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

Demographic model options - correlative assessment

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Executive summary

- A correlative assessment was conducted with the aim of identifying the potential causes (e.g. fishery-related mortality, climate, disease and others) of demographic variation and population change in NZ sea lions at the Auckland Islands.
- Year-varying demographic rate estimates for females at Sandy Bay (Roberts et al., 2014) were related to a collated dataset of climatic, dietary, biological and fishery-related observations. Hypothetical biological and demographic responses to candidate drivers of population change were identified prior to the correlative assessment.
- In most cases, the time series of available data were short and were mostly available for the period of population decline and this compromised the power of correlative assessments. Also, a large number of tests were performed and we would expect some tests to have been 'significantly' correlated by random chance.
- A correlation with cohort survival to age 2 years was consistent with disease-related mortality affecting a decline in survival after 2005. Prior to 2005, pup mass at 3-weeks appeared to have been a good predictor of cohort survival to age 2.
- Poor correlations were obtained when relating survival at ages 2-5 (juveniles) or age 6-14 (adults) to estimated captures and interactions in the Southern arrow squid trawl fishery at the Auckland Islands (SQU6T). However, a strong negative correlation was observed between survival at ages 6-14 (1999-2004) and cohort survival to age 2 in the previous year (1998-2003), which would be consistent with the high energetic costs of lactation affecting maternal survival during this time period.
- Climate indices including Inter-decadal Pacific Oscillation (IPO) and sea surface height (SSH) were well-correlated with the occurrence of an array of key prey species in the diet, from an analysis of scats (Stewart-Sinclair, 2013). However, a longer time series of climate and diet data, with cyclic fluctuations, would be needed to establish a causative correlation with diet.
- Variable diet composition, a decline in maternal condition, changes in milk quality and in pup mass, and depressed pupping rates, are all consistent with changes in nutritional status, though some of these responses could also occur in response to pup mortality that was not driven by nutritional stress.
- The relationships and mechanisms identified should be considered as indicative only, though highlighted some new areas for thorough assessment. This should include a model-based assessment (as opposed to correlative) so that it will be possible estimate effect sizes, which will be necessary for explaining the causes of population decline.

1 Introduction

New Zealand sea lion (*Phocarctos hookeri*) was listed as Nationally Critical (Baker et al., 2010), it has 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 was 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 were 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.

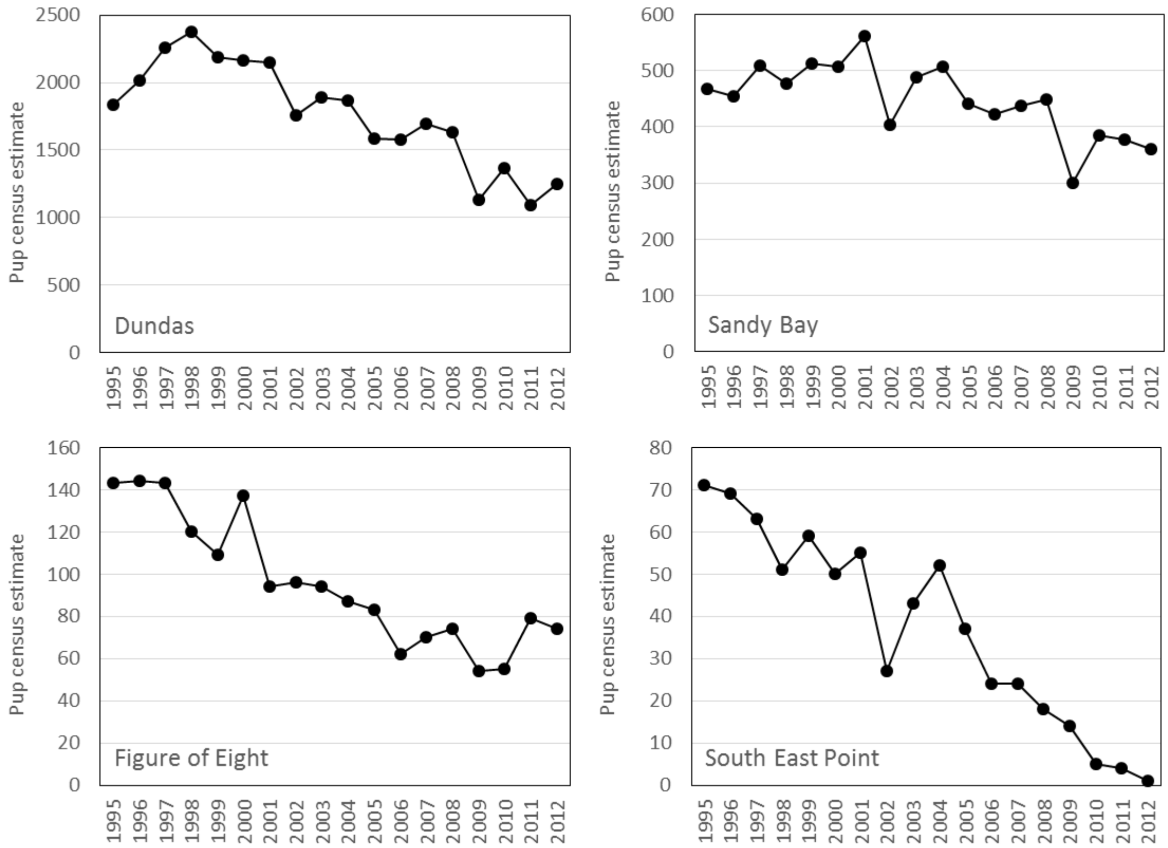

Figure 1-1: Annual pup census estimates of NZ sea lion at the main breeding rookeries of the Auckland Islands. (Childerhouse et al., 2013)

This project broadly aimed 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 final report, summarising a correlative assessment that used the outputs from the first project phase (Roberts et al., 2014) to address the second of these project objectives. In this research component, we adopted a correlative approach to identify ultimate causes of demographic and population change of NZ sea lion at the Auckland Islands.

2 Methods

2.1 Overview

The assessment was split into two main work components, Figure 2.1:

- **Demographic modelling**, which dealt with the estimation of long-term time series in key demographic rates, i.e., survival-at-age, pupping probability or different demographic groupings, 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.
- **Correlative analysis**, 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 second of these project components: a correlative assessment of NZ sea lion at the Auckland Islands. This used demographic rate estimates of female NZ sea lion at Sandy Bay from the first project phase, reported on separately in Roberts et al. (2014).

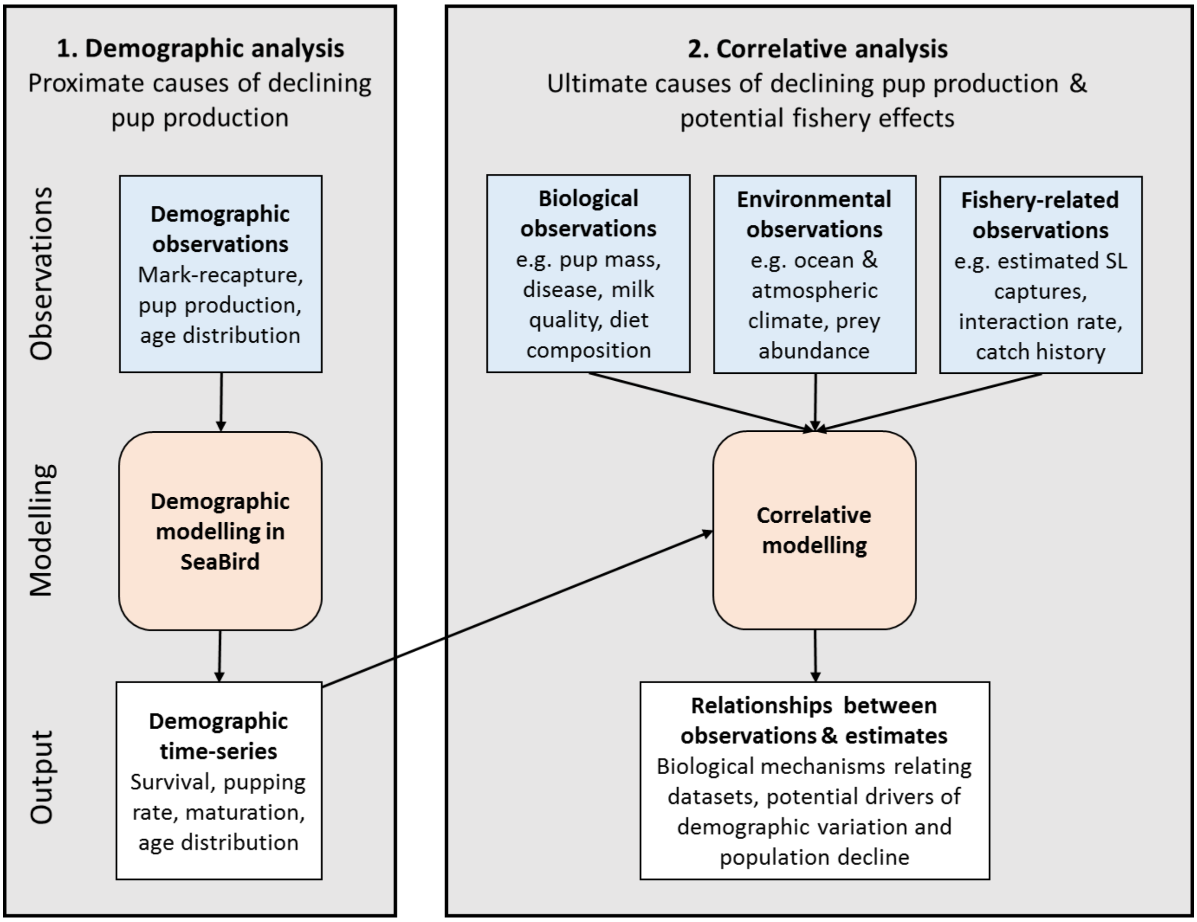

Figure 2-1: Methodological overview of project approach. SeaBird is NIWA's mark-resighting analysis package.

