0.67 (0.53 - 0.77)
Mat_2_2005	1.72 (1.09 - 2.36)	PP_2001	0.83 (0.75 - 0.88)
Mat_2_2006	1.50 (1.10 - 1.86)	PP_2002	0.66 (0.57 - 0.73)
Mat_2_2007	1.82 (1.31 - 2.40)	PP_2003	0.81 (0.70 - 0.87)
Mat_2_2008	1.26 (0.91 - 1.59)	PP_2004	0.83 (0.72 - 0.89)
Mat_2_2009	1.72 (1.31 - 2.25)	PP_2005	0.44 (0.33 - 0.52)
Mat_2_2010	0.96 (0.68 - 1.29)	PP_2006	0.42 (0.29 - 0.52)
Mat_2_2011	2.29 (1.39 - 3.95)	PP_2007	0.75 (0.63 - 0.87)
		PP_2008	0.75 (0.64 - 0.81)
		PP_2009	0.47 (0.38 - 0.54)
		PP_2010	0.77 (0.68 - 0.84)
		PP_2011	0.71 (0.60 - 0.76)

Posterior distributions of all parameters in model run 8

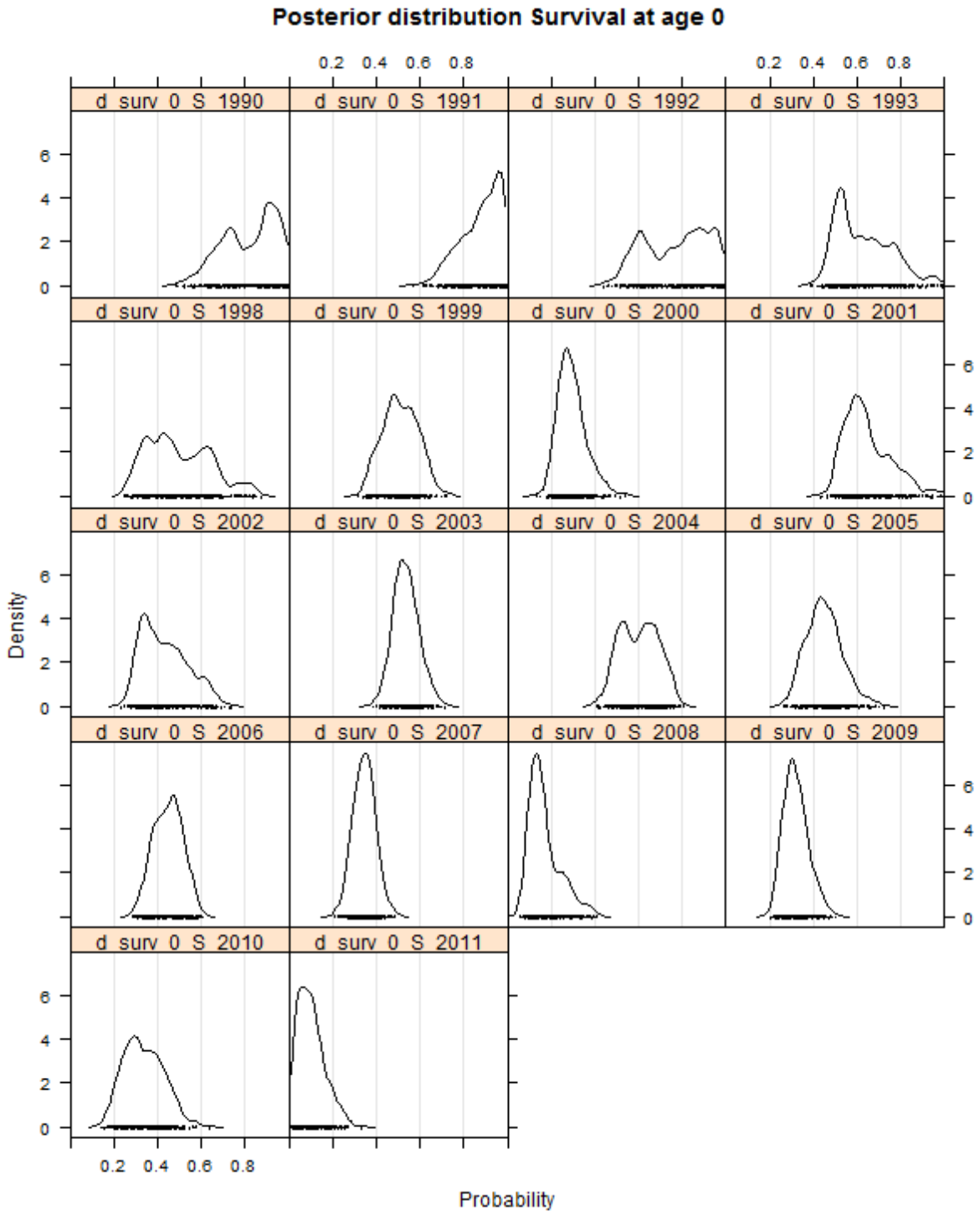

Figure B-17: Posterior distributions of MCMC estimates of survival at age 0 (model run 8).

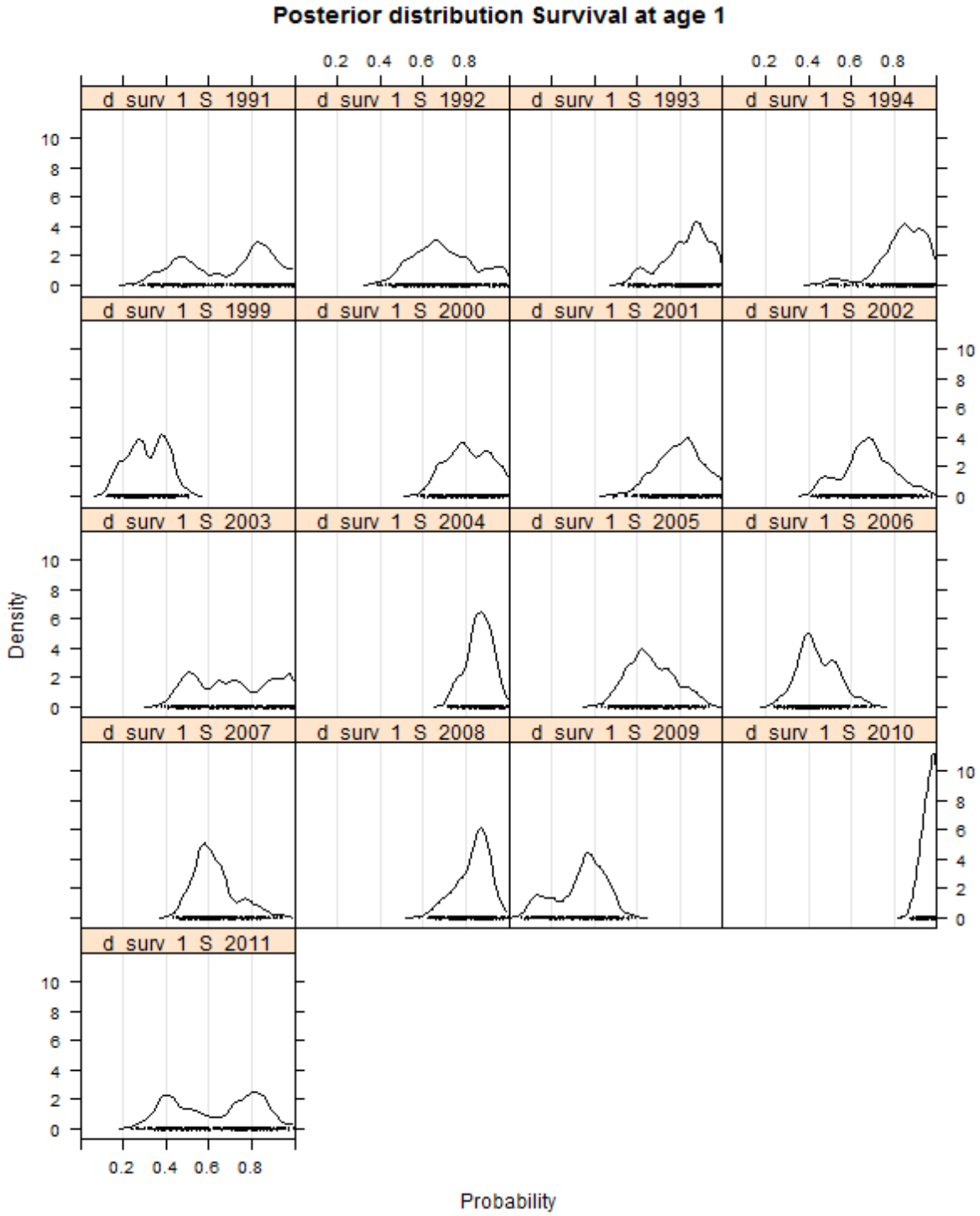

Figure B-18: Posterior distributions of MCMC estimates of survival at age 1 (model run 8).

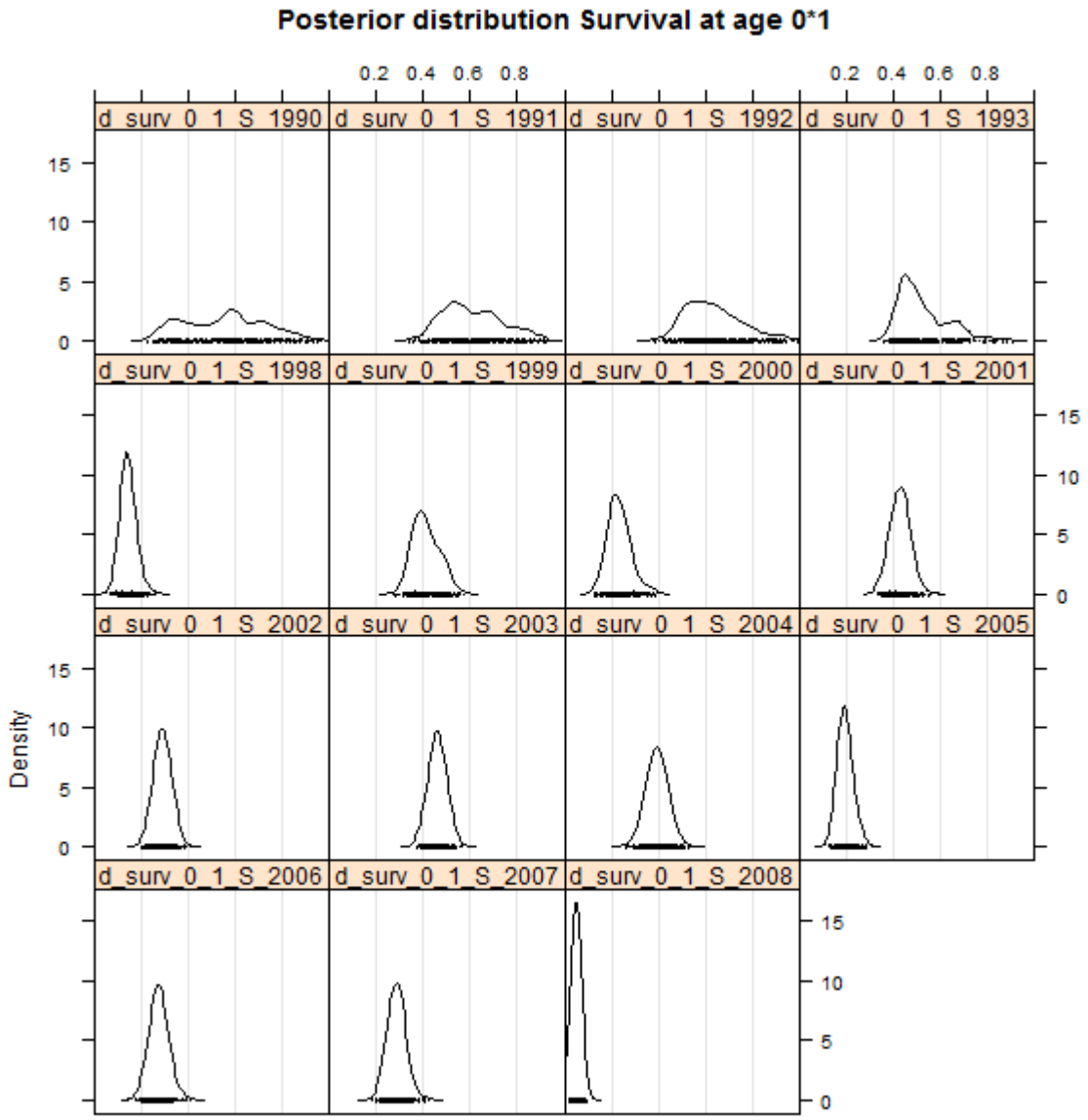

Figure B-19: Posterior distributions of MCMC estimates of cohort survival to age 2 (model run 8).

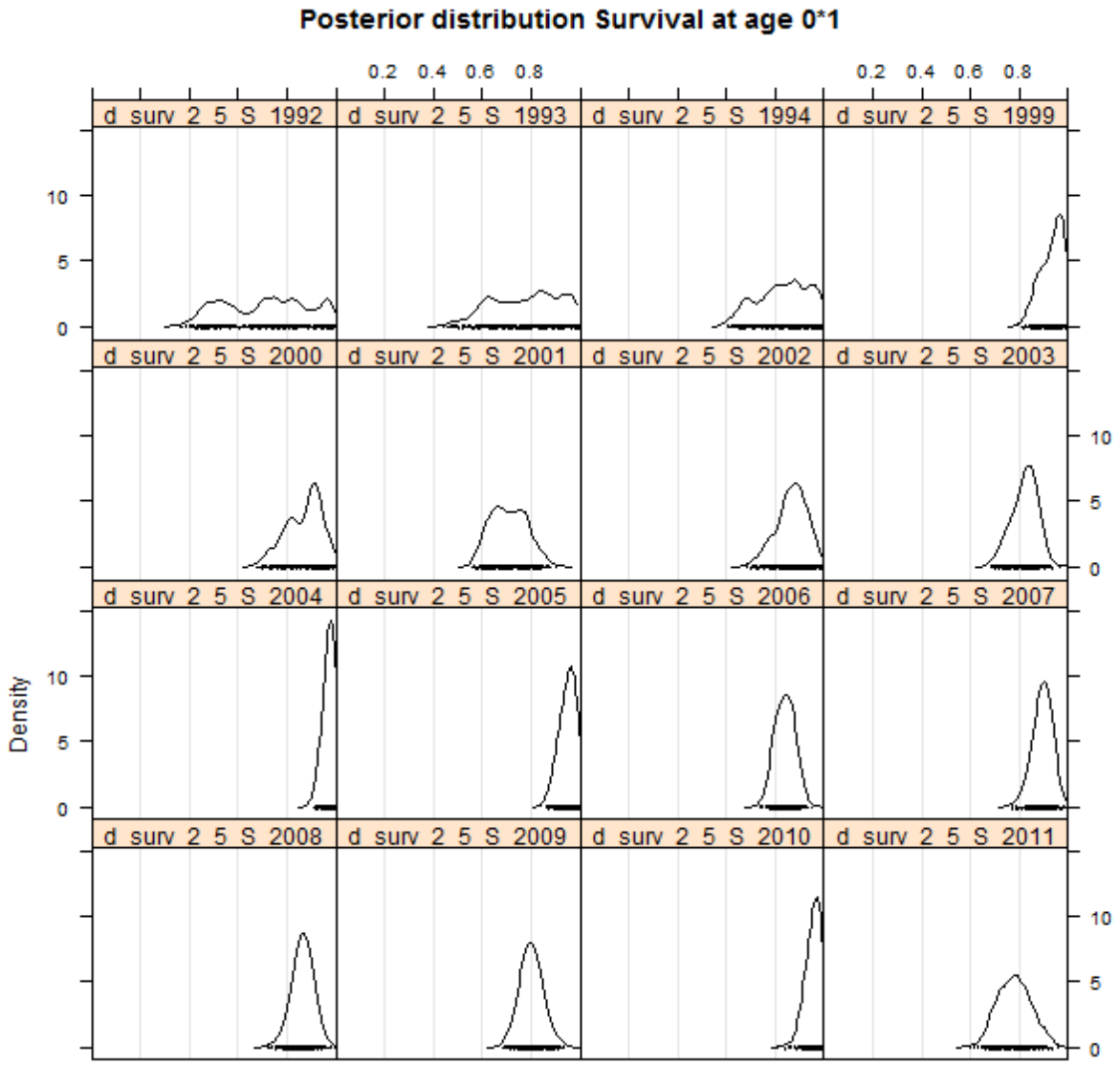

Figure B-20: Posterior distributions of MCMC estimates of survival at age 2-5 (model run 8).

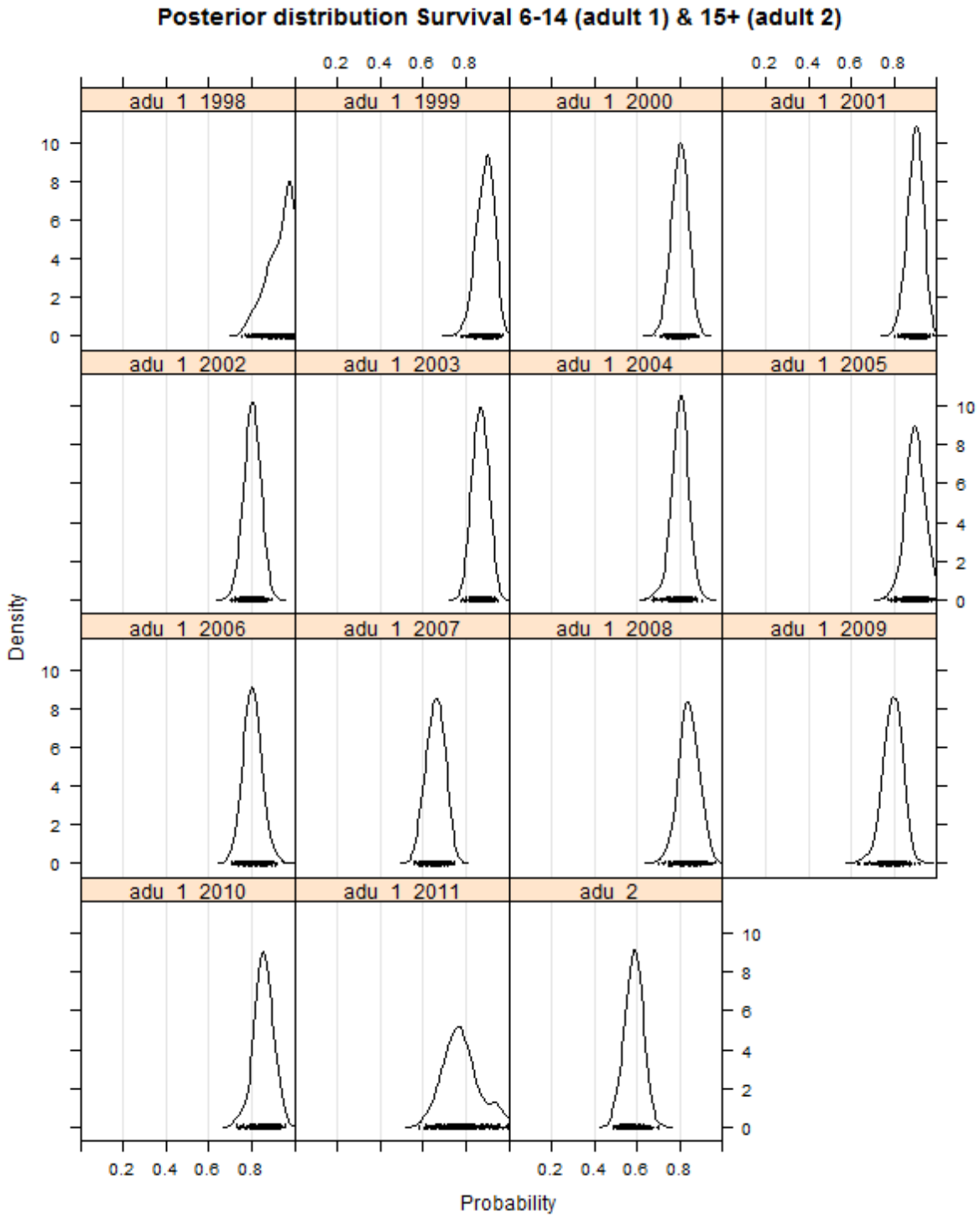

Figure B-21: Posterior distributions of MCMC estimates of survival at age 6-14 (adu_1) and 15+ (adu_2) (model run 8) .