2.2 Use of estimates from the demographic assessment

Demographic rate estimates for females at Sandy Bay were obtained from the "optimal" assessment model (model run 8) (Roberts et al., 2014). Median values of parameter estimates were used as point estimates and the associated error distributions were not used in the correlative analysis.

Tag loss rates were not estimated by model run 8, so estimates of survival are likely to be underestimated in most cases. The survival estimates used in the correlative assessment should be considered as an index of survival, which was related to annual biological, environmental and fishery-related correlates. In addition, the annual variable tag loss rate was likely to have negatively biased the estimates of survival to age 2 of the 1998 and 2008 cohorts.

A break-point analysis conducted by Roberts et al. (2014) indicated that pupping rate and pup survival rates were very different prior to 2005, relative to later years. This was taken as justification for taking year subsets of demographic rates before and after this year when relating to correlates.

2.3 Correlative assessment

Datasets considered in this analysis are presented in Appendix A. Hypothetical models relating environmental, biological and demographic observations were developed with expert consultation at two international workshops and a subsequent literature review of relevant mammalian reproductive biology (e.g. Clutton-Brock et al. 1989; Trillmich 1990) (Appendix B). These models provided a framework for assessing the strength of relationships between datasets obtained for the time period 1990 and 2012 (Appendix A).

This assessment focussed on three of the candidate drivers of population change in NZ sea lions: nutritional stress caused by variation in prey abundance (climate or fishery-driven); disease-related mortality of pups; and direct fishery-related mortality. The models for some candidate drivers included a number of different hypothetical relationships (relating a pair of datasets), identified as: 1a-h (responses to nutritional stress); 2a-c (responses to pup mortality); and 3 (responses to predation or the direct effects of fishing) (Table 4-2 and Figure 2-2). For each relationship assessed, the degree of correlation (Pearson product-moment correlation coefficient) was calculated. A summary of outputs including selected data plots is presented in Appendix C.

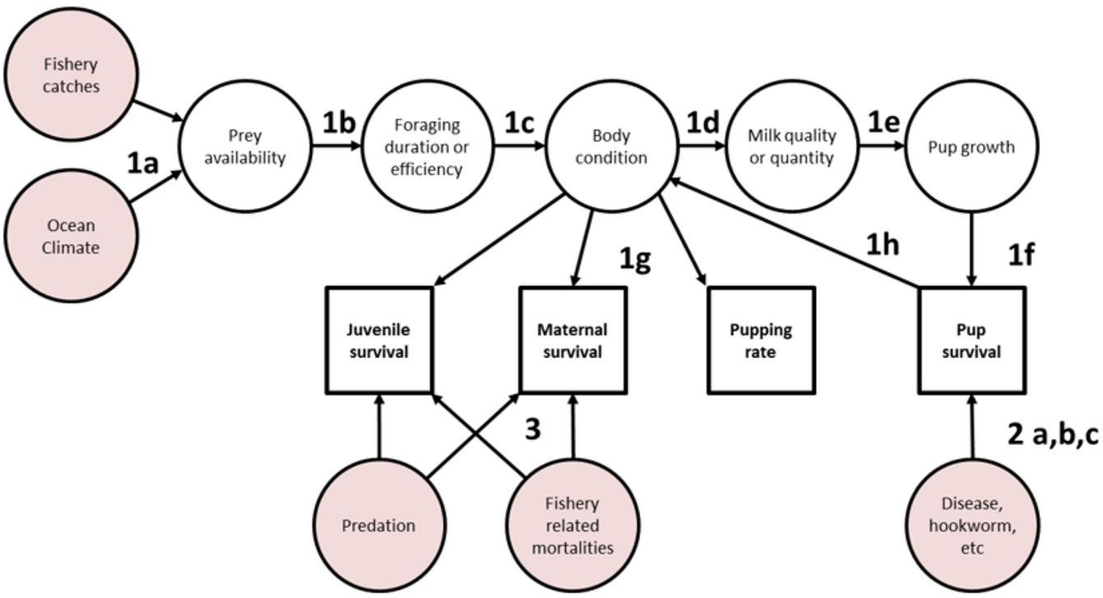

Figure 2-2: Hypothetical model relating the datasets. Relationships denoted with identifier, e.g. "1a", listed in Table 4-2; candidate drivers of population change (shaded circles; were related to biological responses (open circles) and demographic rates (open squares).

3 Results

3.1 Effects of variation in prey abundance/availability

The correlation coefficients of all relationships assessed are presented in Table C-2; also plots of selected relationships are in Appendix C. There were no significant correlations between ocean or atmosphere climate indices and the local abundance of prey species (catch-per-unit effort in commercial fisheries at the Auckland Islands; Roberts, unpublished data), with the exception of ling (*Genypterus blacodes*) and the Inter-decadal Pacific Oscillation (IPO) index (Pearson product-moment correlation – $r = 0.62$, $df = 17$, $p > 0.01$; relationship 1b) (Figure C-4).

Much stronger correlations were obtained between climate indices and the occurrence of prey species in diet (% frequency of occurrence in scats, %O; Childerhouse et al. 2001; Stewart-Sinclair 2013) (relationship 1a). Significant negative correlations were obtained when relating IPO and %O of arrow squid (*Nototodarus sloanii*), ling, red cod (*Pseudophycis bachus*), opalfishes (*Hemerocoetes* spp.), octopus and rattails (Macrouridae) (r, $p < 0.05$, df = 9) (Figure C-2). Sea surface height (SSH) had significant positive correlations with %O of ling, opalfishes, *Octopus* spp. (r, $p < 0.05$, df = 13) and a near-significant positive correlation with red cod (r, $p < 0.10$, df = 13) (Figure 3-1).

Diet composition and body condition index (BCI) of lactating females (from a reanalysis of data from Riet-Sapriza et al. 2012) were not well correlated (relationship 1c) (Figure C-5). Exceptions to this were a significant negative correlation between maternal condition and %O in scats of arrow squid ($r = -0.73$, $p < 0.05$, df = 6) and a near significant negative correlation with %O of red cod ($r = - 0.66$, $p < 0.10$, df = 6). The correlation between diet composition and 3-week pup mass (Chilvers 2012) was also poor (relationship 1c & 1d) with the exception of %O of giant octopus (*Enteroctopus zealandicus*) in scats with that had a highly significant negative correlation ($r = - 0.75$, $p < 0.001$, df = 14). A significant positive correlation was obtained between maternal BCI and pup mass ($r = - 0.71$, $p < 0.05$, df = 6), though only when taking a subset of observations prior to 2005 (Figure C-7).

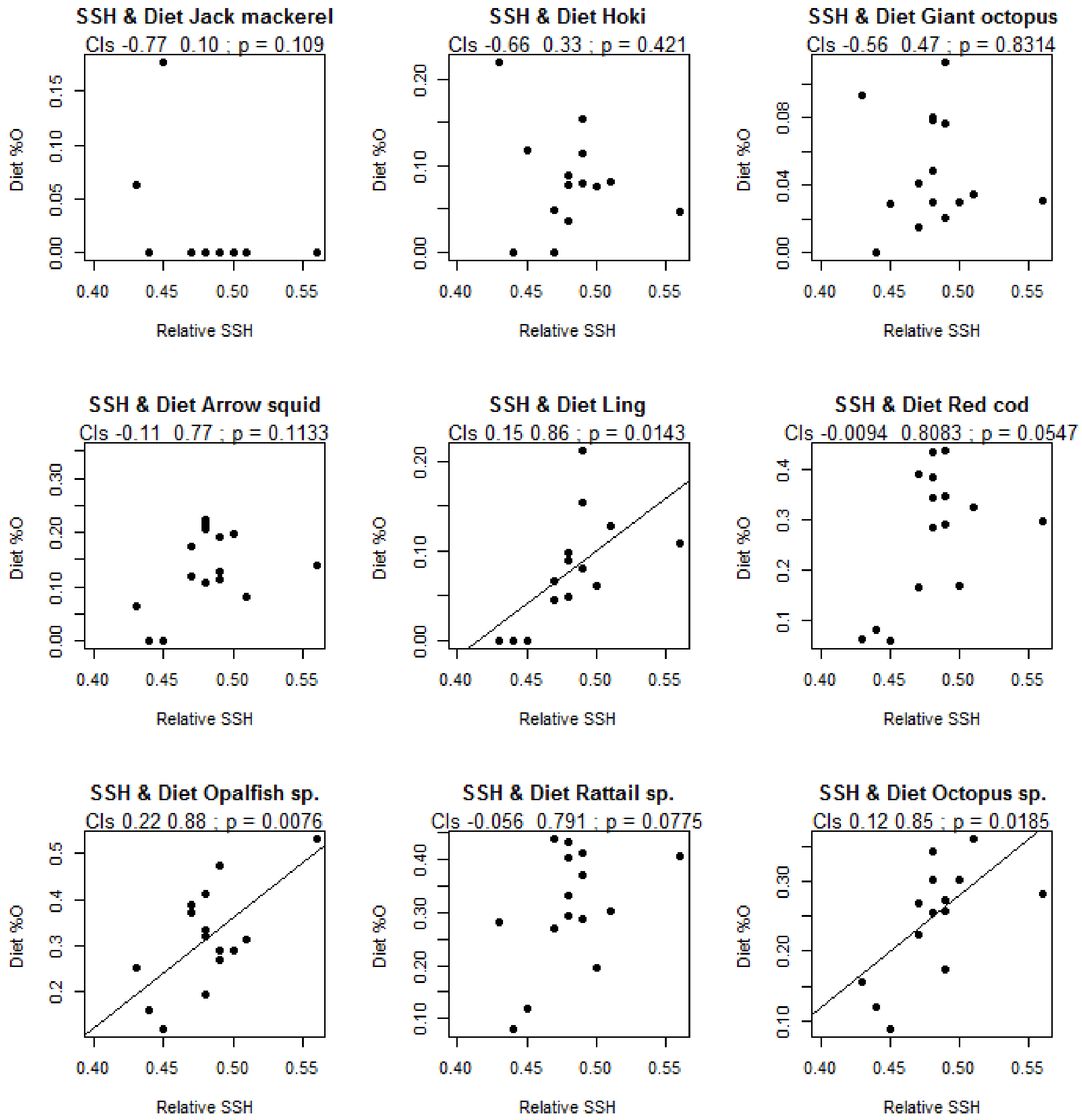

Figure 3-1: Sea surface height (SSH) and occurrence of selected prey species in the diet of NZ sea lions at Sandy Bay. (Childerhouse et al., 2001; Stewart-Sinclair, 2013). Regression lines shown for correlations significant at the 5% level.

3.2 Pup mass, pup survival, adult survival & pupping rates

Cohort survival to age 2 was strongly correlated with female pup mass at 3-weeks when using a subset of years prior to 2005 (r = 0.89, p < 0.01, df = 6; relationship 1f). Correlations using the entire time series or estimates from 2005-2010 were poor (r = 0.10, p = 0.73, df = 12; and r = - 0.38, p = 0.46, df = 4, respectively) (Figure 3-2).

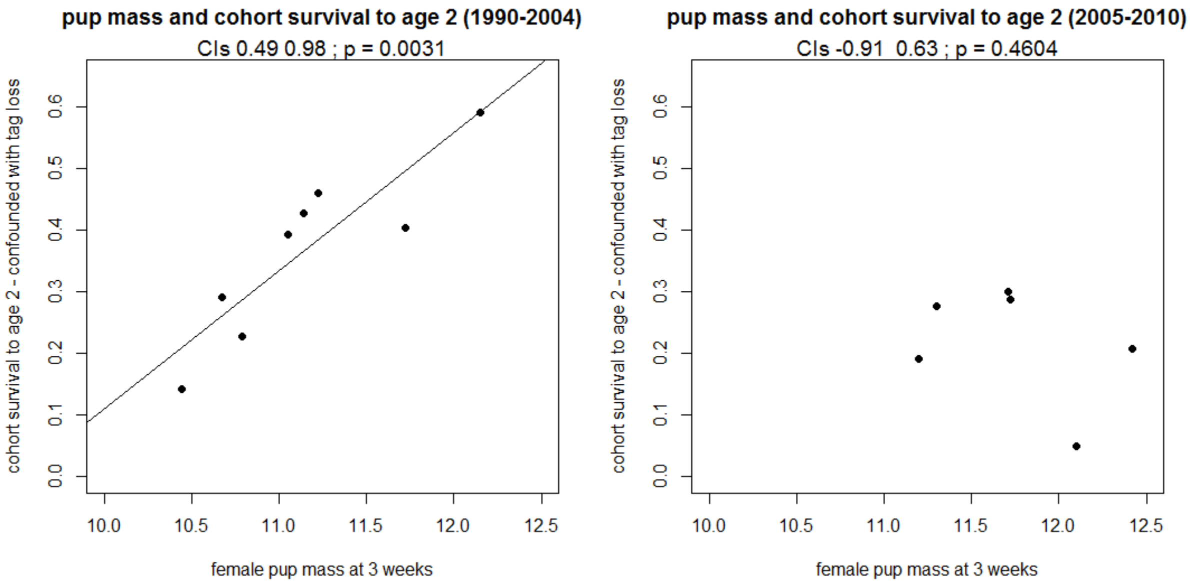

Figure 3-2: Pup mass of females and demographic modelling estimate of cohort survival to age 2. Survival estimates confounded with tag loss rate; regression lines shown for correlations significant at the 5% level.

A negative correlation was obtained when comparing adult survival (age 6-14) with pup/yearling survival in the previous year (relationship 1h), though only when comparing observations from 1990-2004 (r = - 0.99, p < 0.001, df = 4), with no correlation observed in the later period (2005-2010; r = - 0.31, p = 0.49, df = 5) (Figure 3-3). Poor correlations were observed between maternal body condition index (BCI) and pupping rate or maternal survival in the same year (r = 0.17, p = 0.69, df = 6, and r = 0.13, p < 0.73, df = 7, respectively) (Figure C-10).

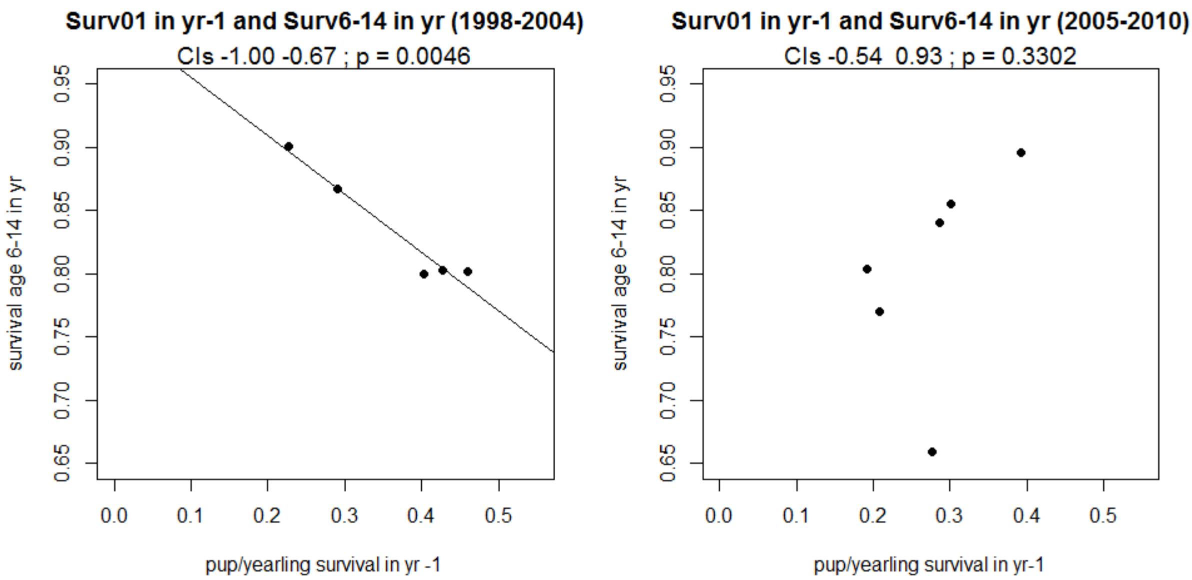

Figure 3-3: Annual survival at age 6-14 (Surv6-14) in year plotted against pup/yearling (Surv01) survival in the previous year. All survival estimates confounded with tag loss rate; regression lines shown for correlations significant at the 5% level.

3.3 Disease-related mortality of pups

Estimates of cohort survival to age 2 were not well correlated with the pup mortality counts at 3 or 7 weeks (Chilvers 2012) (*r* = 0.43, p = 0.14, df = 11; and *r* = - 0.23, p = 0.45, df = 11, respectively; relationship 2a) (Figure C-11). However cohort survival to age 2 was negatively correlated with the frequency of disease-related pup mortality (Castinel et al. 2007; Roe 2012; Roe et al. unpublished data) in the period 8-10 weeks after sampling began (approximately corresponding with the first 3 weeks in February) and close to significant for the period 11-13 weeks after sampling began (end of February/beginning of March) (*r* = - 0.87, p < 0.01, df = 7; and *r* = - 0.67, p < 0.10 , df = 5; respectively, relationship 2c) (Figure 3-4).