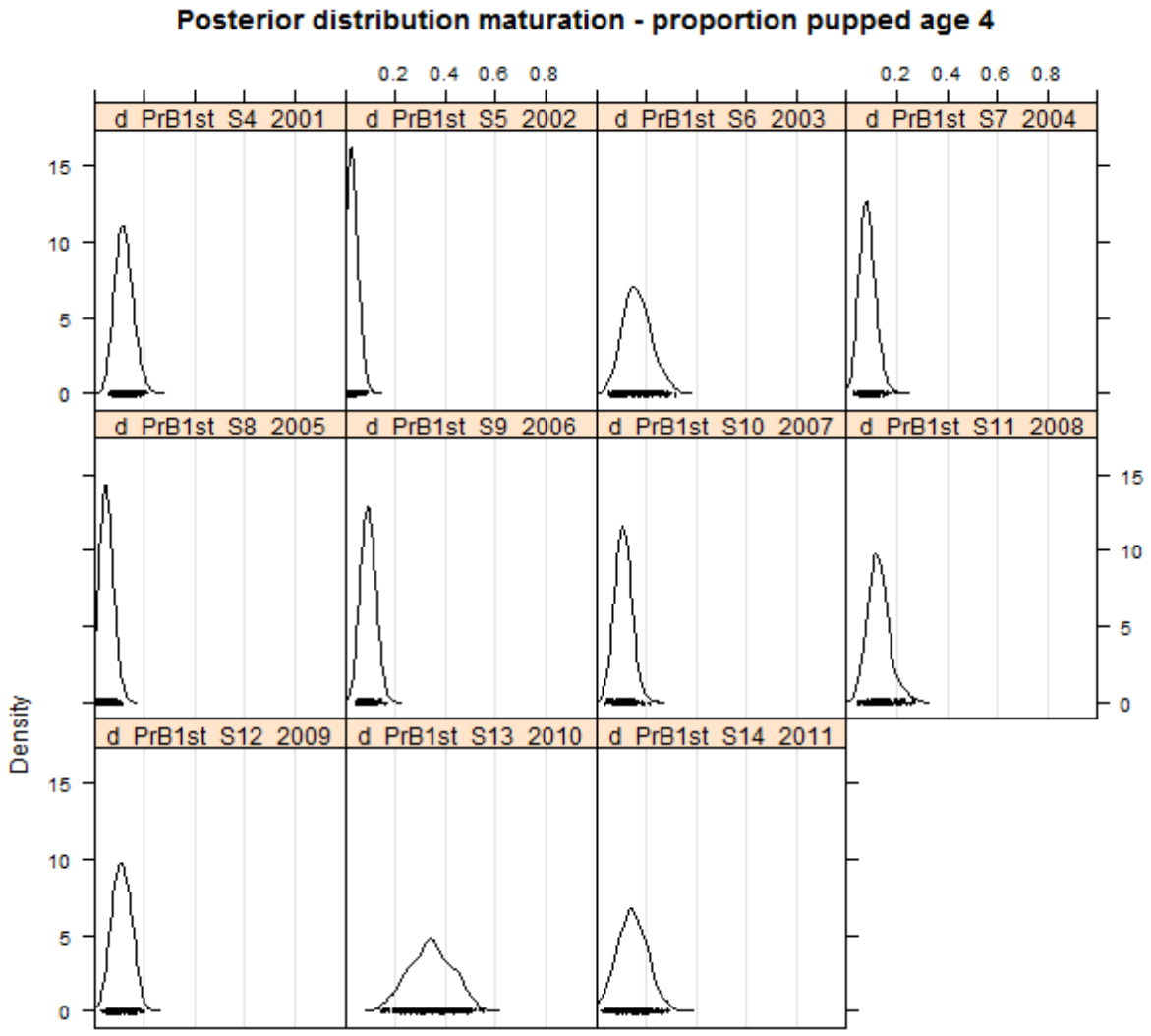

Figure B-22: Posterior distributions of MCMC estimates of age-at-first-pupping parameter PrB1sta (model run 8).

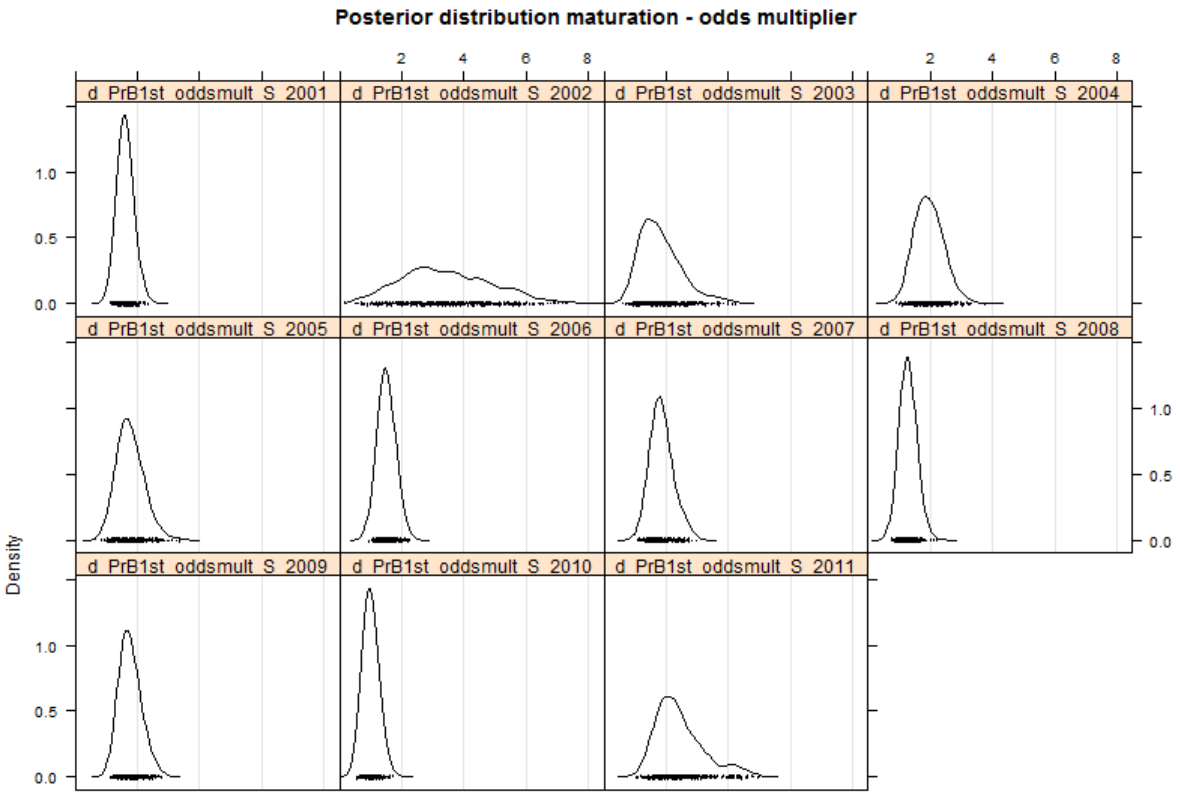

Figure B-23: Posterior distributions of MCMC estimates of age-at-first-pupping parameter oddsmult (model run 8).

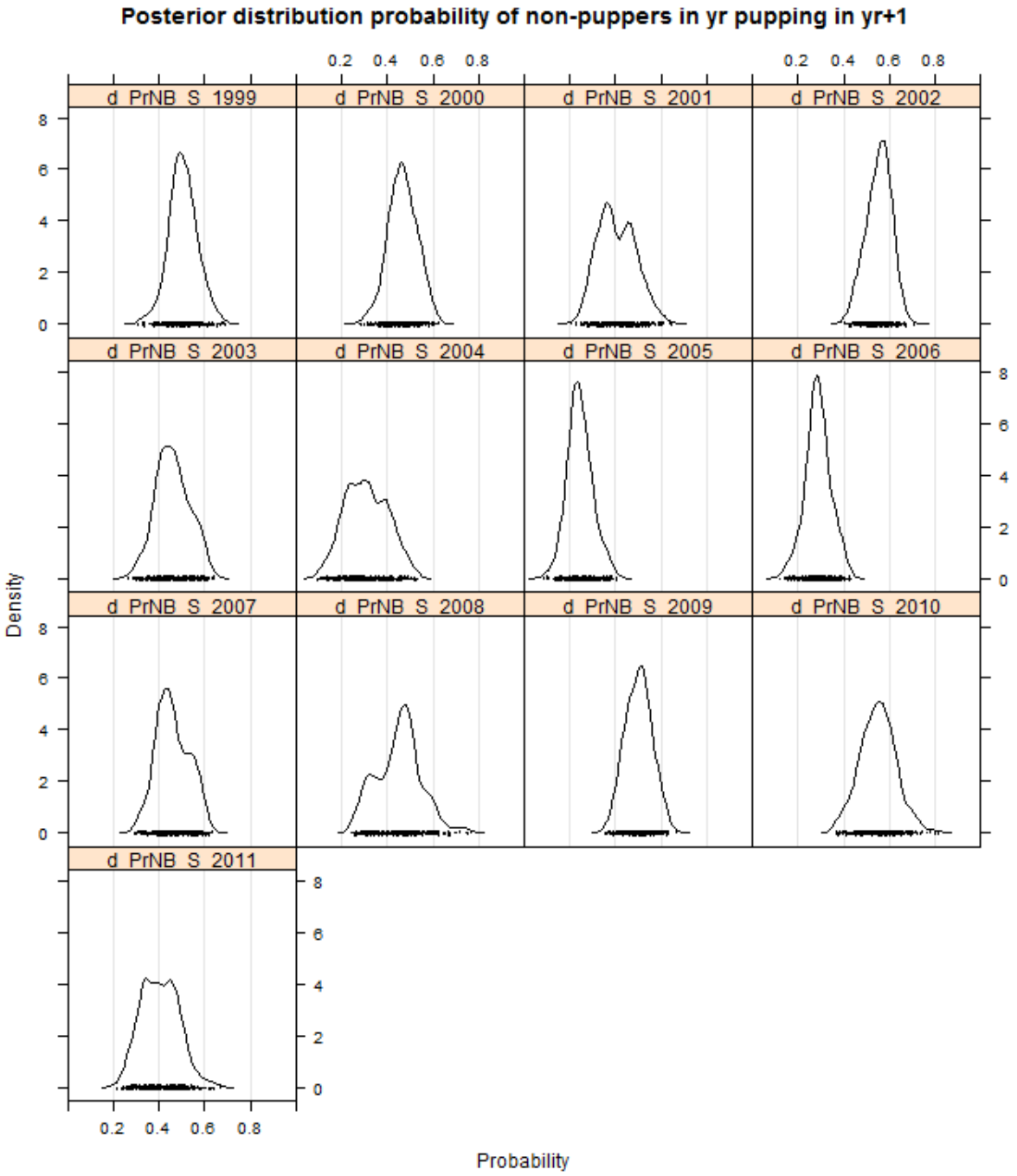

Figure B-24: : Posterior distributions of MCMC estimates of the probability of non-puppers pupping in yr+1 (model run 8).

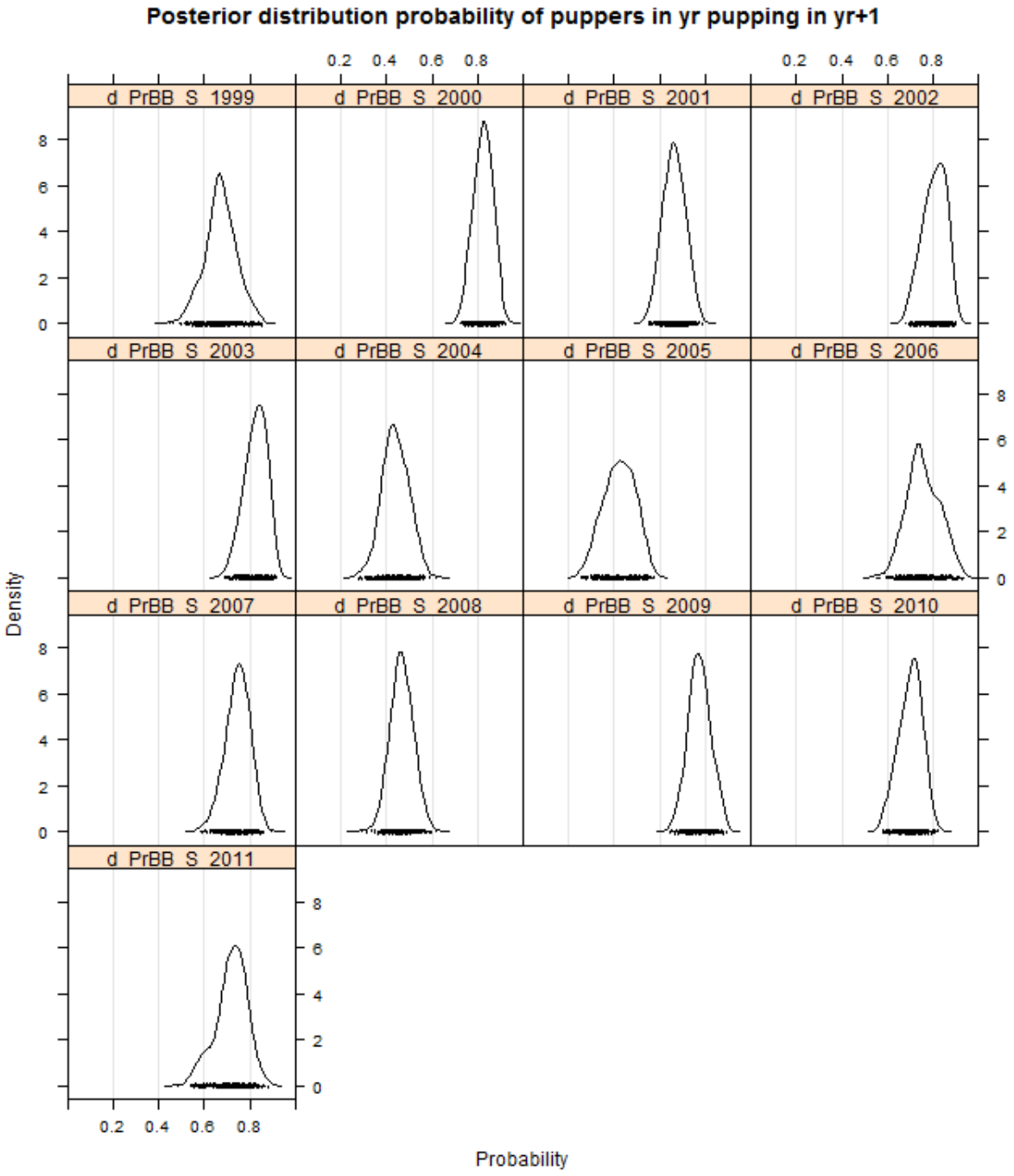

Figure B-25: Posterior distributions of MCMC estimates of the probability of puppers pupping in yr+1 (model run 8).

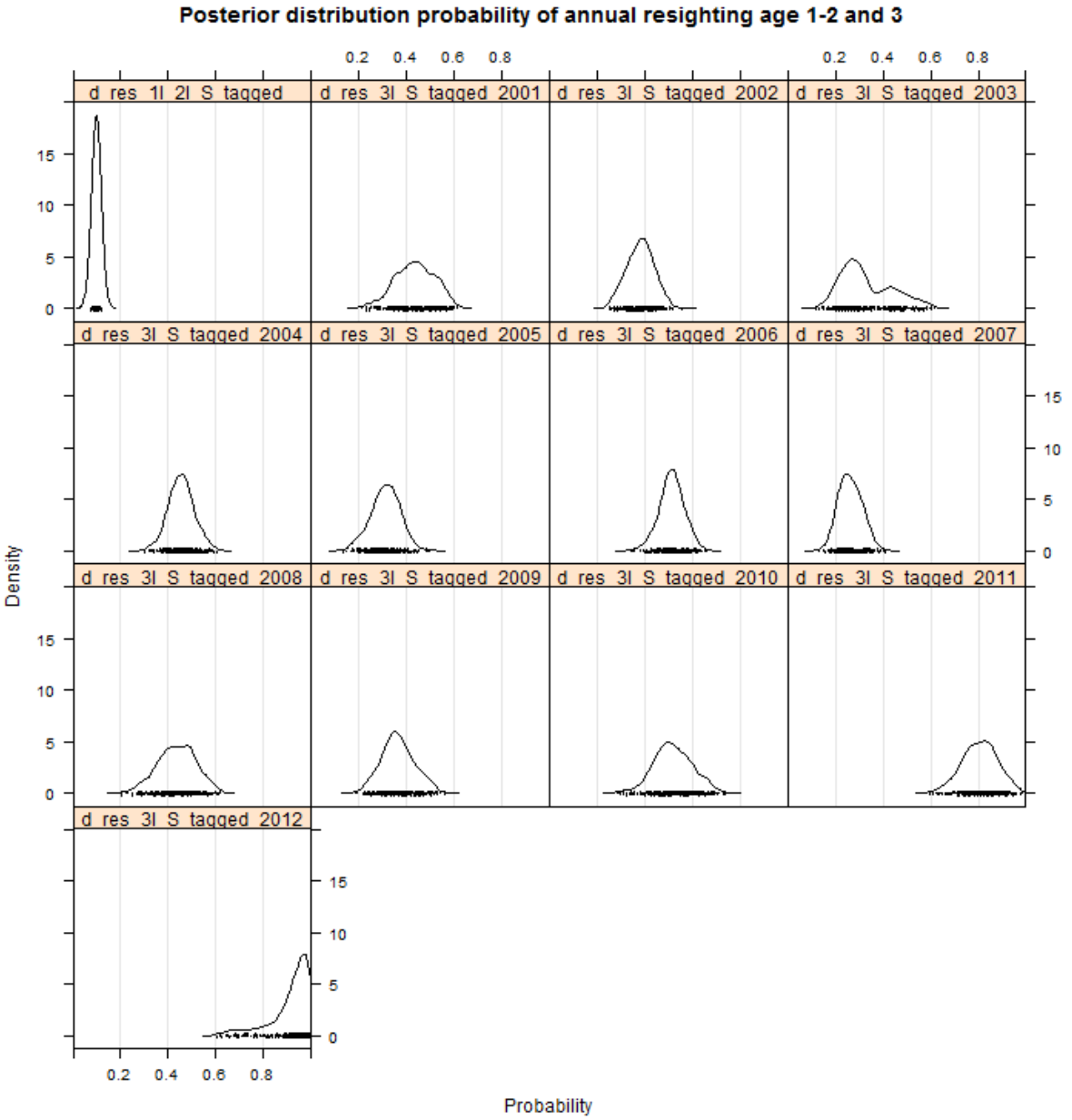

Figure B-26: Posterior distributions of MCMC estimates of annual resighting probability at ages 1-2 and 3 (model run 8).