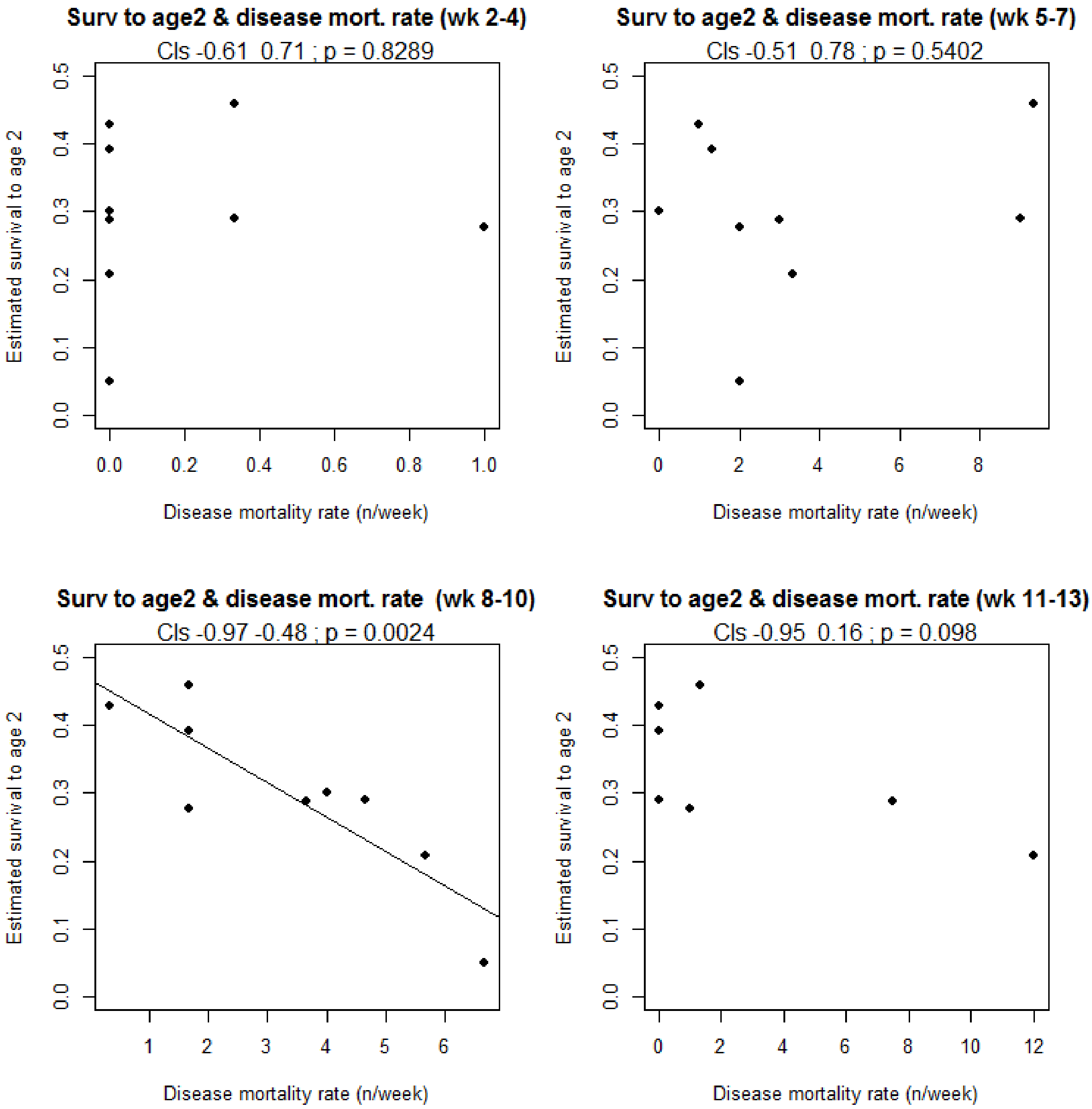

Figure 3-4: Pup disease related mortality rate and estimated cohort survival to age 2. Number of pups diagnosed as disease-related mortality per week with sampling effort, Castinel et al. (2007); Roe (2012); Roe unpub. data; regression lines shown for correlations significant at the 5% level; survival estimates confounded with tag loss rate.

3.4 Direct effects of fishing

Poor correlations were obtained between survival estimates at ages 2-5 (juveniles) or 6-14 (adults) and estimated fishery-related captures or estimated interactions (Thompson & Abraham 2010) (*r*, p > 0.10, df = 12; relationship 3) (Figure 3-5).

An index of the rate of captures or interactions relative to population size was generated using model estimates of population *n* in each age category (2-5 and 6-14 years). In all cases there was no significant correlation between these indices and survival estimates for each respective age class (*r*, p > 0.10, df = 12).

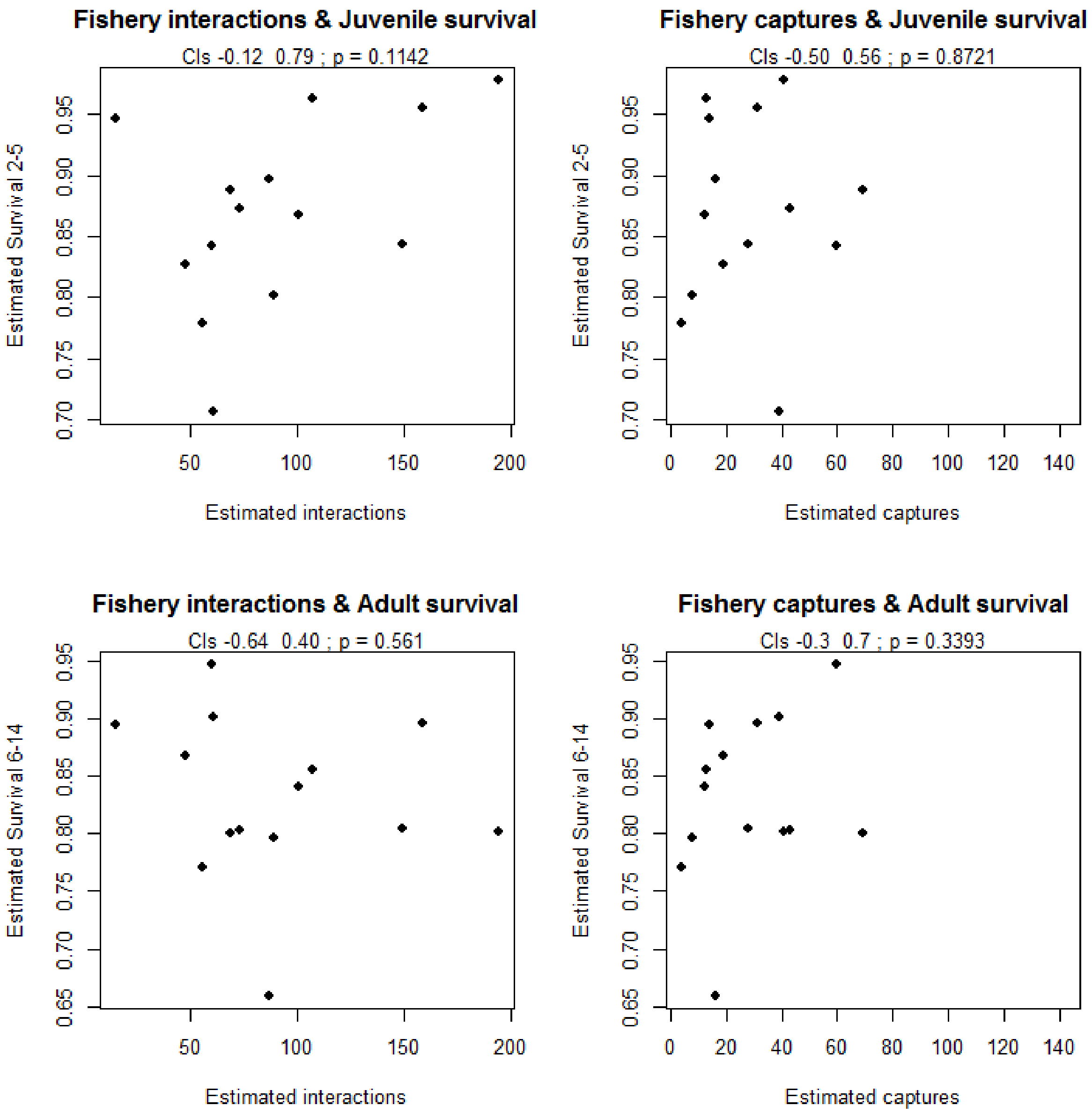

Figure 3-5: Estimated captures and interactions with squid fishery trawls (SQU6T) and estimated cohort survival at vulnerable ages. Thompson & Abraham (2010); survival estimates confounded with tag loss rate.

4 Discussion

4.1 Limitations of this assessment

This correlative assessment used demographic rate estimates from a single model run (model run 8; Roberts et al., 2014), which used mark-recapture observations of females tagged as pups (males were ignored). An alternative approach would have been to incorporate biological and environment observations as covariates in the demographic assessment, rather than use two separate analyses.

A break-point analysis (Roberts et al. 2014) was taken as justification for using year subsets of demographic rates before and after this year when relating to correlates. For both pupping rate and pup/yearling survival, year grouping were identified in the mid-2000s. While neither of these could explain the initial phase of declining pup production in the late 1990s, they may indicate that biological/demographic processes have occurred which may have exacerbated the decline or may lead to a continuation of the decline in the near future.

A number of other limitations were identified, that compromise the power of this assessment. For instance: only point estimates were used, ignoring any associated uncertainty; a large number of relationships were assessed and we would expect a few of these to be correlated by random chance; and in most cases the time series of available data was short and the weight of observations were collected from the post-2000 period of population decline at the Auckland Islands.

Given these limitations, the relationships and mechanisms identified should be considered as indicative only, although they highlight some areas for more thorough assessment.

4.2 Prey abundance and nutrient stress

Poor correlations between commercial fishery catch rates of selected prey species and their occurrence in NZ sea lion diet (all prey species except jack mackerels) suggest that further research is required to assess the extent to which abundance indices calculated from commercial fishery catch and effort data adequately reflect the availability of prey to sea lions in their foraging areas. Good correlations between diet composition and climate indices (IPO) or SSH (indicative of water temperature throughout the water column) suggest that the diet of NZ sea lion at Sandy Bay has responded to changes in ocean climate, including abrupt shifts in both IPO and SSH during the mid to late-1990s (Figure A-9). Climate indices relevant to physical ocean climate conditions (e.g. temperature at depth) should be considered in a more in-depth analysis. In addition, a longer time series of climate data including cyclic fluctuations may be needed to establish causative correlations with diet composition.

Multiple sets of evidence point to nutritional stress as being a strong candidate driver of biological and demographic changes in NZ sea lion at the Auckland Islands, including: periods of low pupping rate (Figure A-1), a decline in maternal condition and variation in both milk quality (both Figure A-3) and pup mass though time (Figure A-4). Some of these may also occur in response to pup disease not driven by nutritional stress (**Table 4-1** and Figure B-2). However, depressed pupping rates would not be expected in response to pup mortality driven purely by disease (Table 4-1). In addition an abrupt decline in maternal condition coincident with the onset of declining pup production at Sandy Bay (Figure 1-1 and Figure A-3) suggests that reduced nutritional status may have played a key role in the decline of the breeding population.

A shift in diet composition appears to have occurred between 1997 and 2000 (Childerhouse et al., 2001; Stewart-Sinclair, 2013), which for a number of prey species was correlated with long-term shifts in IPO index and SSH (Figure 3-1 and Figure C-2). The hypothesised relationships between diet composition and maternal BCI and milk quality were not obtained for most prey species, with the exception of arrow squid and a near-significant negative correlation with red cod occurrence in scats (Figure C-5). Both of these species appear to have become more prevalent in the diet of NZ sea lion at Sandy Bay during the period of population decline (Figure 1-1 and Figure A-2).

Table 4-1: Summary of hypothetical biological/demographic responses to drivers of population change.

Response variable	Predation or fishery captures	Nutritional stress	Pup mortality (but non-nutritional stress driven)
Adult condition	No variation	Will vary in response to changing resources & reproductive success in yr-1	Will increase in response to reduced reproductive success in yr-1
Adult survival	Affects age classes vulnerable to fishery captures or predation	Will vary in response to changing resources & reproductive success in yr-1	Increases adult survival in response to reduced reproductive success in yr-1
Pupping rate (includes age at first pupping)	No variation	Will vary in response to changing resources & reproductive success in yr-1	Increased pupping rate in response to reduced reproductive success in yr-1
3-week pup mass (pup growth)	Reduced pup mass/growth of pups affected by mortality of mother	Will vary in response to changing resources & reproductive success in yr-1	No effect prior to infection
Milk quality	No variation	Will vary in response to changing resources & reproductive success in yr-1	Will vary in response to reproductive success in yr-1
Pup/post-weaning survival	Reduced survival of pups affected by mortality of mother	Will vary in response to pup growth rate & resources available to pup on weaning (disease may be a consequence)	Reduced pup or post-weaning survival of affected cohort

4.3 Causes of pup mortality

The positive correlation between maternal BCI and 3-week pup mass prior to 2005 (Figure 3-2) is a classic response that has been observed in terrestrial mammal populations, e.g. Soay Island sheep (Ozgul et al., 2009). This suggests that inter-annual variation in pup mass at Sandy Bay was related to changes in maternal nutritional status over time. Over this same time period a very strong correlation was obtained between pup mass and survival of the respective cohort to age 2. This is also a classically observed relationship of pinniped species, e.g. harbour seals (Harding et al., 2005) and it suggests that pup/yearling survival was largely dependent on maternal nutritional status during this time period.

However, pups born post-2004 were relatively large in size, though still had a low probability of survival. Between 2007 and 2010, a large proportion of autopsied dead pups were found to be infected with the bacterium *Klebsiella pneumoniae,* though rates of infection were much higher during the period 8-13 weeks after sampling began (from the beginning of February to the middle of March) (Roe, 2011). A significant negative correlation between pup/yearling survival and rate of disease-related pup mortality at 8-10 weeks indicated that disease is a strong candidate driver of low cohort survival to age 2 for cohorts born 2007-2010. The rate of disease-related mortality prior to 8 weeks was not a good indicator of pup survival, even though survival estimates will have been reduced by the inclusion of pup mortalities prior to the date of flipper tagging or "phantom tag" observations – a number of which may have been disease-related mortalities. As such, a large proportion of mortality was likely to have occurred late in the field season or after the field season was completed in those years.

4.4 Causes of juvenile/adult mortality

Poor correlations were obtained between estimates of sea lion captures/interactions with the Southern arrow squid commercial trawl fishery (Fishery Management Area SQU6T) and estimated survival at ages 2-5 and 6-14. A number of other factors could also be considered in a more rigorous analysis of these relationships. For instance, in this assessment combined-sex capture and interaction estimates for the Auckland Islands region were compared with demographic rate estimates of females at Sandy Bay. In addition, variation in the age frequency of captures was not accounted for in this analysis. These are all factors that could be addressed with a more in-depth analysis and a longer time series of observations with fluctuations in capture/interaction rates, and would improve the assessment of causative relationships.

A strong negative correlation between survival at ages 6-14 and survival of pups/yearling in the previous year (from 1998 to 2004) indicate that the energetic costs associated with nursing a pup had a negative effect on maternal survival during this time period (Figure 3-3). This suggests that the nutritional status of breeding females was not sufficient in these years to produce pups without compromising survival.

4.5 Ultimate causes of population decline at the Auckland Islands

This assessment has led to the identification of a number of potential relationships between biological measurements and demographic rates (Table 4-2 and Figure 4-1). Many of these relationships are classically observed in other pinniped species (and terrestrial mammals with a similar reproductive biology) that are responding to external pressures.

A shift in diet composition and decline in maternal body condition since the late 1990s strongly suggests that reduced nutritional status may have played a key role in affecting population decline. Potential relationships between maternal condition and pup mass, and consequently, pup/yearling survival, indicates that nutritional status also affected cohort-specific survival to age 2. In addition, disease-related mortality is a strong candidate cause of pup/yearling mortality after 2006, coincident with the post-2004 period of low pup/yearling survival identified in the demographic modelling assessment (Roberts et al., 2014). This occurred sometime after the decline in pup production began in the late-1990s/early 2000s, and so does not fully explain the observed decline in pup production at Sandy Bay, though is likely to affect future breeding population size.

4.6 Further research

This report summarised a relatively simple correlative assessment aimed at identifying the ultimate external causes of demographic and population change of the Auckland Islands population. A large number of correlation tests were performed of which we would expect 5% to be 'significantly' correlated by random chance, even when not truly correlated (when using $p<0.05$). As such, the results should be treated as indicative and a number of promising areas were identified for more in-depth analysis, such as the relationship between pup mass and survival. Taking this example, a more thorough assessment could include consideration of birth date and growth rate effects on pup mass, or could relate individual (as opposed to year-averaged) pup mass to maternal biology and reproductive history.

This study has highlighted a number of knowledge gaps and additional observations that could be collected to further explore the mechanisms of demographic change (e.g., disease-related mortality rates of pups after 12 weeks and continuous collection of observations for monitoring maternal condition). Also, given the short time series of observations available at the time of assessment, we recommend re-assessment of these relationships with a longer time series of observations once available.

Further exploration of the identified relationships should include a model-based assessment (as opposed to correlative), such that it will be possible the estimate effect sizes relating to drivers of demographic changes. This will be required to more adequately explain the ultimate causes of population decline.

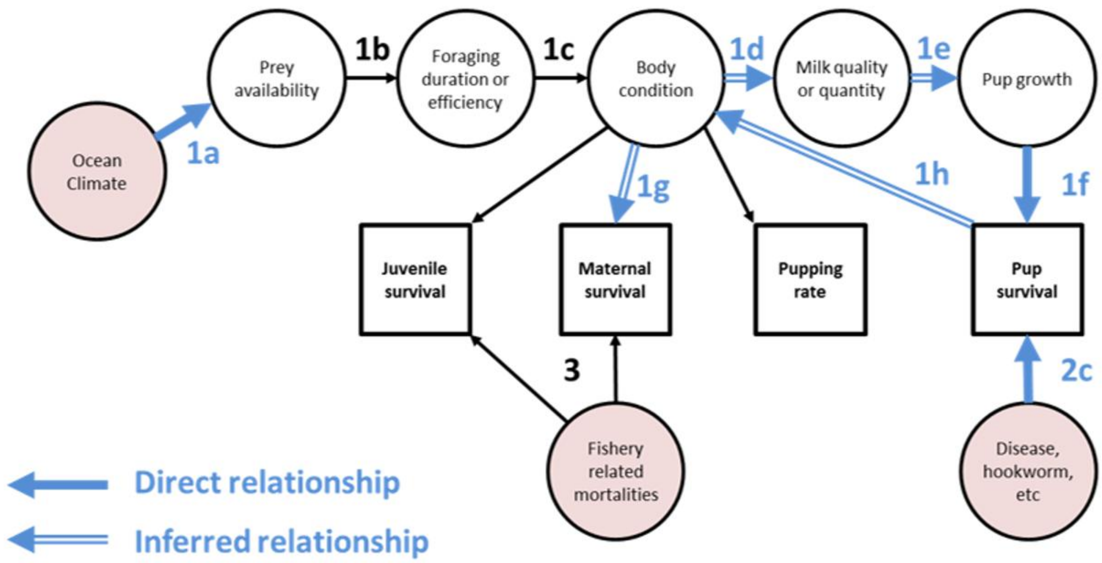

Figure 4-1: Hypothetical model highlighting relationships that were supported by the correlative assessment. Relationships denoted with identifier, e.g. "1a", listed in Table 4-2; candidate drivers of population change (shaded circles; were related to biological responses (open circles) and demographic rates (open squares).

Table 4-2: List of hypothetical relationships between datasets assessed in this study and degree of correlation obtained. Relationships supported by correlative assessment bolded. In addition, relationships 1d, 1e and 1g were inferred by the results of the assessment.

Candidate driver of population change	Relationship ID	Relationships assessed	Correlation
Nutritional stress	**1a**	**Climate and diet**	**Yes (SSH, IPO)**
	1b	Prey abundance and diet	Only one prey species
	1c	Diet and maternal condition	Only one prey species
	1d	Diet and milk quality	Only one prey species
	1e	Maternal condition/milk quality and pup mass	Yes – maternal condition and pup mass
	1f	**Pup mass and pup/yearling survival**	**Yes**
	1g	Maternal condition and maternal survival/pupping rate	No
	1h	**Pup/yearling survival and demographic response in yr+1**	**Yes between pup/yearling survival and adult survival as well as pup mass**
Disease-related pup mortality	2a	Pup mortality at 3/7 weeks and pup/yearling survival	No
	2b	Pup mortality by cause and pup/yearling survival – all sampling	No
	2c	**Bacterial disease-related mortality and pup/yearling survival**	**Yes**
Direct fishery-related mortality	3	Estimated fishery interactions/captures and juvenile/adult survival	No

5 Acknowledgements

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6 References

Baker CS, Chilvers BL, 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.