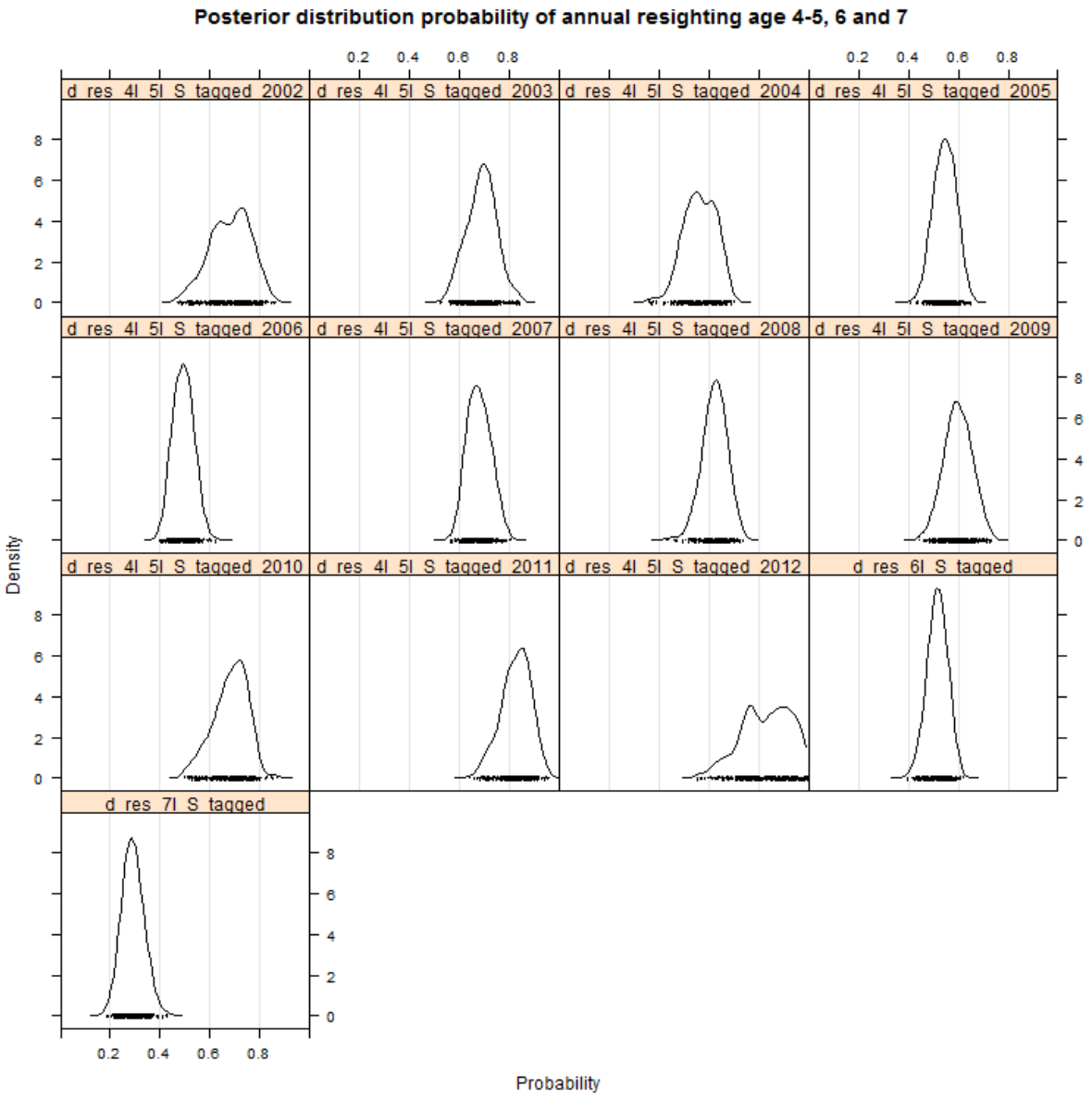

Figure B-27: Posterior distributions of MCMC estimates of annual resighting probability at ages 4-5, 6 and 7 (model run 8).

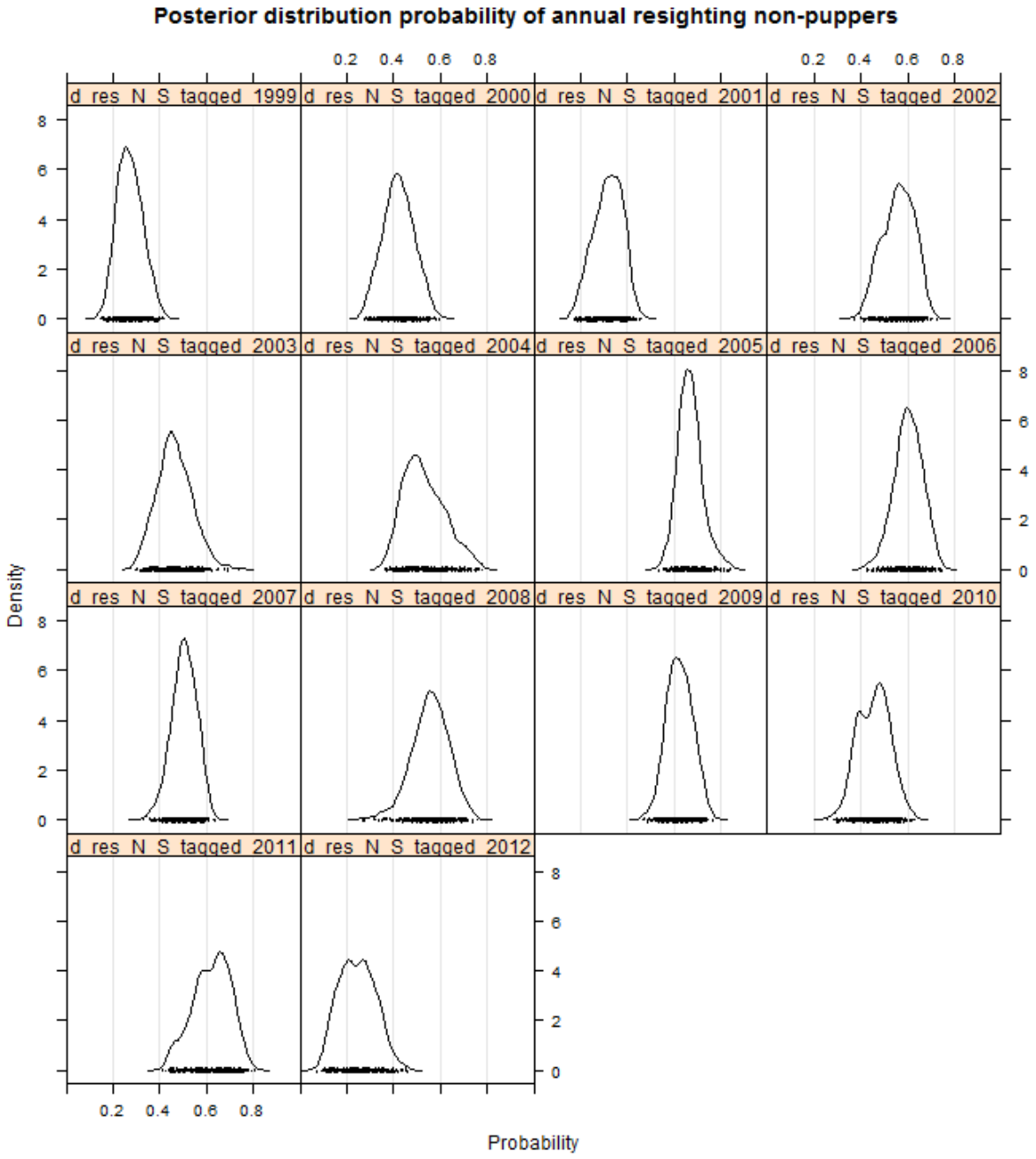

Figure B-28: Posterior distributions of MCMC estimates of annual resighting probability of non-puppers (model run 8).

Assessment of degree of correlation between parameter estimates from model run 8

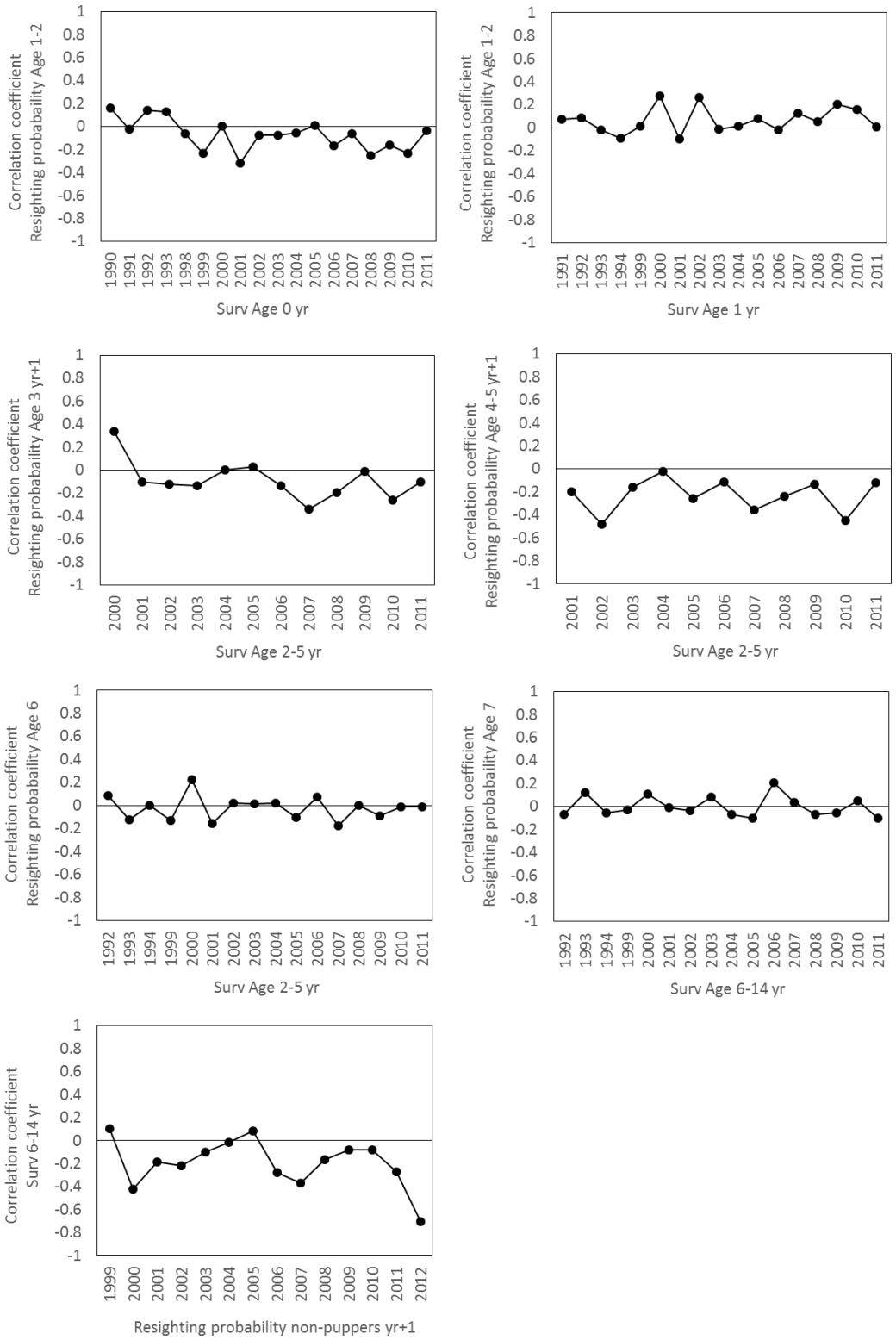

Figure B-29: Correlation coefficients between MCMC annual estimates of age-specific resighting probability and survival. Females at Sandy Bay; model run 8.

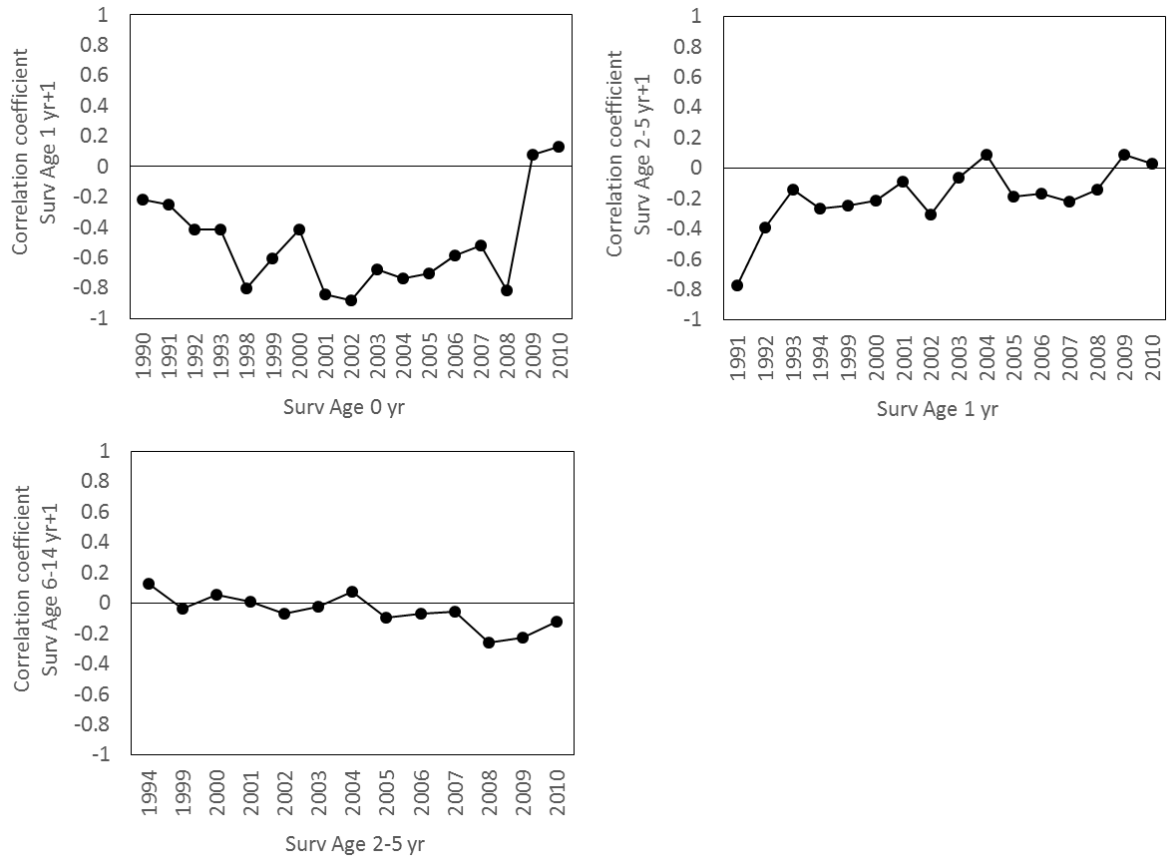

Figure B-30: Correlation coefficients between MCMC annual estimates of survival comparing different age groupings. Females at Sandy Bay; model run 8.

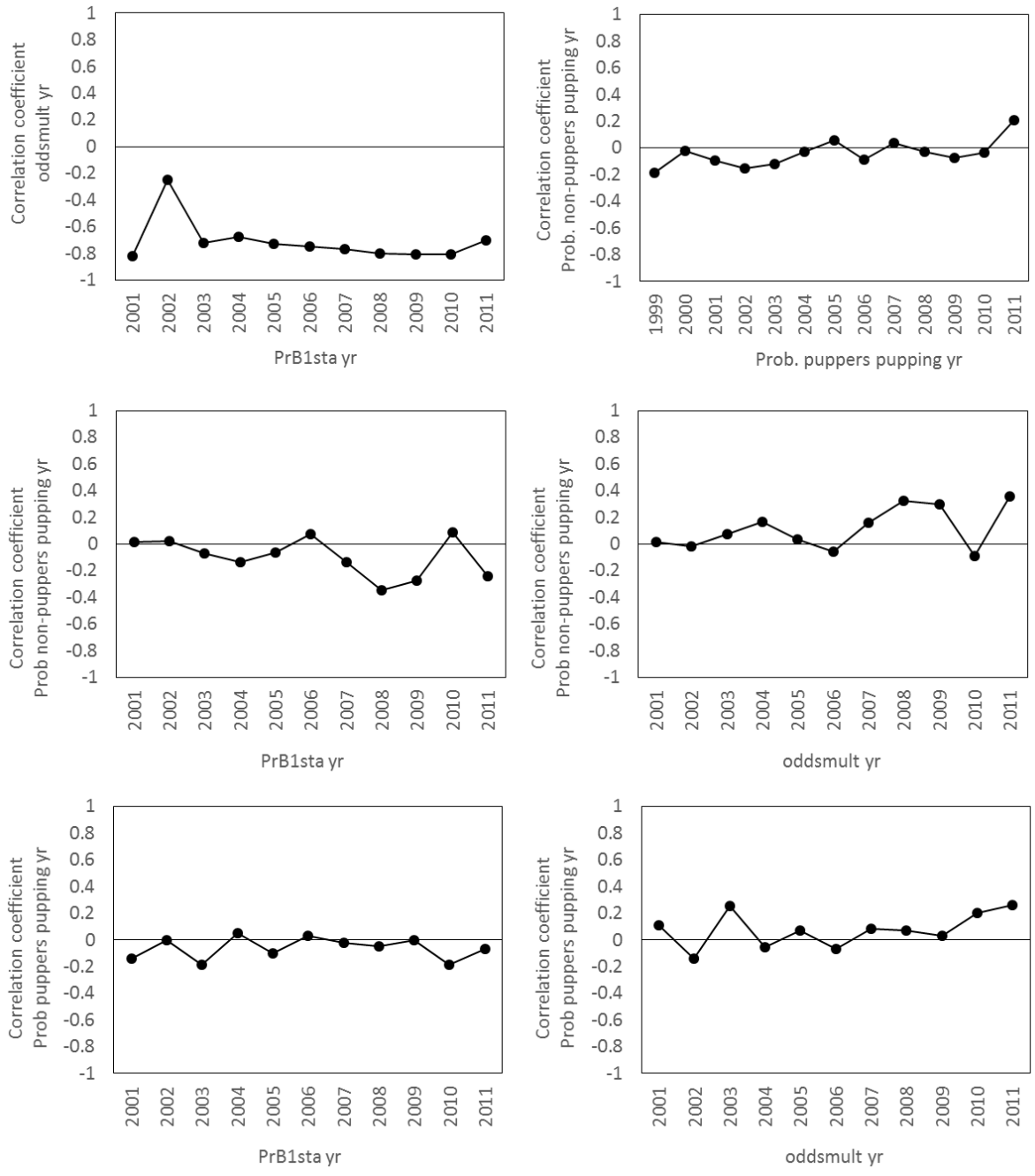

Figure B-31: Correlation coefficients between MCMC annual estimates of maturation parameters and pupping rate estimates. Females at Sandy Bay; model run 8.

Estimates from model validation runs

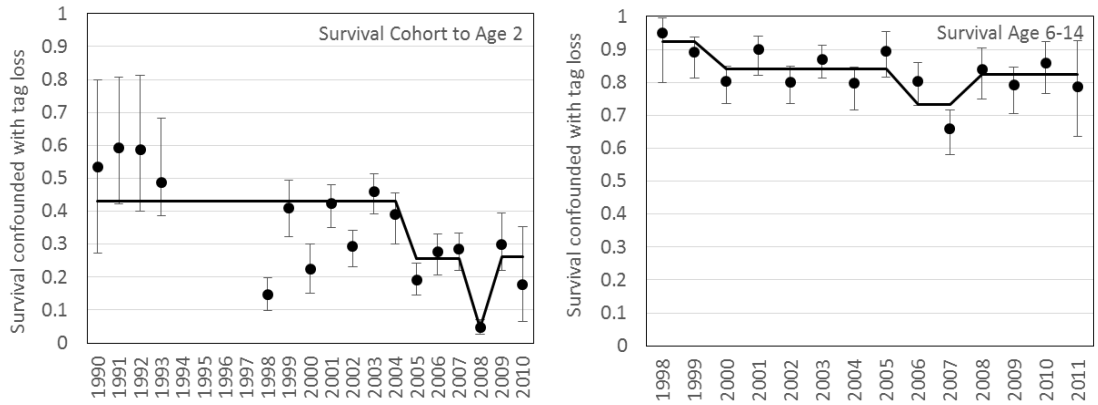

Figure B-32: Year group estimates from the breakpoint analysis and MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Sandy Bay (model run 8). Points are median estimates, bars are 95% confidence intervals.

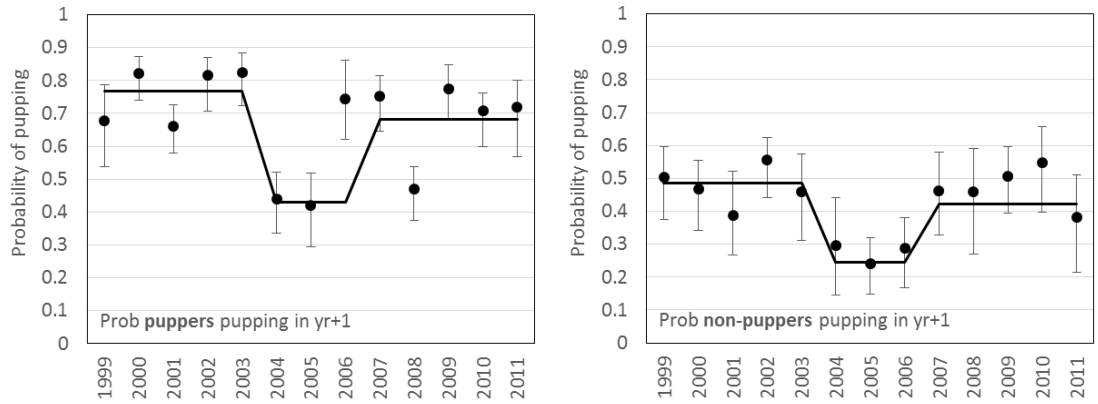

Figure B-33: Year group estimates from the breakpoint analysis and; MCMC estimates of probability of pupping. Probability of puppers pupping in year +1 (left) and non-puppers pupping in year+1 (right) of female NZ sea lions at Sandy Bay (model run 8); points are median estimates, bars are 95% confidence intervals.

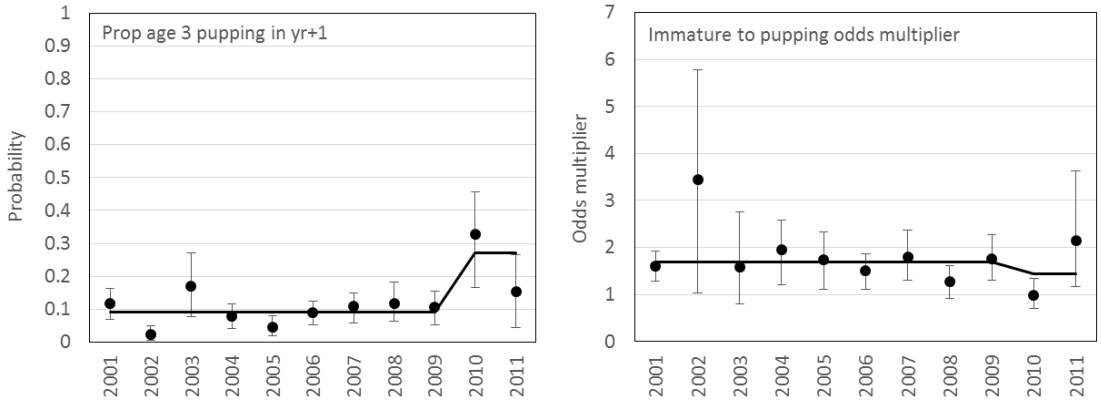

Figure B-34: Year group estimates from the breakpoint analysis and MCMC estimates of age-at-first-pupping parameters $\Pr B1st_a$ (left) and *oddsmult* (right) of female NZ sea lions at Sandy Bay (model run 8); . Points are median estimates, bars are 95% confidence intervals.

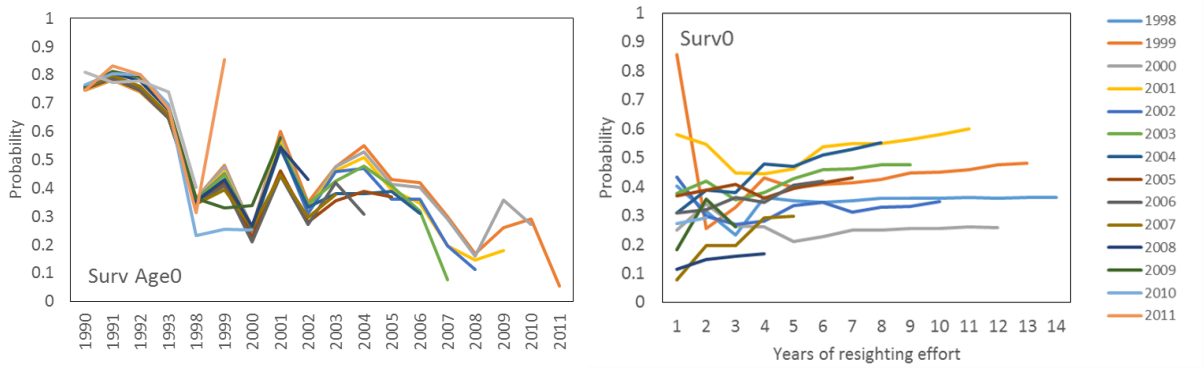

Figure B-35: Retrospective analysis showing dataset time series and year effects on estimates. Of survival at age 0 (left); and the same estimates presented as effect of number of years of resighting effort on estimates for a particular year (right); model run 10; females at Sandy Bay.

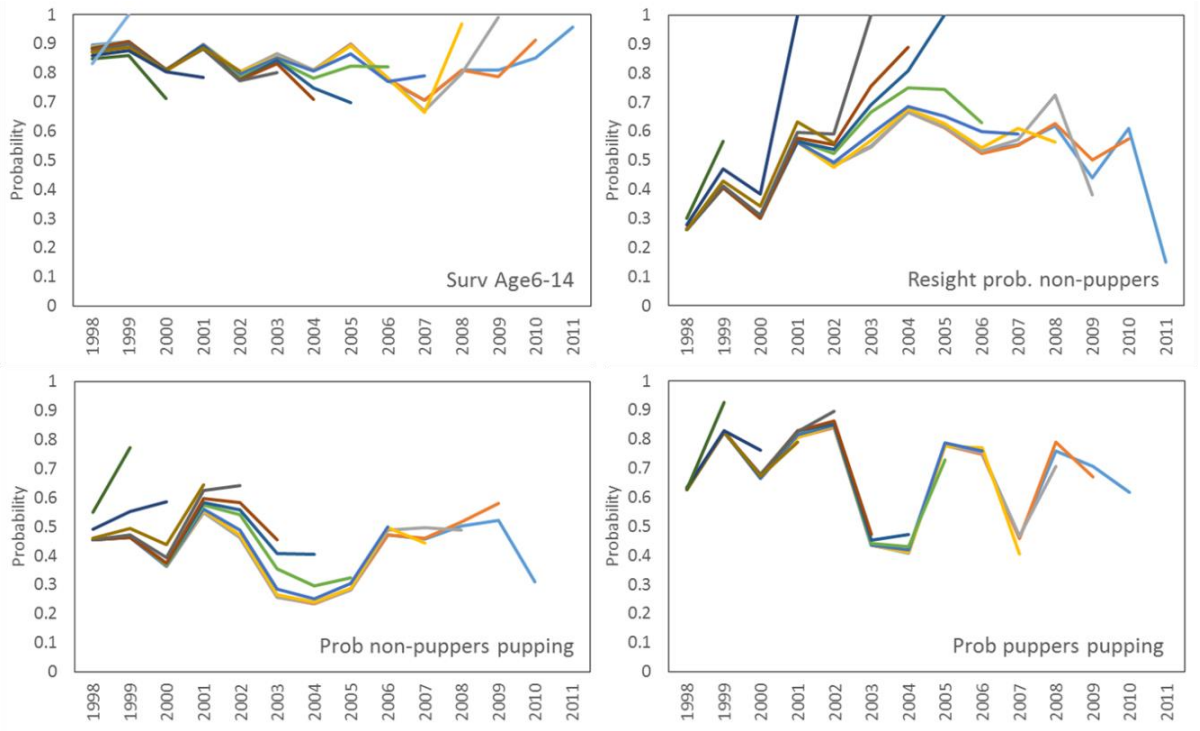

Figure B-36: Retrospective analysis showing dataset time series and year effects on estimates. Of survival at age 6-14 (top left); resighting probability of non-puppers (top-right); probability of non-puppers pupping (bottom-left); and probability of puppers pupping (bottom-right); model run 10; females at Sandy Bay.

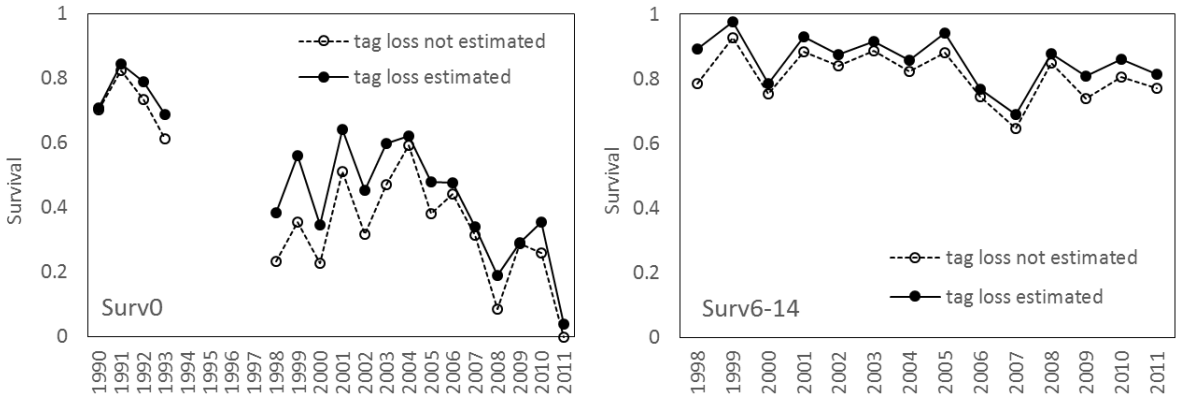

Figure B-37: Estimates of survival at ages 0 and 6-14 for model run with tag loss parameters. Model run 11; females at Sandy Bay.

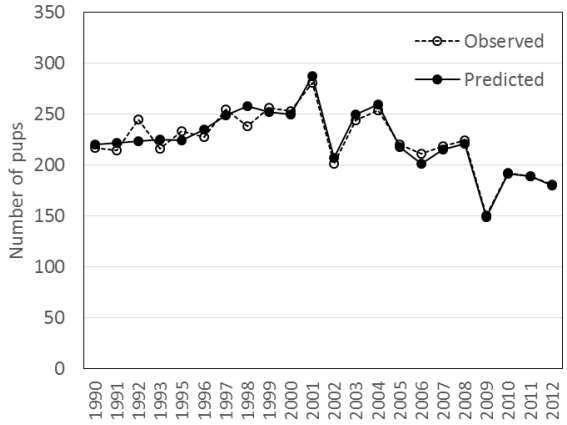

Figure B-38: Model fits to pup census observations. Model run 12; females at Sandy Bay.

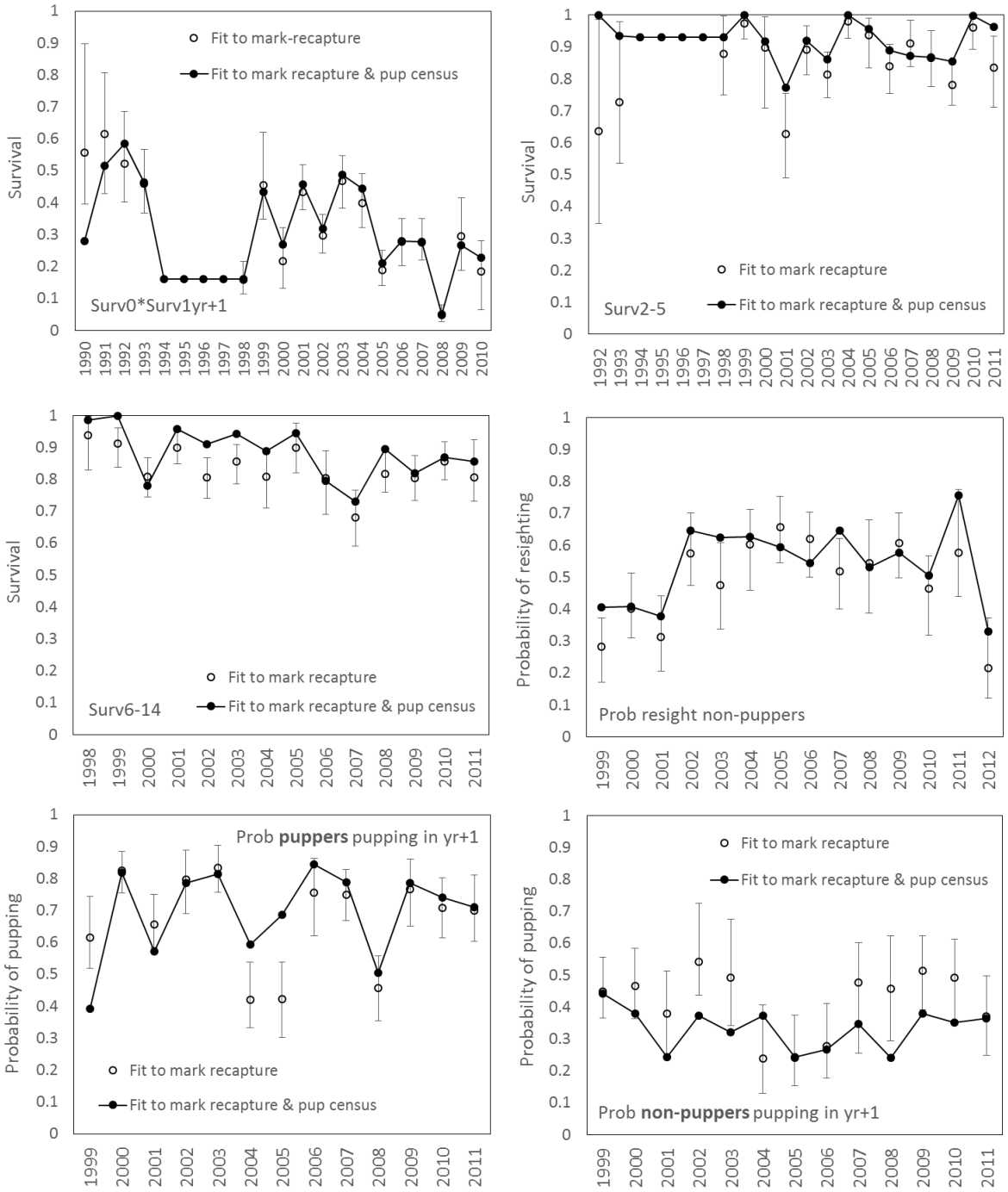

Figure B-39: Model estimates of survival, pupping probability and resighting probability from the model fit to pup census observations (model run 12) compared with MCMC median estimates and confidence intervals (model run 7). Females at Sandy Bay.