Castinel A, Duignan PJ, Pomroy WE, Lopez-Villalobos N, Gibbs NJ, Chilvers BL, Wilkinson IS. 2007. Neonatal mortality in New Zealand sea lions (*Phocarctos hookeri*) at Sandy Bay, Enderby Island, Auckland Islands from 1998 to 2005. *Journal of Wildlife Diseases 43*: 461-474.

Childerhouse S, Dix B, Gayles N, 2001. Diet of New Zealand sea lions (*Phocarctos hookeri*) at the Auckland Islands. *Wildlife Research 28*: 291-298.

Childerhouse SJ, Dawson SM, Fletcher DJ, Slooten E, Chilvers BL, 2010. Growth and reproduction of female New Zealand sea lions. Journal of Mammalogy, 91: 165-176.

Childerhouse SJ, 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.

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

Clutton-Brock TH, Albon SD, Guinness FE, 1989. Fitness costs of gestation and lactation in wild animals. *Nature 337*: 260-262.

Harding KC, Fujiwara M, Axberg Y, Harkonen T, 2005 Mass-dependent energetics and survival in Harbour Seal pups. *Functional Ecology*, 19: 129–135.

Meynier L, Mackenzie DDS, Duignan PJ, Chilvers BL, Morel PCH, 2009. Variability in the diet of New Zealand sea lion (*Phocarctos hookeri*) at the Auckland Islands, New Zealand Marine Mammal Science, 25: 302–326.

National Climate Database, 2014. Climate data accessed via the CliFlo portal maintained by NIWA, from their website http://cliflo.niwa.co.nz/

NASA, 2014. *SEAWIFS ocean colour data* provided by NASA, USA, from their website http://disc.sci.gsfc.nasa.gov/giovanni

NOAA, 2012. *NOAA_ERSST_V3* data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/

NOAA, 2013. *NOAA_SSH* data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://coastwatch.pfeg.noaa.gov/coastwatch

Ozgul A, Tuljapurkar S, Benton TG, Pemberton JM, Clutton-Brock TH, Coulson T, 2009. The Dynamics of Phenotypic Change and the Shrinking Sheep of St. Kilda. *Science*, 325: 464-467.

Riet-Sapriza FG, Duignan D, Chilvers L, Wilkinson IS, Lopez-Villalobos N, Mackenzie A, MacGibbon A, Costa DP, Gales N, 2012. Interannual and individual variation in milk composition of New Zealand sea lions (*Phocarctos hookeri*). *Journal of Mammalogy 93*: 1006-1016.

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

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

Roe WD, 2011. *A study of brain injury in New Zealand sea lion pups*. PhD Thesis. Massey University, Palmerston North.

Stewart-Sinclair P, 2013. *The role of long-term diet changes in the decline of the New Zealand sea lion population*. MSc Thesis. Massey University, Palmerston North.

Thompson FN, Abraham ER, 2010. Estimation of the capture of New Zealand sea lions (*Phocarctos hookeri*) in trawl fisheries from 1995-96 to 2009-10. *New Zealand Aquatic Environment and Biodiversity Report 66*, Wellington.

Trillmich F, 1990. The behavioural ecology of maternal effort in fur seals and sea lions. *Behaviour 114*.

Appendix A Datasets used in correlative assessment

Demographic datasets

Demographic rates were obtained from a demographic assessment of female NZ sea lions at Sandy Bay. These included survival at age, age at first pupping (the probability of pupping at age 4) and probability of mature individuals pupping, contingent on pupping status in the previous year (Roberts et al., 2014) (Table A-1 and Figure A-1).

Table A-1: Time series of demographic rates used in this assessment. (Roberts et al., 2014).

Year	Demographic rates				
	Cohort survival to age 2	Survival ages 2-5	Survival ages 6-14	Age at first pupping	Pupping rate
1990	Y				
1991	Y				
1992	Y	Y			
1993	Y	Y			
1994					
1995					
1996					
1997					
1998	Y	Y	Y		
1999	Y	Y	Y		
2000	Y	Y	Y		Y
2001	Y	Y	Y	Y	Y
2002	Y	Y	Y	Y	Y
2003	Y	Y	Y	Y	Y
2004	Y	Y	Y	Y	Y
2005	Y	Y	Y	Y	Y
2006	Y	Y	Y	Y	Y
2007	Y	Y	Y	Y	Y
2008	Y	Y	Y	Y	Y
2009	Y	Y	Y	Y	Y
2010	Y	Y	Y	Y	Y
2011		Y	Y	Y	Y
2012				Y	Y

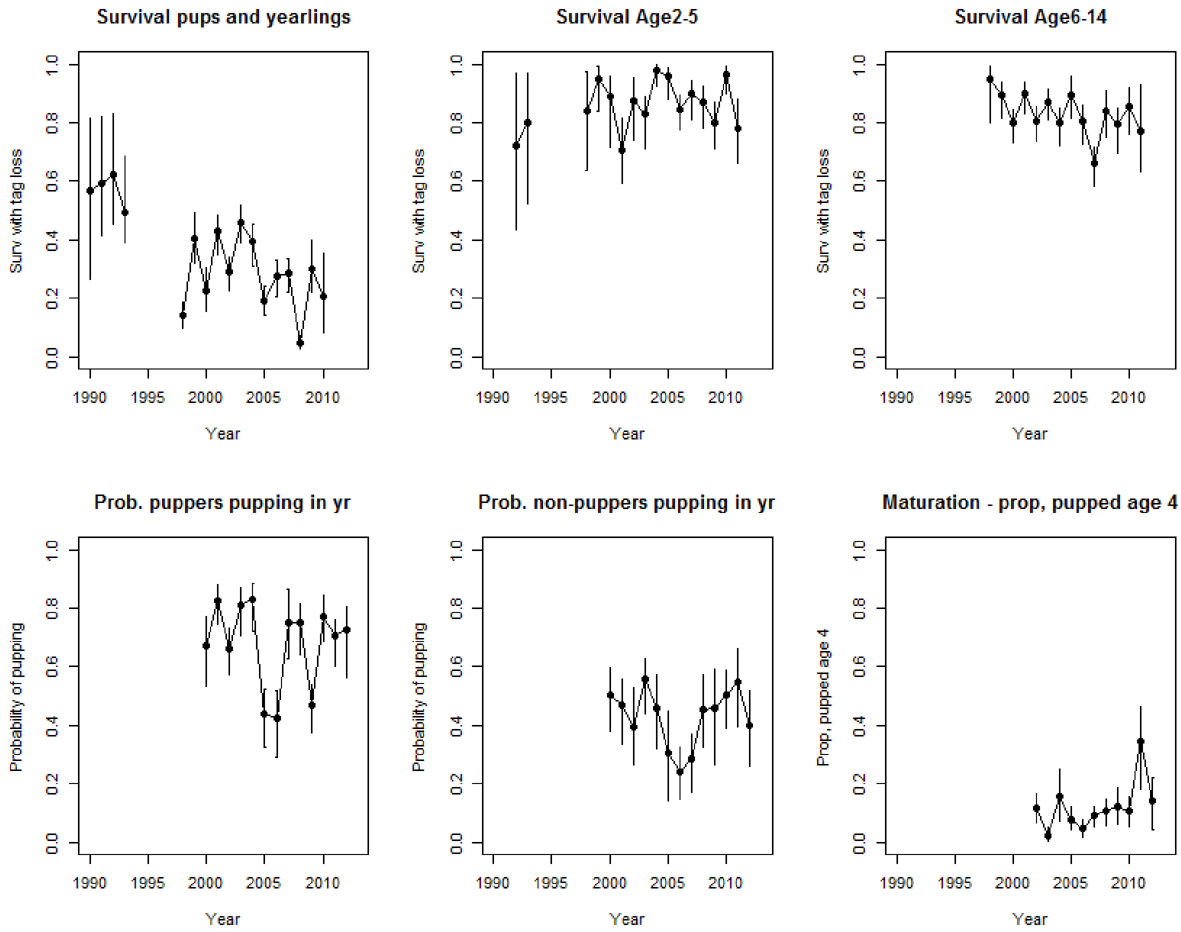

Figure A-1: Demographic rate estimates used in this assessment. Only point estimates (median values) used; bars are 95% CI (Roberts et al., 2014).

Biological datasets

Biological datasets included research outputs on diet composition (Stewart-Sinclair, 2013), maternal condition and milk quality (re-analysis of Riet-Sapriza et al., 2012), pup sex ratio at tagging (using observations from the NZ sea lion mark recapture database), pup mass (Cawthorn, unpub data; Childerhouse et al., 2013; Chilvers, 2012) and pup mortality (Castinel et al., 2007; Chilvers, 2012; Roe, 2011; Roe, unpub. data) of NZ sea lions at Enderby Island (Table A-2, data sources are listed in the table legend; Figure A-2 to Figure A-8).

Table A-2: Time series of biological datasets used in this assessment. Condition and milk = Body Condition Index and milk protein/fat content (re-analysis of Riet-Sapriza et al., 2012); pup mass = mass of pups measured at 3-weeks after the median birth date (Cawthorn, unpub. data; Childerhouse et al., 2013; Chilvers, 2012); pup sex ratio = sex ratio of pups at date of tagging; early pup mortality = mortality percentage of pups at 3 and 7-weeks after median birth date (Chilvers, 2012); pup mortality cause = death by diagnosis as a proportion of pup census estimate; and bacterial disease-related pup mortality rate (Castinel et al., 2007; Roe, 2011; Roe, unpub. data); diet = frequency of occurrence of selected prey species from an analysis of sea lions scats (Childerhouse, 2001; Stewart-Sinclair, 2013).