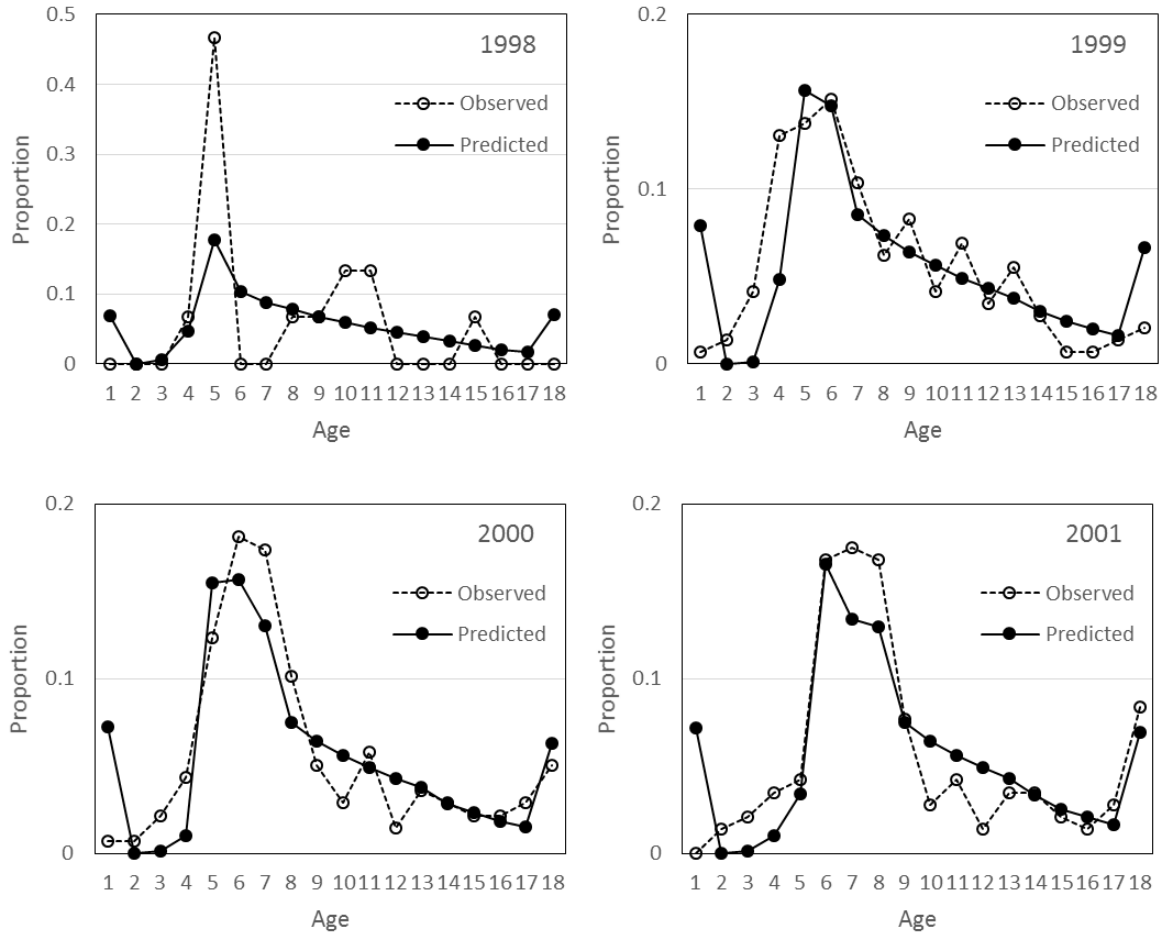

Figure B-40: Model fits to age distribution observations (model run 13).

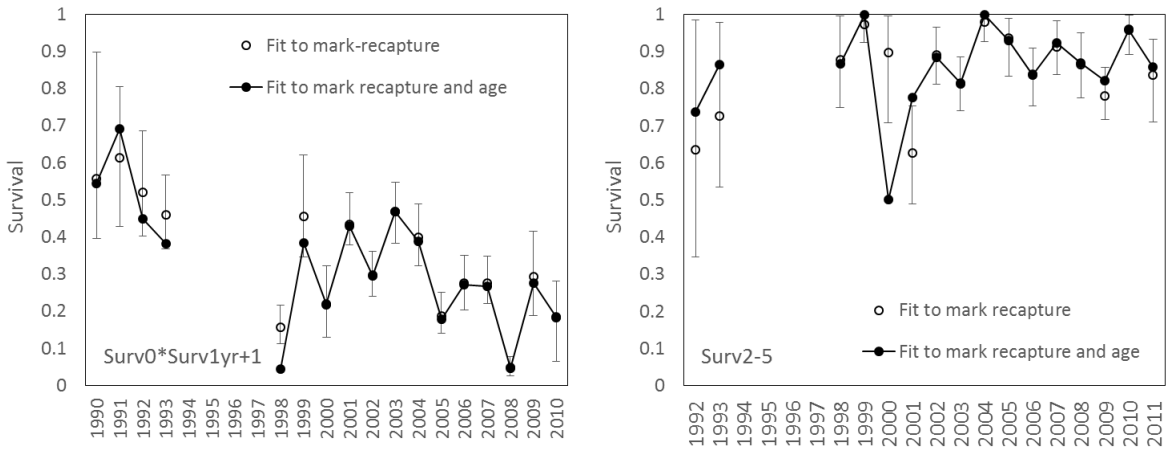

Figure B-41: : Model estimates of survival at age 0 and 6-14 from the model fit to age distribution observations (model run 13) compared with MCMC median estimates and confidence intervals (model run 7). Females at Sandy Bay.

Demographic assessment of females at Dundas

MCMC parameters estimates

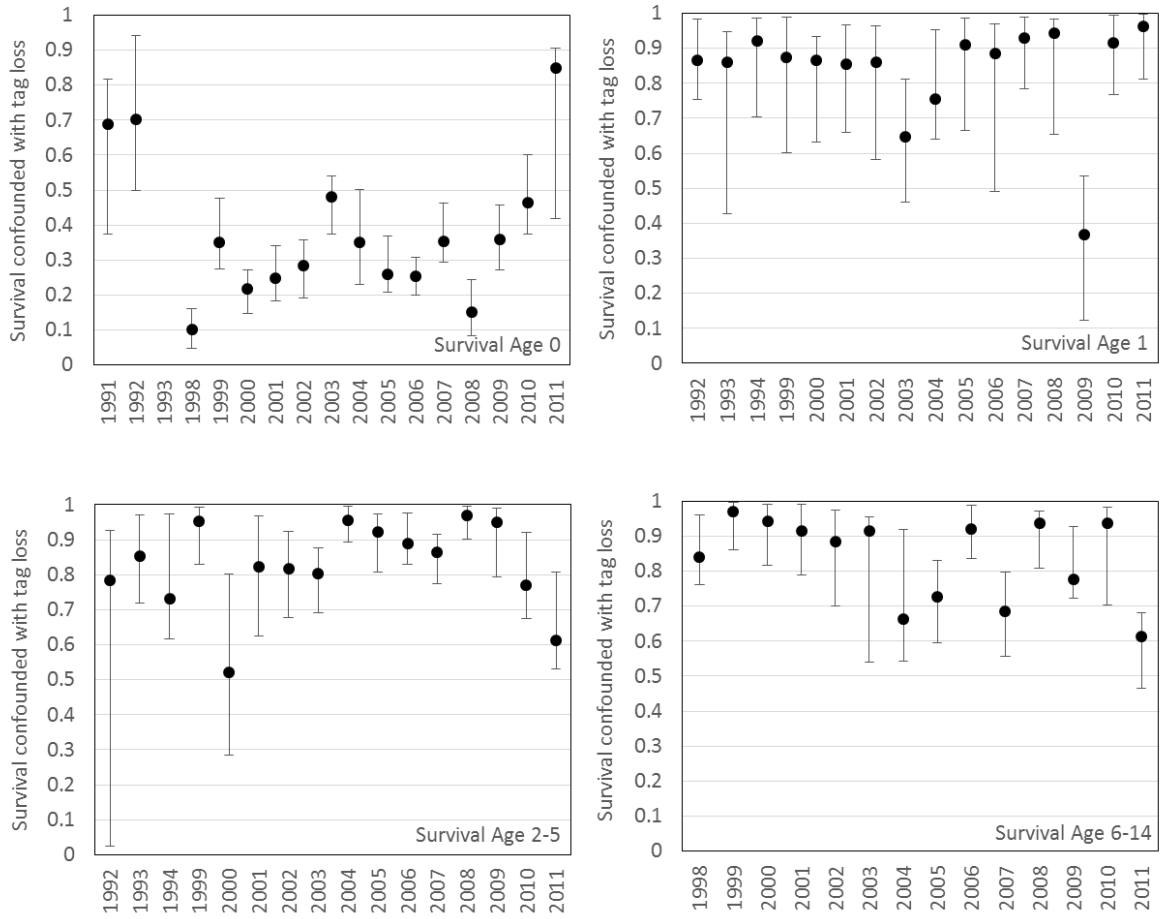

Figure B-42: MCMC estimates of age-specific survival of female NZ sea lions at Dundas (model run 9). Points are median estimates, bars are 95% confidence intervals.

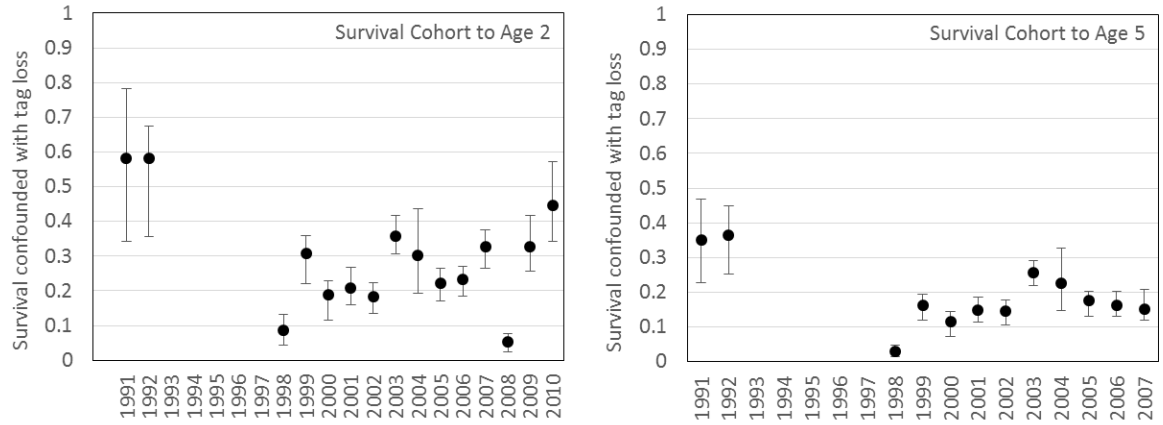

Figure B-43: MCMC estimates of cohort-specific survival to age 2 (left) and age 5 (right) of female NZ sea lions at Dundas (model run 9). Points are median estimates, bars are 95% confidence intervals.

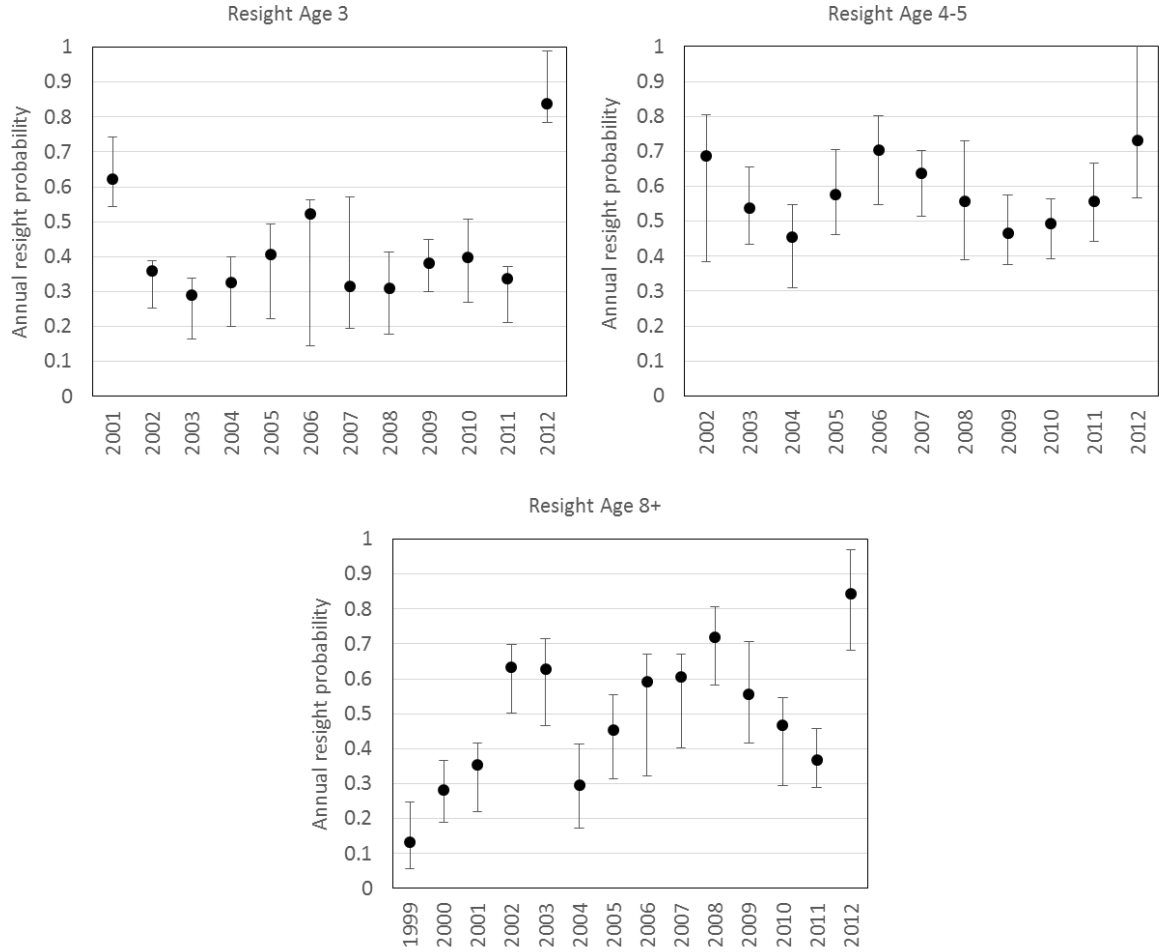

Figure B-44: Comparison of MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay and Dundas (model runs 8 and 9).

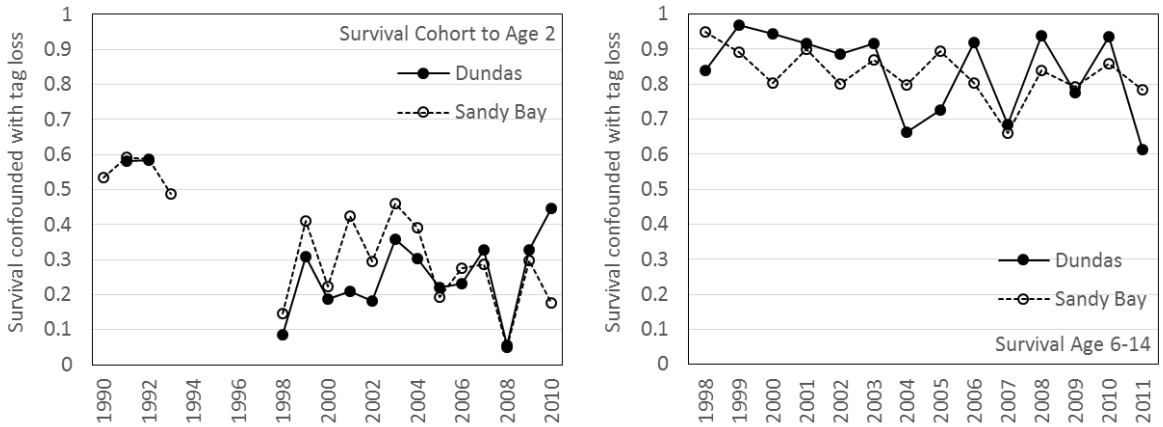

Figure B-45: Comparison of MCMC estimates of age-specific survival of female NZ sea lions at Sandy Bay and Dundas (model runs 8 and 9).

Posterior distributions of all parameters in model run 9

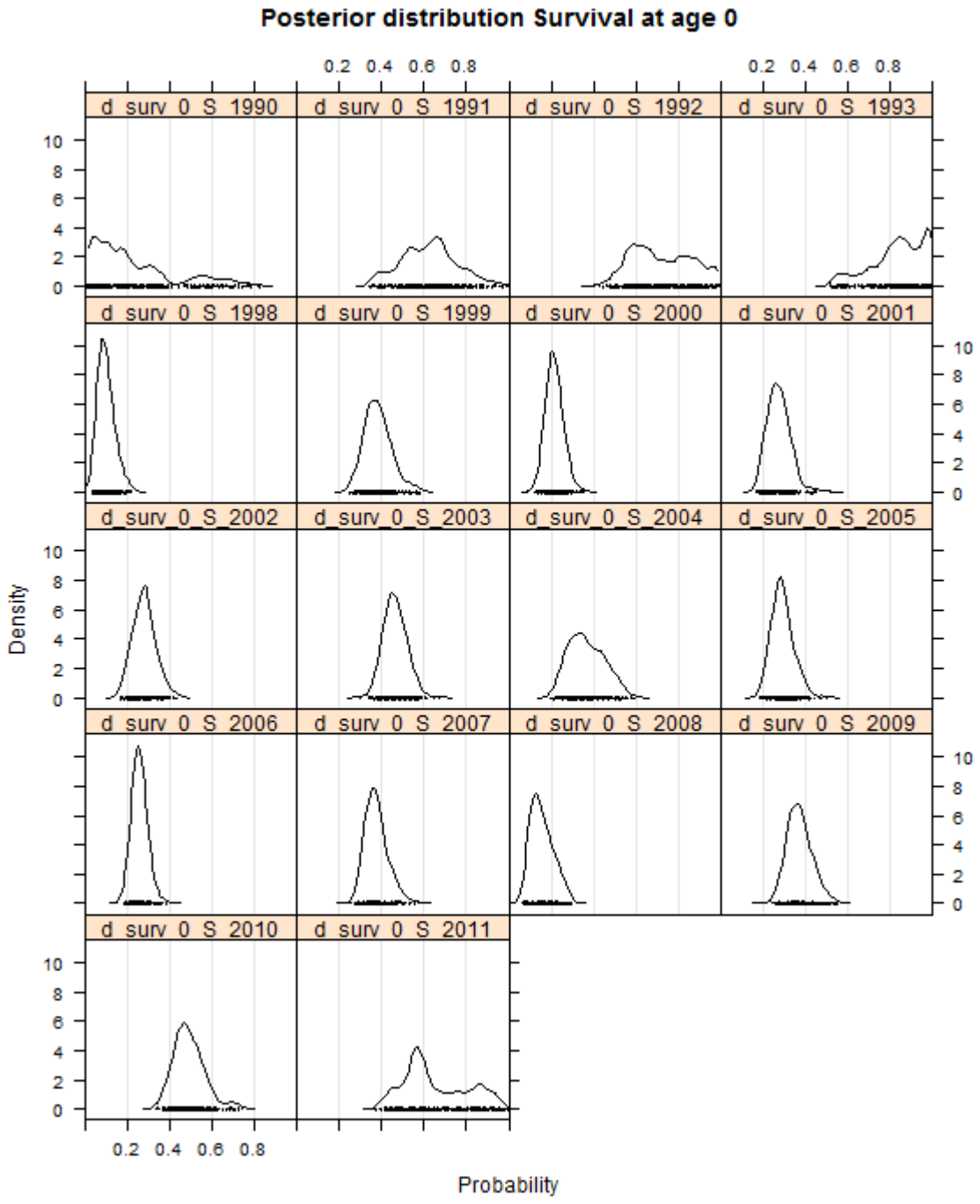

Figure B-46: Posterior distributions of MCMC estimates of survival at age 0 (model run 9).