Year	Biological observations						
	Diet	Maternal condition	Milk quality	Pup mass	Pup sex ratio	Early pup mortality	Pup mortality cause
1990					Y		
1991				Y	Y		
1992					Y		
1993					Y		
1994							
1995	Y			Y		Y	
1996	Y			Y		Y	
1997	Y	Y	Y	Y		Y	
1998		Y		Y	Y	Y	
1999		Y	Y	Y	Y	Y	
2000	Y	Y	Y	Y	Y	Y	
2001	Y	Y	Y	Y	Y	Y	Y
2002	Y	Y	Y	Y	Y	Y	Y
2003	Y	Y	Y	Y	Y	Y	Y
2004	Y	Y		Y	Y	Y	Y
2005	Y	Y	Y	Y	Y	Y	
2006	Y			Y	Y	Y	
2007	Y			Y	Y	Y	Y
2008	Y			Y	Y	Y	Y
2009	Y			Y	Y	Y	Y
2010	Y			Y	Y	Y	Y
2011	Y	Y		Y	Y	Y	
2012	Y	Y		Y	Y	Y	

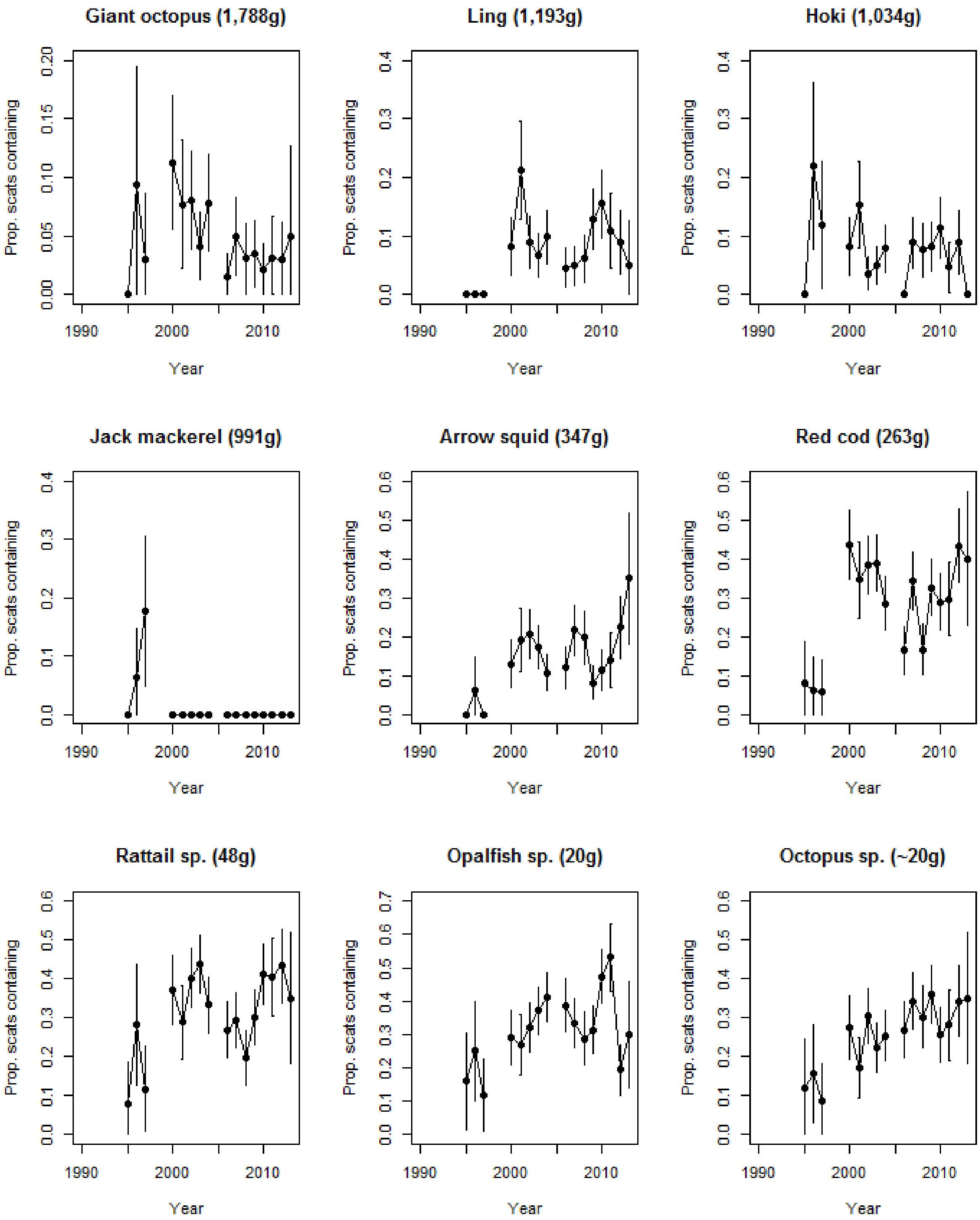

Figure A-2: Frequency of occurrence of selected NZ sea lions at Sandy Bay. Prey species frequency of occurrence in scats (Childerhouse, 2001; Stewart-Sinclair, 2013); mean prey mass estimates from reconstituted biomass (Meynier et al., 2009); only point estimates (mean values) used; bars are 95% CI.

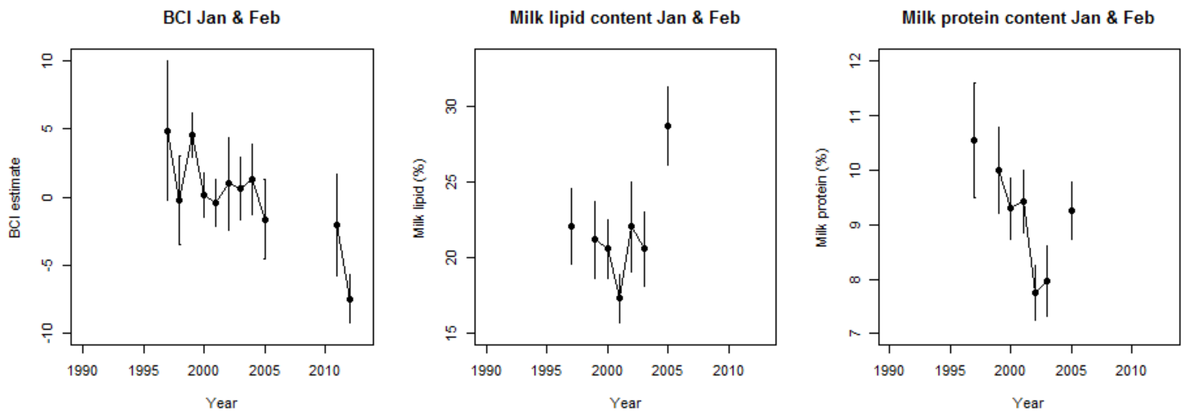

Figure A-3: Estimates of maternal body condition index (BCI) and milk quality (lipid and protein %) at Sandy Bay. Reanalysis of maternal condition (body condition index) and milk quality observations presented by Riet-Sapriza et al. (2012); Additional maternal condition data from Childerhouse (2010) and Chilvers unpub. data; Only point estimates (mean values) used; bars are 95% CI.

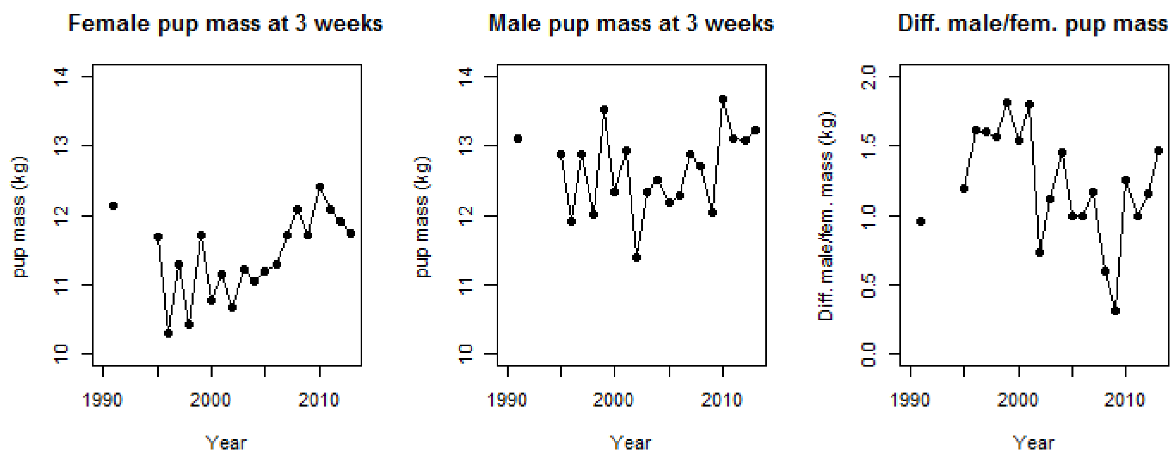

Figure A-4: Female and male pup mass and mass difference comparing males and females. Only point estimates (mean values) used (Cawthorn, unpub.data, Childerhouse et al., 2013; Chilvers, 2012).

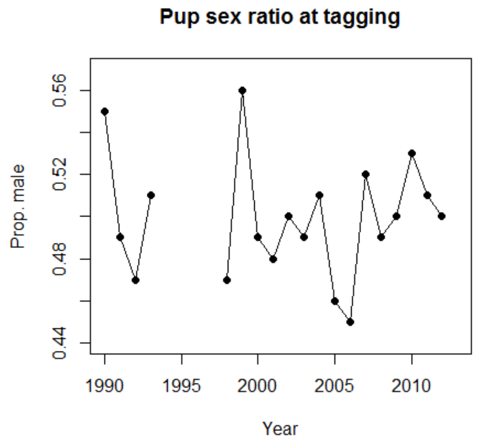

Figure A-5: Sex ratio of flipper tagged NZ sea lion pups at Sandy Bay.