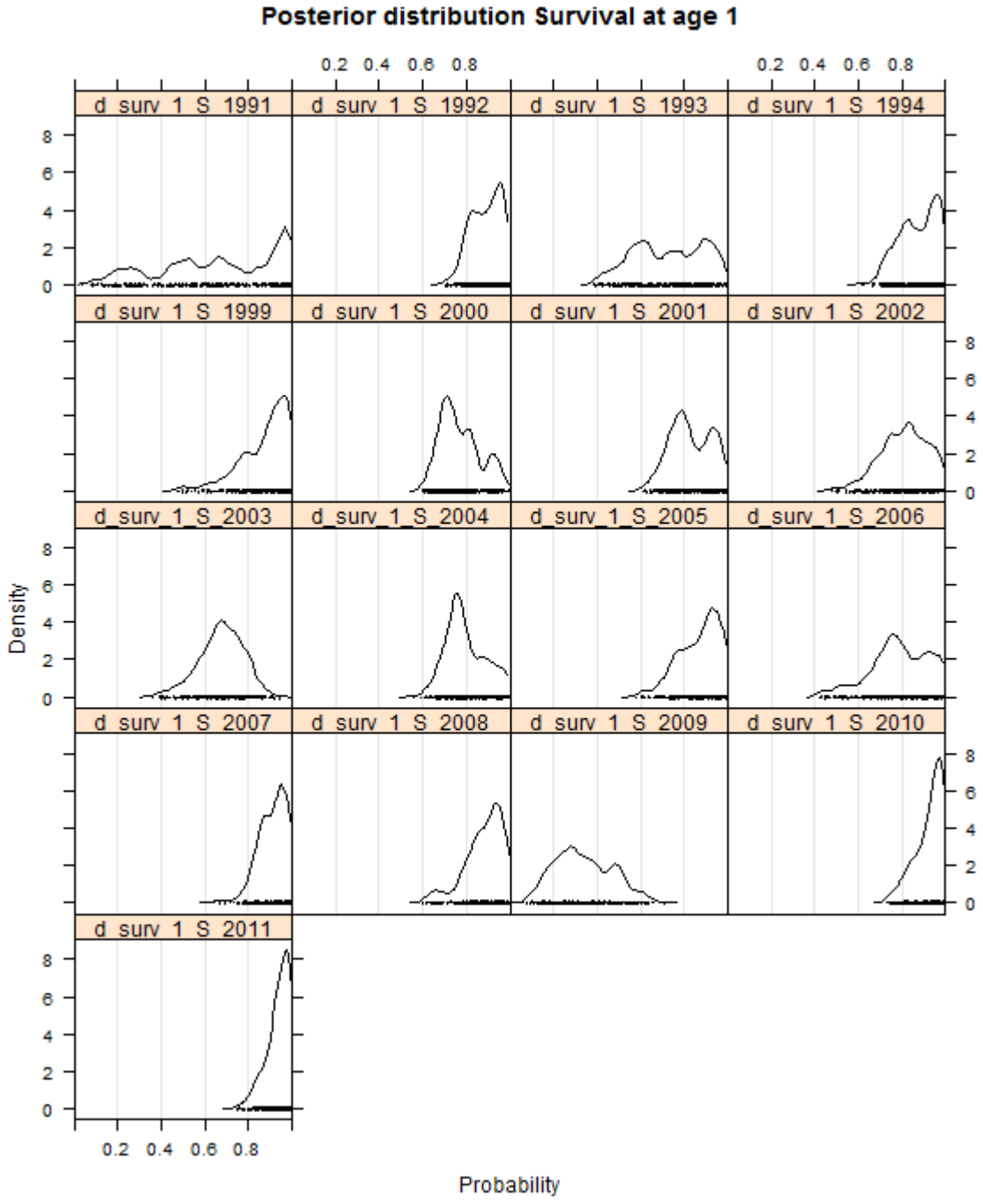

Figure B-47: Posterior distributions of MCMC estimates of survival at age 1 (model run 9).

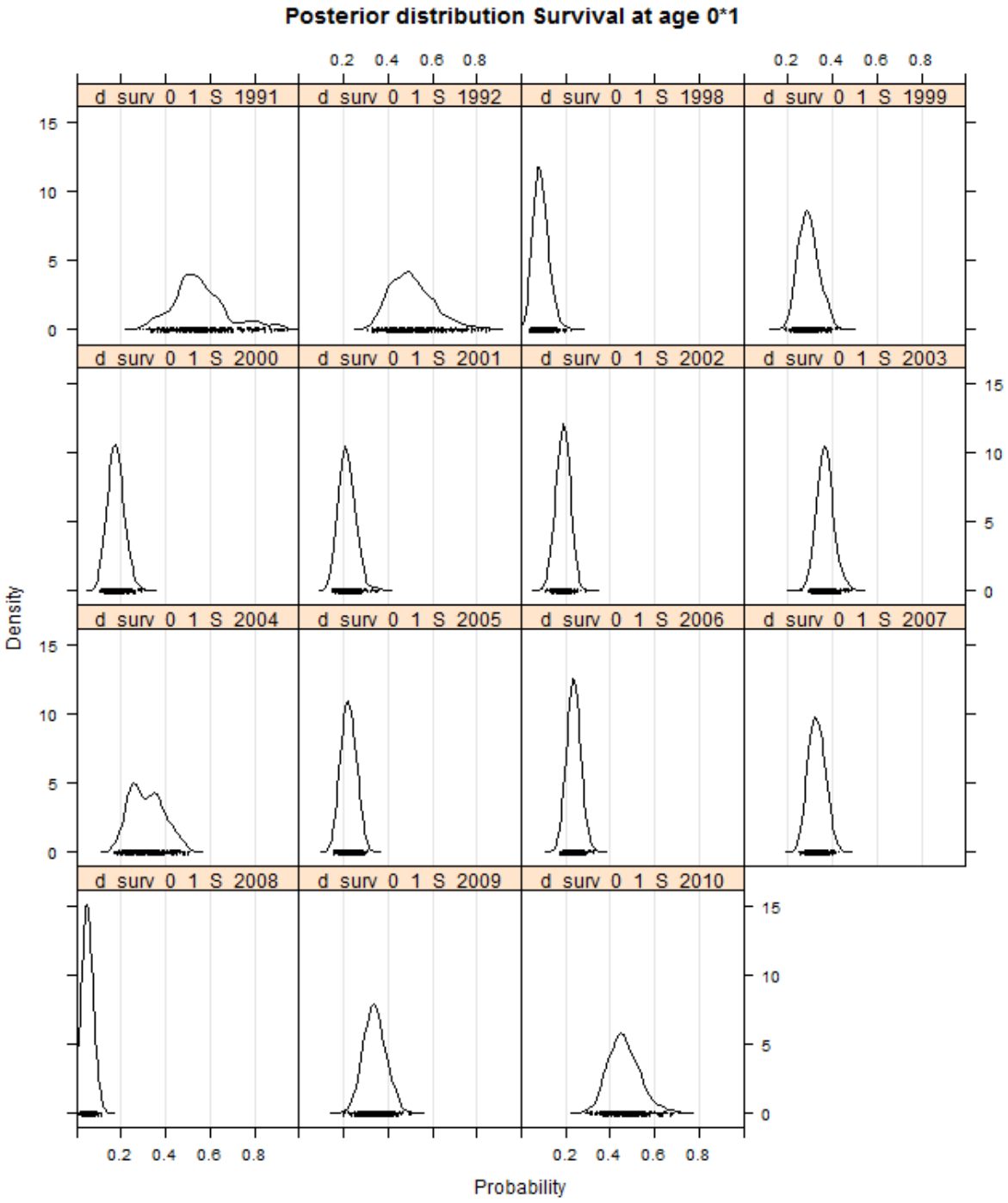

Figure B-48: Posterior distributions of MCMC estimates of cohort survival to age 2 (model run 9).

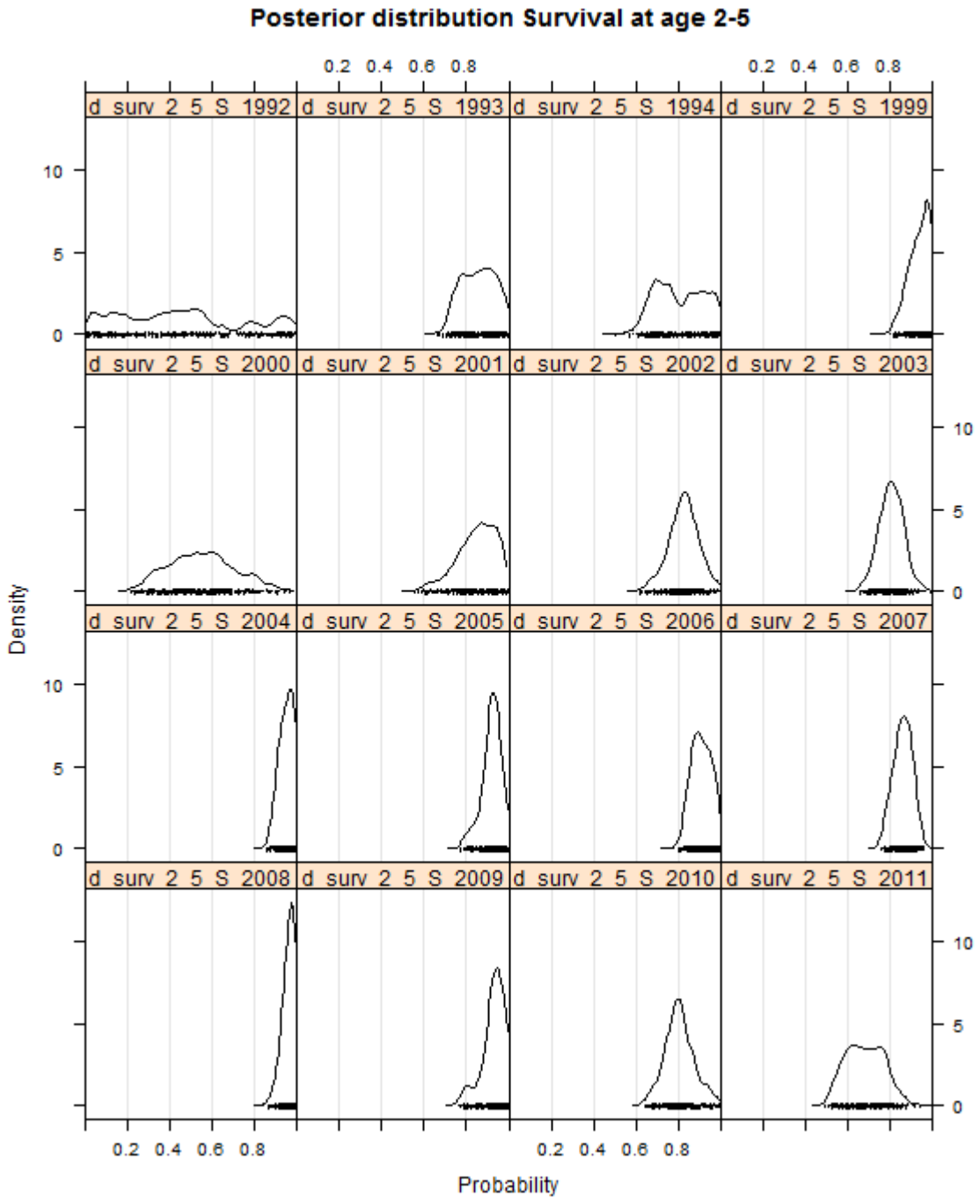

Figure B-49: :Posterior distributions of MCMC estimates of survival at age 2-5 (model run 9).

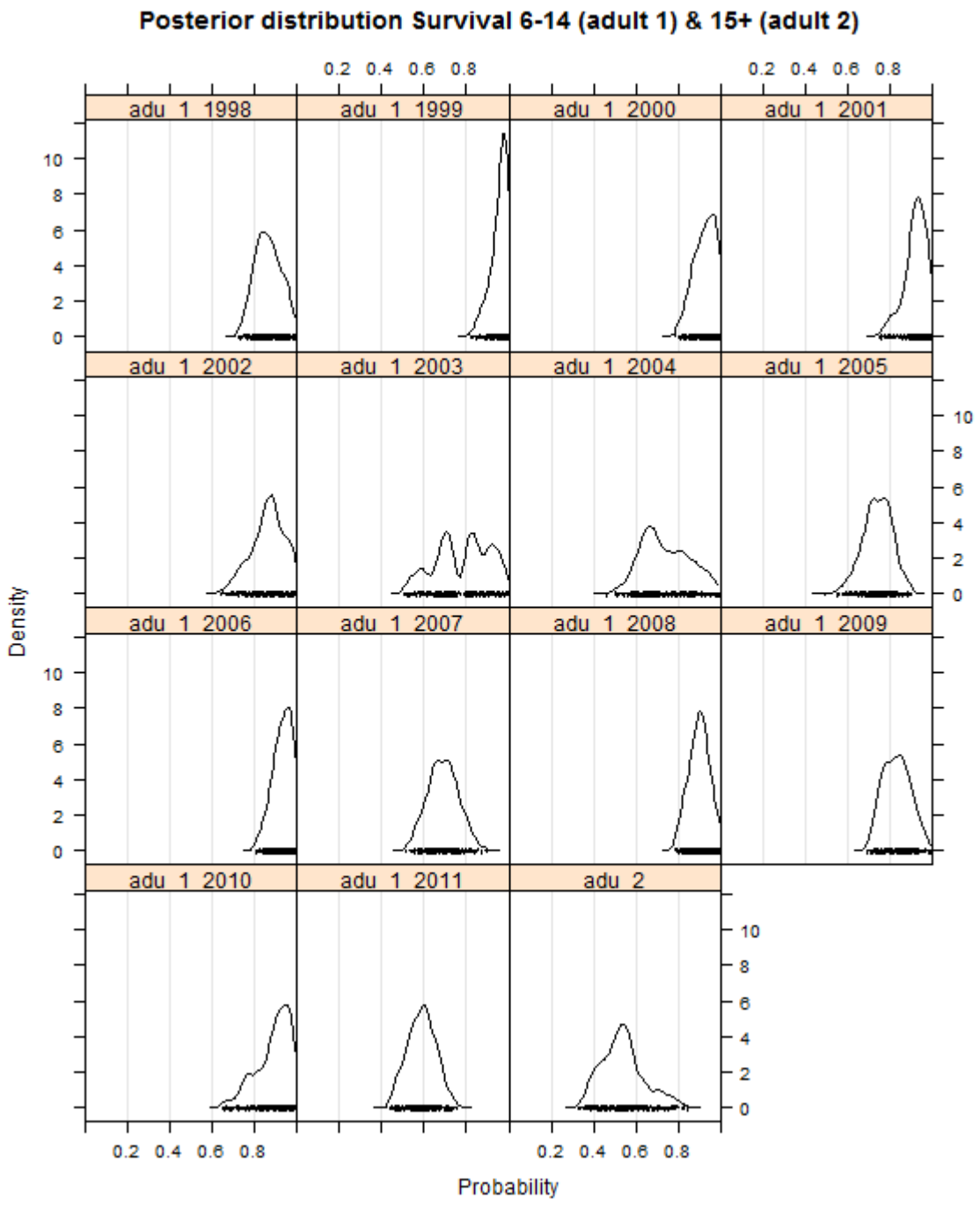

Figure B-50: Posterior distributions of MCMC estimates of survival at age 6-14 (adu_1) and 15+ (adu_2) (model run 9).

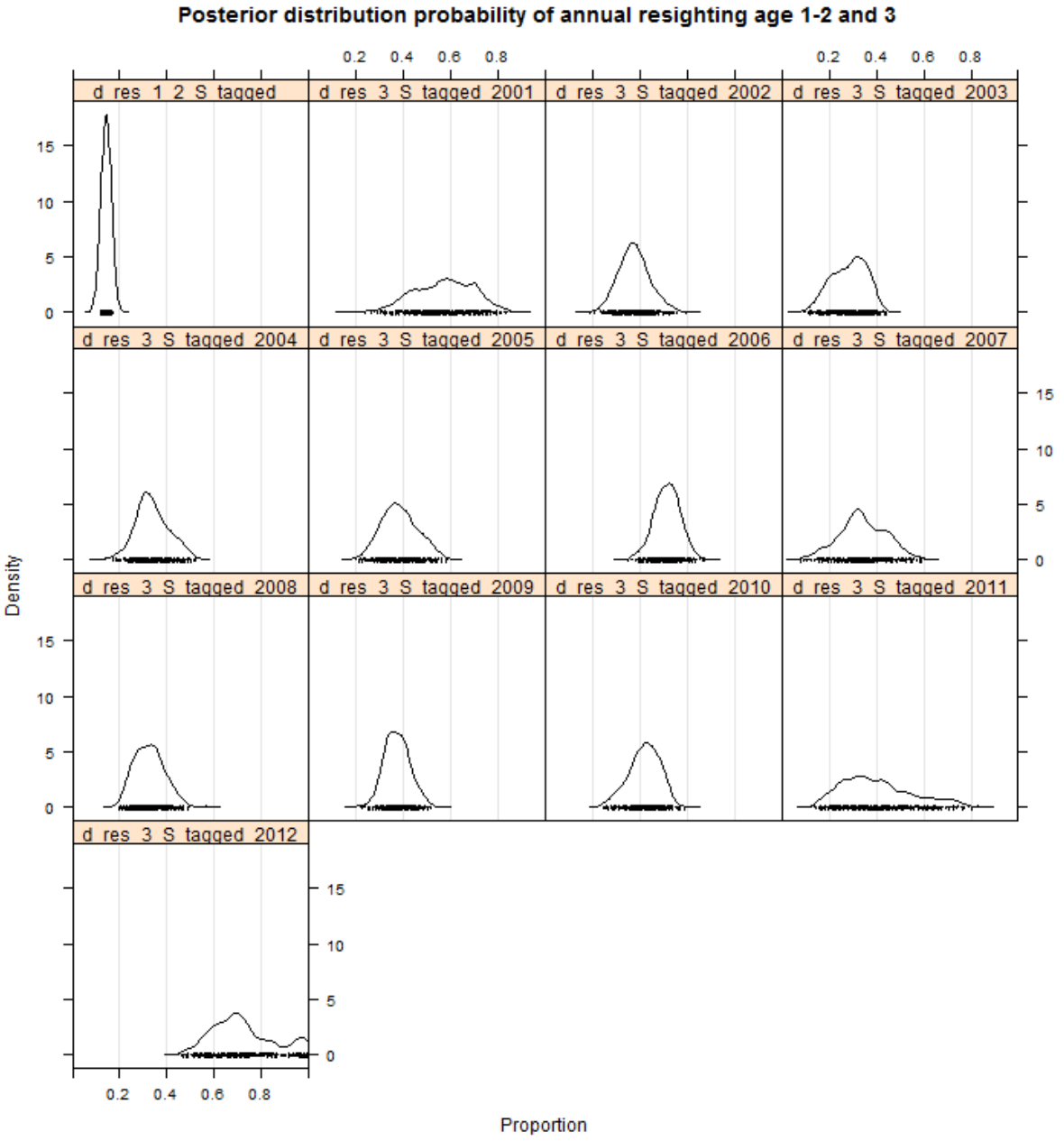

Figure B-51: Posterior distributions of MCMC estimates of annual resighting probability at ages 1-2 and 3 (model run 9).

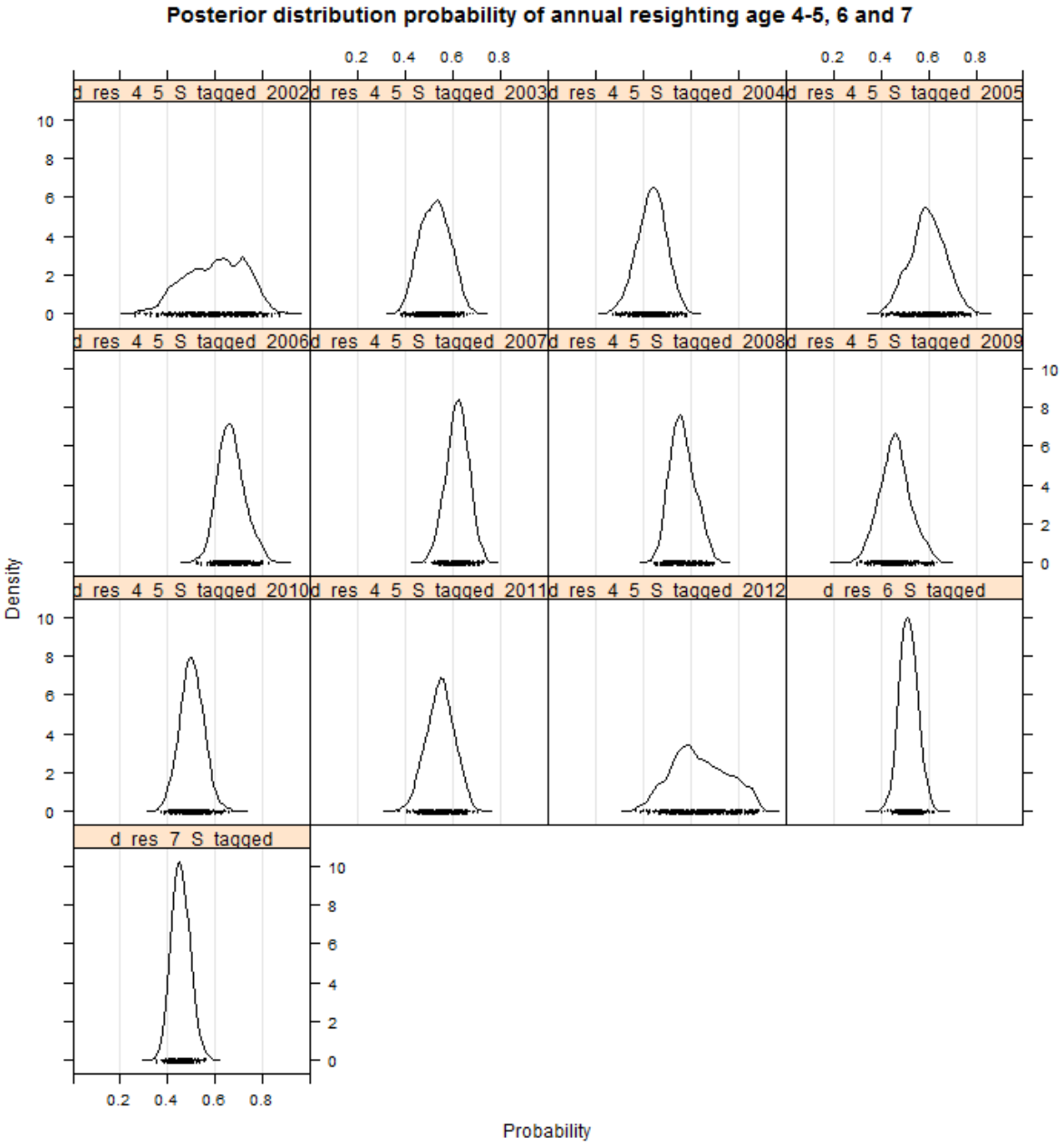

Figure B-52: Posterior distributions of MCMC estimates of annual resighting probability at ages 4-5, 6 and 7 (model run 9).

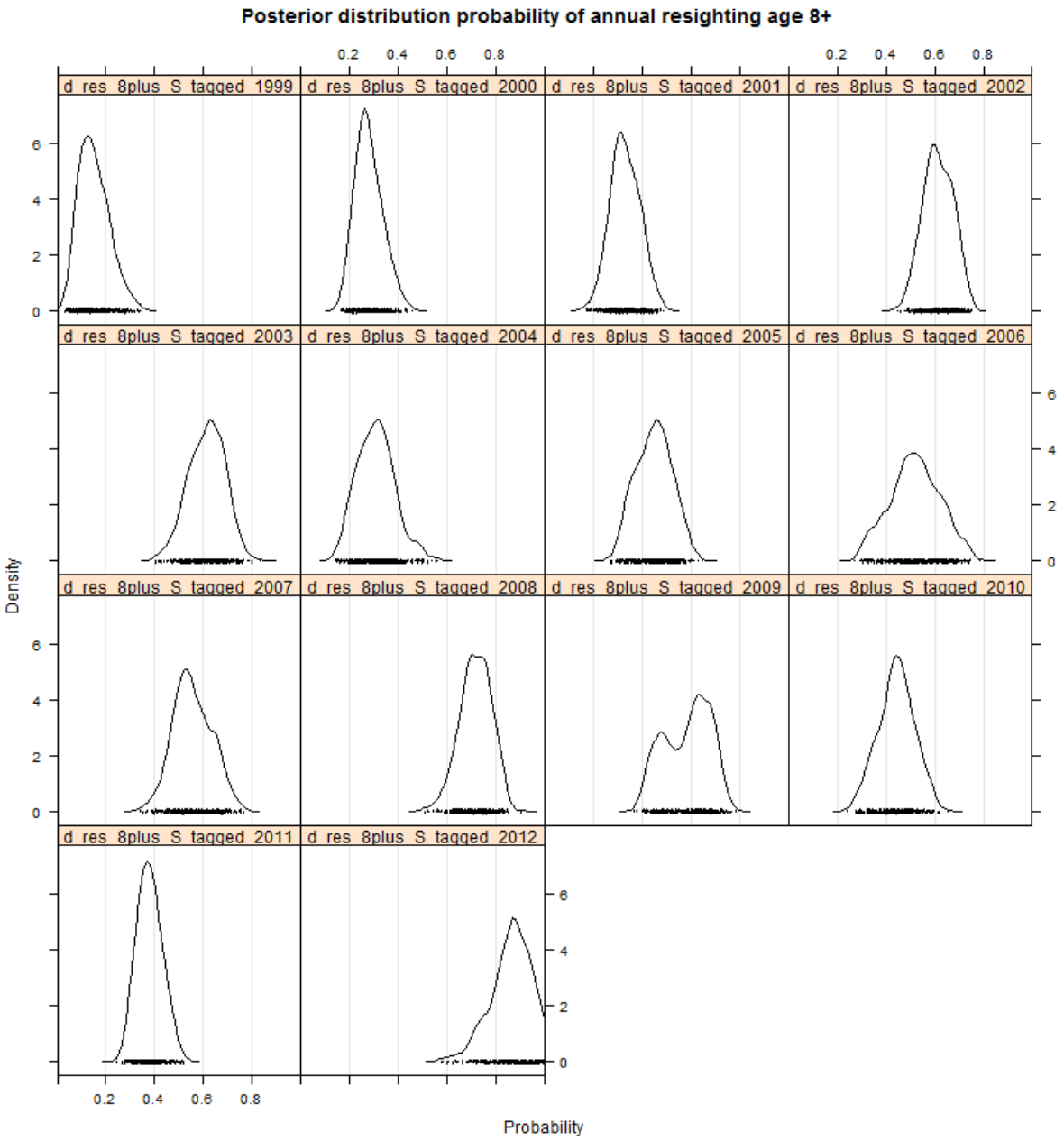

Figure B-53: Posterior distributions of MCMC estimates of annual resighting probability at age 8+ (model run 9).

Assessment of degree of correlation between parameter estimates from model run 9

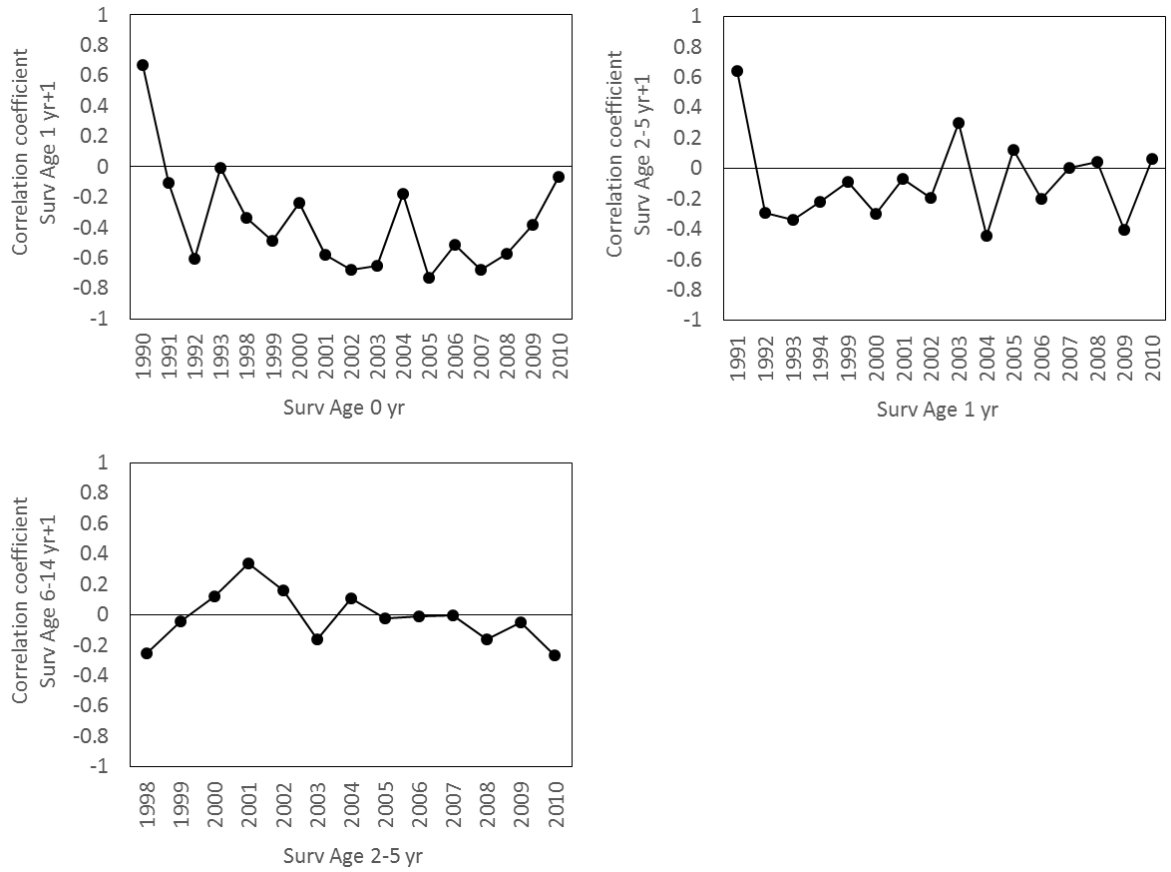

Figure B-54: Correlation coefficients between MCMC annual estimates of survival comparing different age groupings. Females at Dundas; model run 9.

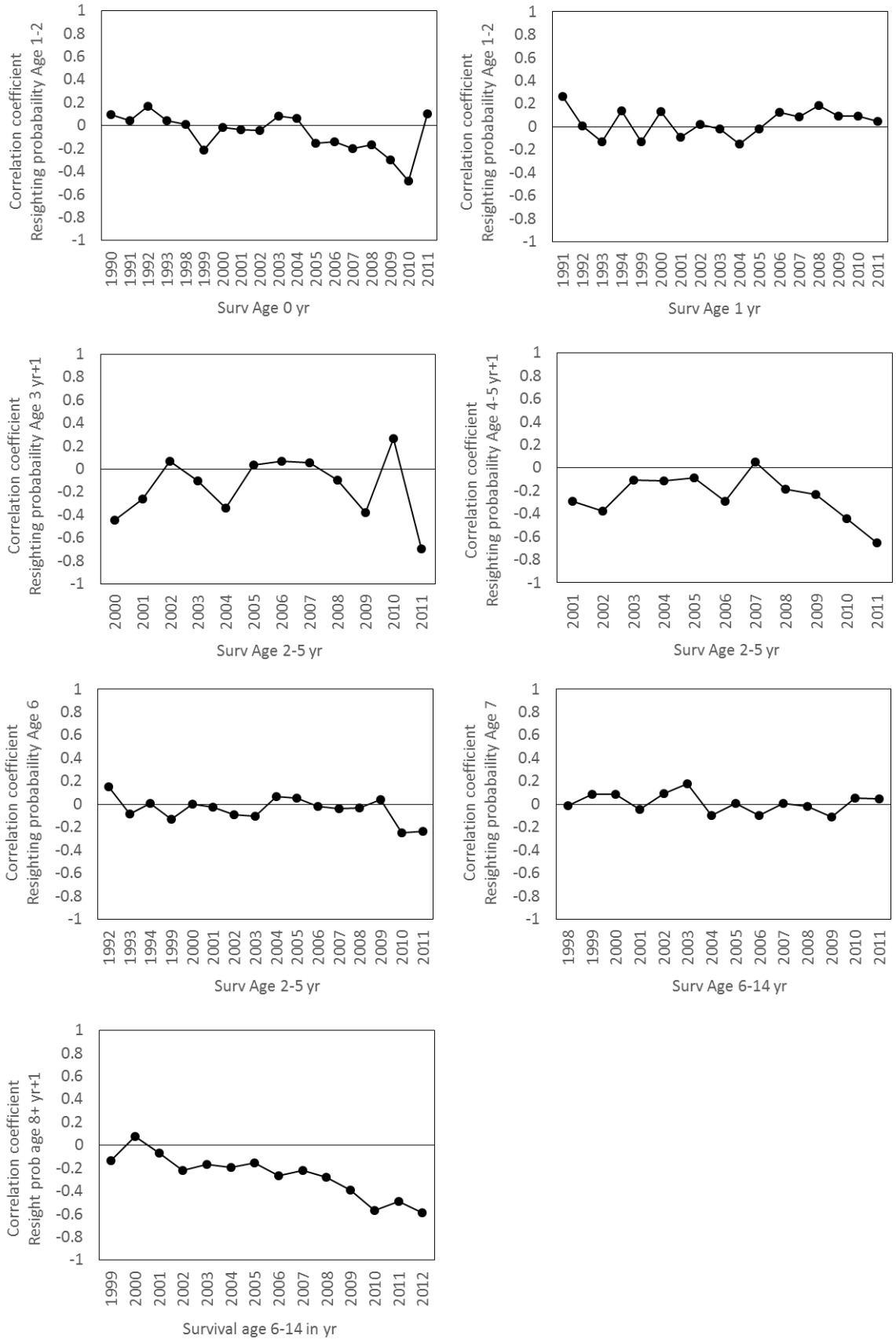

Figure B-55: Correlation coefficients between MCMC annual estimates of age-specific resighting probability and survival. Females at Dundas; model run 9.

Appendix C Exploratory analysis of mark-type effect on individual resighting frequency on females at Sandy Bay.

A brief analysis of tag type effects on resightings was conducted for cohorts that were PIT-tagged as pups. For the 1998 cohort, the relatively large proportion of resightings based on PIT-tag ID and that did not have flipper tags suggests that tag loss rates were particularly high for this cohort (Figure C-1). Round flipper tags were used in this year and were thought to have a greater tag loss rate relative to coffin flipper tags used in all subsequent years (Louise Chilvers pers. comm.). Even so, the relatively low resighting rate per individual for this cohort (from all mark types) indicates that survival of this cohort was still low relative to other cohorts, though SeaBird model estimates will have a strongly negative bias. We do not intend to correct for this bias within this project though may omit pup/yearling survival estimates for the 1998 cohort (and also the 2008 cohort for which a high tag pull out rates was estimated) from the correlative assessment as a sensitivity analysis.
This analysis also suggests that tag loss rate was relatively high for the 1999 cohort relative to all subsequent cohorts (2000 to 2002) and this may reflect the learning experience of taggers in the field with respect to tag application.

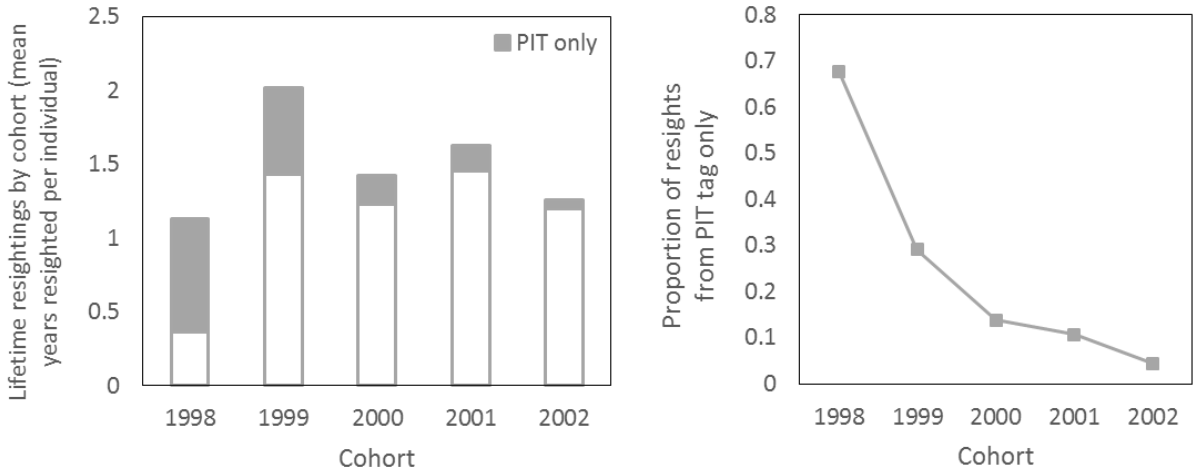

Figure C-1: Cohort effect on resightings of females at Sandy Bay over lifetime that were recorded as PIT-tagged only at the time of resighting (and not flipper tagged or branded) as a proportion of resightings from all mark types. Lifetime resightings were defined as the number of years in which an individual was resighted. Data subset included only individuals that were PIT-tagged as pups at Sandy Bay and subsequently resighted at Sandy Bay.

Appendix D Analysis of cohort effects on pupping parameters using estimates from population model runs

Model estimates of numbers in each age partition in the model fit to pup census observations (model run 12) were used to derive cohort specific pupping rates for all individuals at ages 4-7 (during maturation) and 8-14 (all assumed to be mature) (Figure 4). The results indicate that the pupping rate of the 1998 cohort was relatively good. In a previous analysis this cohort was previously found to have a low pupping rate, though there are some major differences in model configuration, which may led to these opposing results (Gilbert & Chilvers 2008). Gilbert & Chilvers (2008) estimated year-invariant survival for age 0 only and a functional form was used to estimate survival at all other ages, with year-invariant parameter estimation.

In our assessment (model 7), survival was estimated separately for ages 0, 1, 2-5, 6-14 and 15+ and survival of the 1998 cohort at age 2-5 was the lowest of any cohort (cross-ref). Thus the model configuration adopted by Gilbert and Chilvers (2008) will have underestimated pre-breeding mortality of this cohort and overestimated the number of non-breeding individuals (which have a low resighting probability). In any case, given that pup/yearling of this cohort was relatively low and very few individuals were observed at breeding age, there will be a high degree of uncertainty in the estimates of pupping rate from this cohort and this will generally be the case for all cohorts for which few individuals survived to breeding age.

Estimated pupping rates for the 1999 and 2001 cohorts were relatively low, whilst those of the 2000 cohort and all born since 2002 are relatively high at ages 8-14 (also high pupping rate for cohort born since 2003 for ages 4-7).

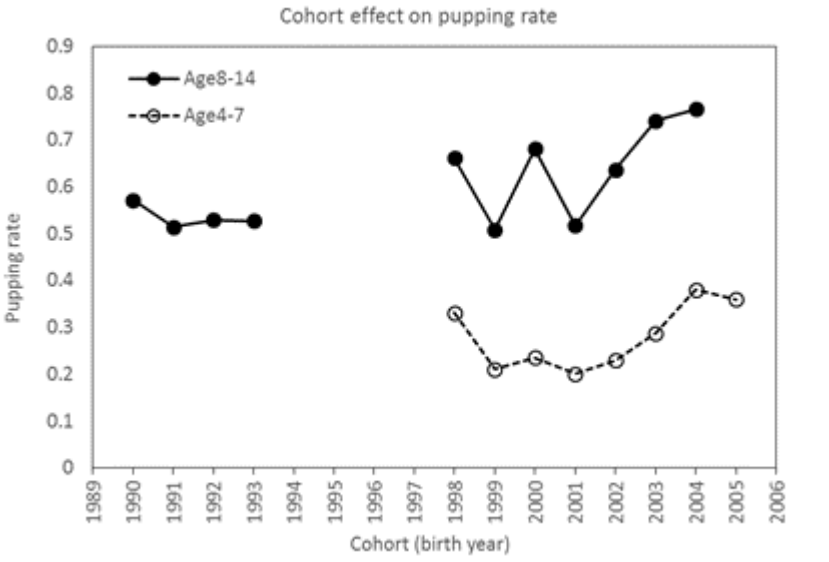

Figure D-1: Pupping rate derived from model estimates of numbers in each model partition, from the model run fit to pup census observations (model run 12).

Using the same model estimates of numbers in each demographic partition, we also found evidence for cohort effects on the age-at-first-pupping, with an increased proportion of individuals from cohorts born since 2004 pupping by age 6. This was detected in the model development phase as a change in maturation in parameters since 2010 and it is not possible to differentiate year from cohort effects on maturation.

Figure D-2: Cohort effects on the proportion of individuals that have pupped at age. Derived from model estimates of numbers in each model partition, from the model run fit to pup census observations (model run 12).

Appendix E Age-specific survival estimates for New Zealand sea lions *Phocarctos hookeri* (MARK assessment)

Clive R McMahon and Mark A. Hindell

Institute for Marine and Antarctic Studies, University of Tasmania, Hobart 7001, Tasmania, Australia.

clive.mcmahon@utas.edu.au

Abstract

Estimating vital rates is an essential part for quantifying population viability. Uncertain estimates reduce the confidence in quantifying and projecting population size overtime, which in itself compromises developing robust policy for conservation. To date, few data are available on the age-specific vital rates of New Zealand sea lions and those that are presented here, as a point of comparison for those estimated from a custom built demographic program (Seabird), show that: (1) survival varies with age, (2) first-year survival varies between years, (3) there is little confidence in estimates of pre-breeding juvenile survival because animals are not available for recapture during the annual breeding season resight effort and (4) recapture effort prior to 1999 was essentially zero. Given the importance of juvenile survival in determining population variability in seals it is paramount that effort be extended to increasing resight effort for juvenile seals by extending the annual recapture effort beyond that occurring only during the breeding season.

Introduction

The endemic New Zealand Sea Lion, *Phocarctos hookeri*, is one of rarest seals in the world and classified as "Vulnerable in slow decline" by the International Union for the Conservation of Nature (Gales 2008). Consequently, there is an urgent need for information of the vital rates of this rare animal. However, determining age-specific vital rates requires dedicated capture-mark-recapture (CMR) study whereby individual seals are marked and resighted over their lives - up to 23 years for *P. hookerii*.

The aim of this study was to estimate age-specific survival for female sea lions using a generic CMR program, MARK (White & Burnham 1999), to provide a point of comparison for custom built CMR program - SEABIRD.

Methods

At Enderby Island 3602 female New Zealand sea lion pups were marked from 1990 to 2011. Searches of the island's beaches were made to re-sight (re-capture) marked seals during the breeding season only. Capture-history matrices were constructed from the resight histories of individual seals. Multiple resights within a season were treated as a single sighting. These capture matrices were used as input files for the capture–mark–recapture (CMR) program MARK (White & Burnham 1999) to estimate survival and capture probabilities after weaning. MARK provides survival (ϕ) and recapture (ρ) estimates under the Cormack–Jolly–Seber (CJS) model.

Parametric goodness–of–fit (GOF) tests within MARK were used to test whether the CJS model assumptions were met. To accommodate lack of fit, the amount of over-dispersion ($\hat{c}$) was quantified. When there was sufficient evidence for over-dispersion, we corrected for the extra-binomial variation in the data by the variance inflation factor $\hat{c}$ (Lebreton et al. 1992) to adjust the deviance in the calculation of the AICc (quasi–likelihood AICc=QAICc) and parameter standard errors (Lebreton et al. 1992).

Results

Goodness-of-fit. The goodness–of–fit simulations indicated some over-dispersion (median ĉ =2.701), demonstrating moderate violation of the assumption that all individuals were equally catchable or have similar apparent survival probabilities. We accounted for this by applying the ĉ over-dispersion correction factor (Table 1). Survival was age-specific, but, best described by separating survival in the first year, grouping survival in ages two, three and four, splitting survival from age five to 15 and grouping all the ages from 16-21 (Table 1).

Table 1. Model ranking and criteria that best describe survival of New Zealand sea lions

Model	*QAICc*	*Delta QAICc*	*QAICc Weights*	*Model Likelihood*	*# Par*	*Q-Deviance*
ϕ(a1, 2-4., 5-15, 16.) ρ(t)	5416.5	0	0.578	1	36	1830.06
ϕ(a1, 2-3., 4-15, 16.) ρ(t)	5417.57	1.0	0.351	0.606	37	1829.03
ϕ(a) ρ(t)	5422.5	6.0	0.028	0.049	43	1821.915
ϕ(a_10.) ρ(t)	5423.6	7.2	0.016	0.028	32	1845.31
ϕ(a_15.) ρ(t)	5423.7	7.2	0.016	0.027	37	1835.23
ϕ (t) ρ(t)	5974.9	558	0	0	43	2374.33
ϕ (.) ρ(t)	6143.7	727	0	0	23	2583.555
ϕ (t) ρ(.)	6659.0	1242	0	0	23	3098.83
ϕ (.) ρ(.)	6811.4	1394	0	0	2	3293.40

Recapture probability. Recapture probability varied significantly between years so that from 1990 to 1990 recapture probability and effort was zero (Fig. 1). After 1999, recapture probabilities increased and varied between 40.7% and 67.1%. Variation in recapture effort - and reflected in the recapture probability estimates, is extremely important so that survival estimates are significantly (χ^2_{21} = 709.8 p <.0001) affect by capture effort (*c.f.* ϕ(constant) ρ(constant) and ϕ (constant) ρ (time).

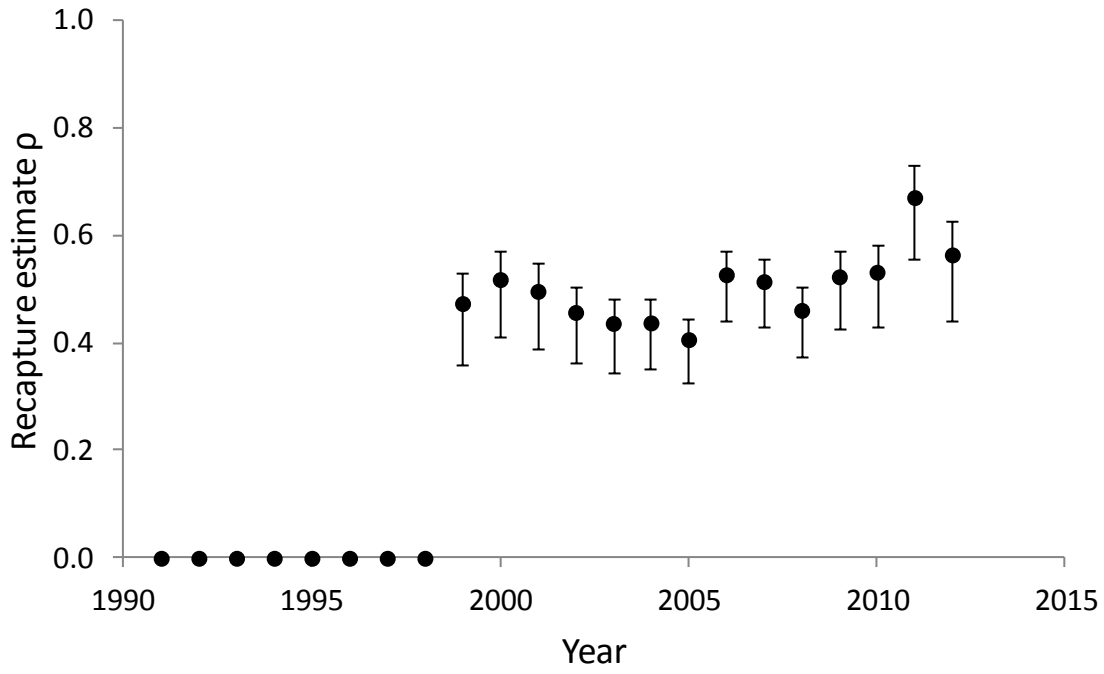

Figure 1. **The recapture probabilities of sea lions. The vertical bars indicate the 95% confidence intervals.**

Survival estimates. Significant (χ^2_{20} = 761.4 p <.0001) differences were evident in the age-specific survival estimates of sea lions. Age-specific survival was best described by separating survival in the first year, grouping survival in ages two, three and four, splitting survival from age five to 15 and grouping survival for all the ages from 16-21 (Fig. 2). First-year survival was low (6-50%) and varied between the 13 cohorts from 1998-2010 (Fig. 3). We estimated survival for the latter 13 cohorts only because the probability of recapturing a seal before 1999 was essentially zero (Fig. 1).

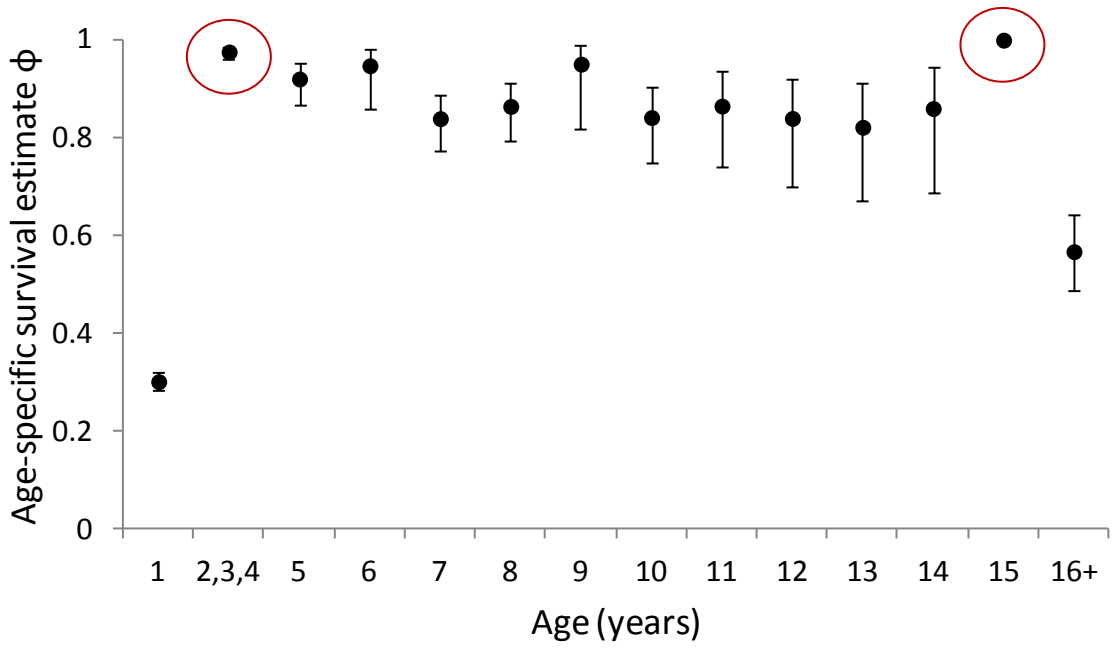

Figure 2. **Age-specific survival estimates for New Zealand sea lions. The vertical bars indicate the 95% confidence intervals. Confidence intervals for estimates circled in red extend beyond one and consequently have low interpretive value and need to be treated cautiously.**

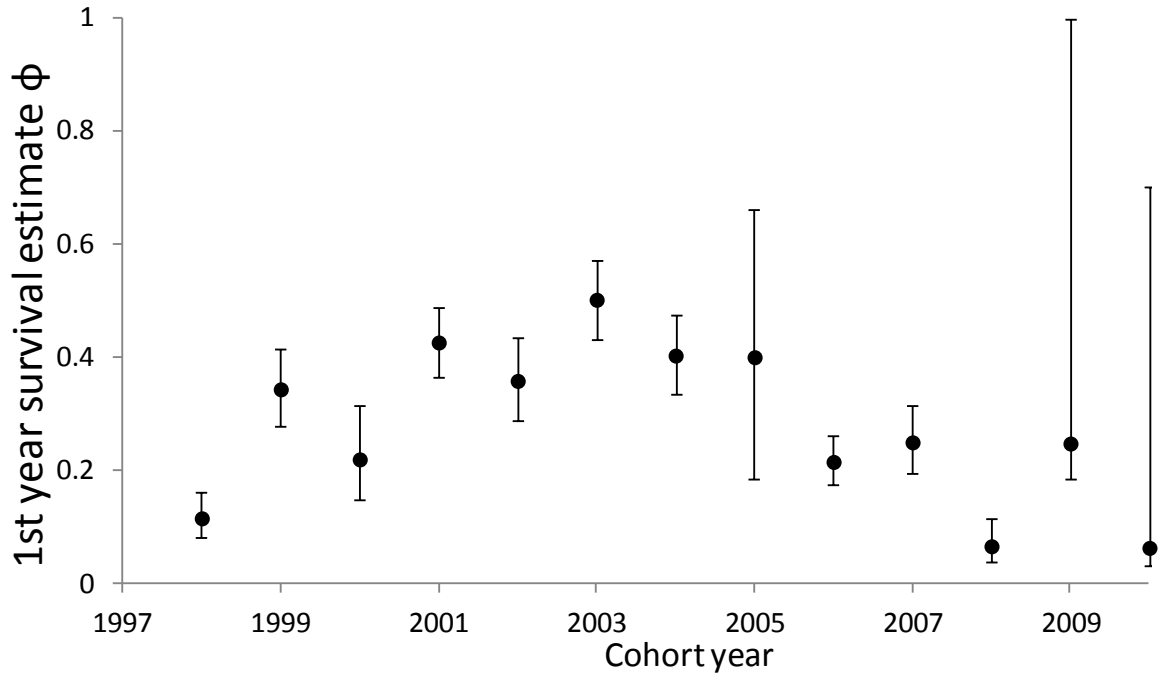

Figure 3. First-year survival estimates for 13 cohorts (1998-2010) of New Zealand sea lions. The vertical bars indicate the 95% confidence intervals.

Discussion

The recapture probabilities of marked sea lions varied between years with the most important observation being that effort to recapture seals prior to 1999 was essentially zero which compromised estimating survival prior to 1999, especially for estimates of first-year survival that varied between years. This variability in first-year survival is noteworthy and deserving of further investigation, by linking this variation to annual differences in the environment that affects maternal investment in offspring which can be informative in terms of modelling population viability (McMahon et al. 2005).

A key finding to come out of these preliminary analyses is that when seals are not recaptured or not available for recapture, survival estimates are compromised e.g. estimates of pre-breeding juvenile survival - 2-4 years, and largely uninformative. The most useful and robust way to resolve this, is to increase the recapture/resight effort by extending it to periods when these juvenile seals are ashore during the winter. Quantifying vital rates in these juvenile ages is important given that juvenile survival is a key driver of population growth rates (McMahon et al. 2005). It is especially important to have robust estimates for New Zealand sea lions given the population is decreasing and the overall vulnerability of this rare population to extinction (Gales 2008).

References

Gales, N. (2008) Phocarctos hookeri. IUCN 2010: IUCN Red List of Threatened Species. www.iucnredlist.org.

Lebreton, J.D., Burnham, K.P., Clobert, J. & Anderson, D.R. (1992) Modeling survival and testing biological hypotheses using marked animals: a unified approach with case studies. Ecological Monographs, 62, 67-118.

McMahon, C.R., Hindell, M.A., Burton, H.R. & Bester, M.N. (2005) Comparison of southern elephant seal populations, and observations of a population on a demographic knife-edge. Marine Ecology Progress Series, 288, 273-283.

White, G.C. & Burnham, K.P. (1999) Program MARK: survival estimation from populations of marked animals. Bird Study, 46, 120-139.