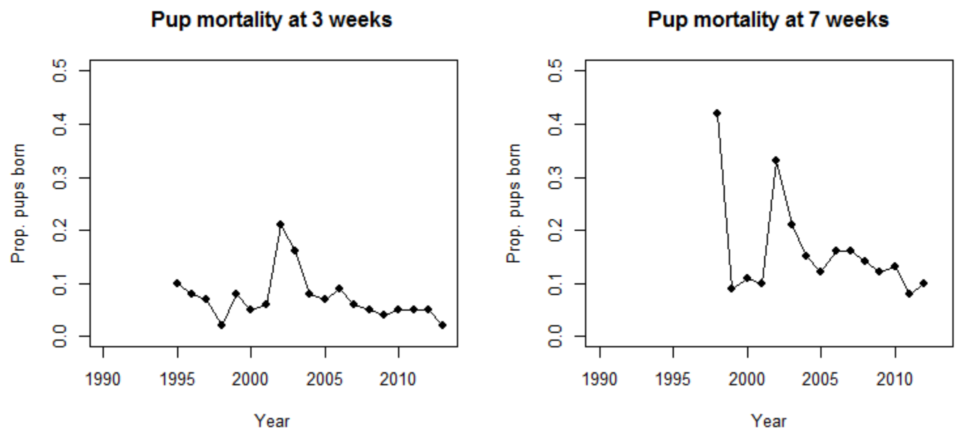

Figure A-6: Three and seven-week pup mortality rate at Sandy Bay. Chilvers (2012).

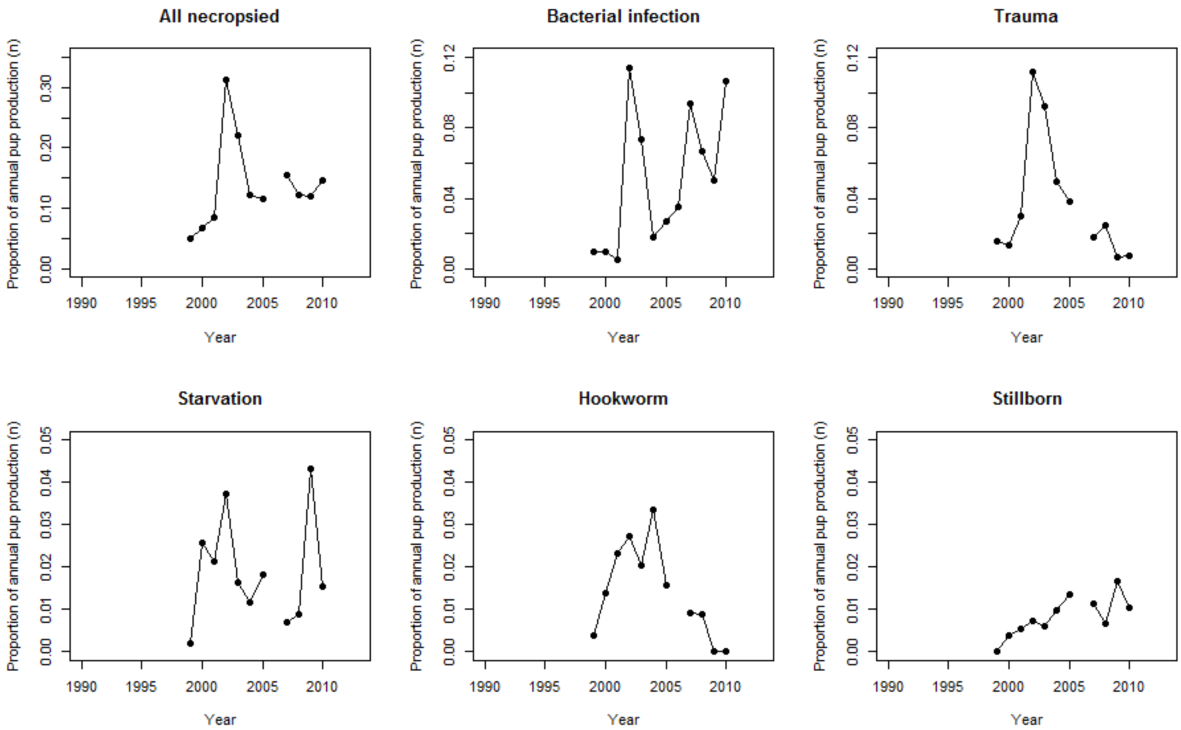

Figure A-7: Pup mortality rate at Sandy Bay by diagnosis. Mortality rate calculated as the proportion of pup estimate for each respective year (Castinel et al., 2007; Roe, 2011; Roe unpub. data). Note, a number of trauma diagnoses pre-2006 are likely to be bacterial disease-related mortalities that were incorrectly diagnosed (Michael, Roe, pers. comm.).

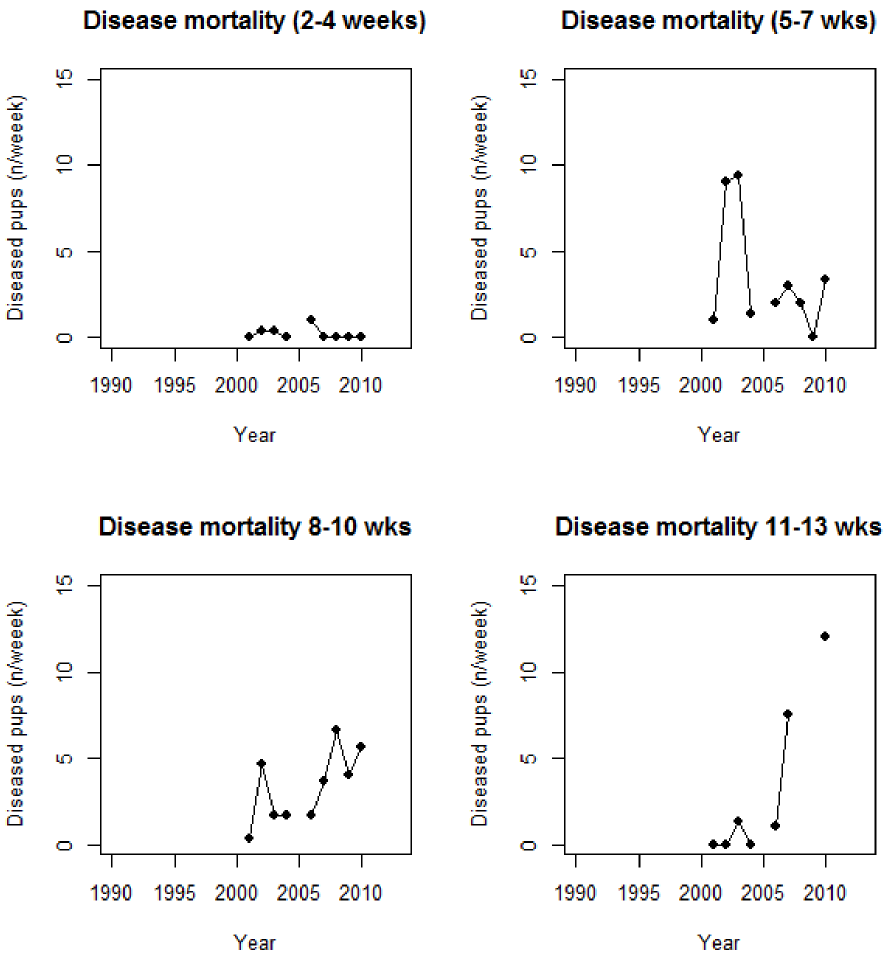

Figure A-8: Pup disease-related mortality rate at Sandy Bay by sampling week. Mortality rate calculated as the number of mortalities attributed to bacterial disease per week in which sampling was conducted (Castinel et al., 2007; Roe, 2011; Roe unpub. data)

Climatic datasets

An array of ocean and atmospheric climate datasets were used in this assessment, including climate indices (e.g. Inter-decadal Pacific Oscillation, El Nino Southern Oscillation and Southern Oscillation Index), ocean physical measurements (e.g. sea surface height and sea surface temperature) and atmospheric climate measurements (e.g. wind and atmospheric temperature) (Table A-3, data sources are listed in the table legend).

Table A-3: Time series of climatic datasets used in this assessment. IPO = Inter-decadal Pacific Oscillation; ENSO = El Nino Southern Oscillation; SOI = Southern Oscillation Index; SST = Sea Surface Temperature (NOAA, 2012); SSH = sea surface height (NOAA, 2013); Chla = Chlorophyll a concentration (NASA, 2014).

Year	Climate					
	IPO	ENSO	SOI	SST	SSH	Chla
1990	Y	Y	Y	Y		
1991	Y	Y	Y	Y		
1992	Y	Y	Y	Y	Y	
1993	Y	Y	Y	Y	Y	
1994	Y	Y	Y	Y	Y	
1995	Y	Y	Y	Y	Y	
1996	Y	Y	Y	Y	Y	
1997	Y	Y	Y	Y	Y	
1998	Y	Y	Y	Y	Y	Y
1999	Y	Y	Y	Y	Y	Y
2000	Y	Y	Y	Y	Y	Y
2001	Y	Y	Y	Y	Y	Y
2002	Y	Y	Y	Y	Y	Y
2003	Y	Y	Y	Y	Y	Y
2004	Y	Y	Y	Y	Y	Y
2005	Y	Y	Y	Y	Y	Y
2006	Y	Y	Y	Y	Y	Y
2007	Y	Y	Y	Y	Y	Y
2008	Y	Y	Y	Y	Y	Y
2009		Y	Y	Y	Y	Y
2010		Y	Y	Y	Y	Y
2011		Y	Y	Y	Y	Y
2012		Y	Y	Y	Y	

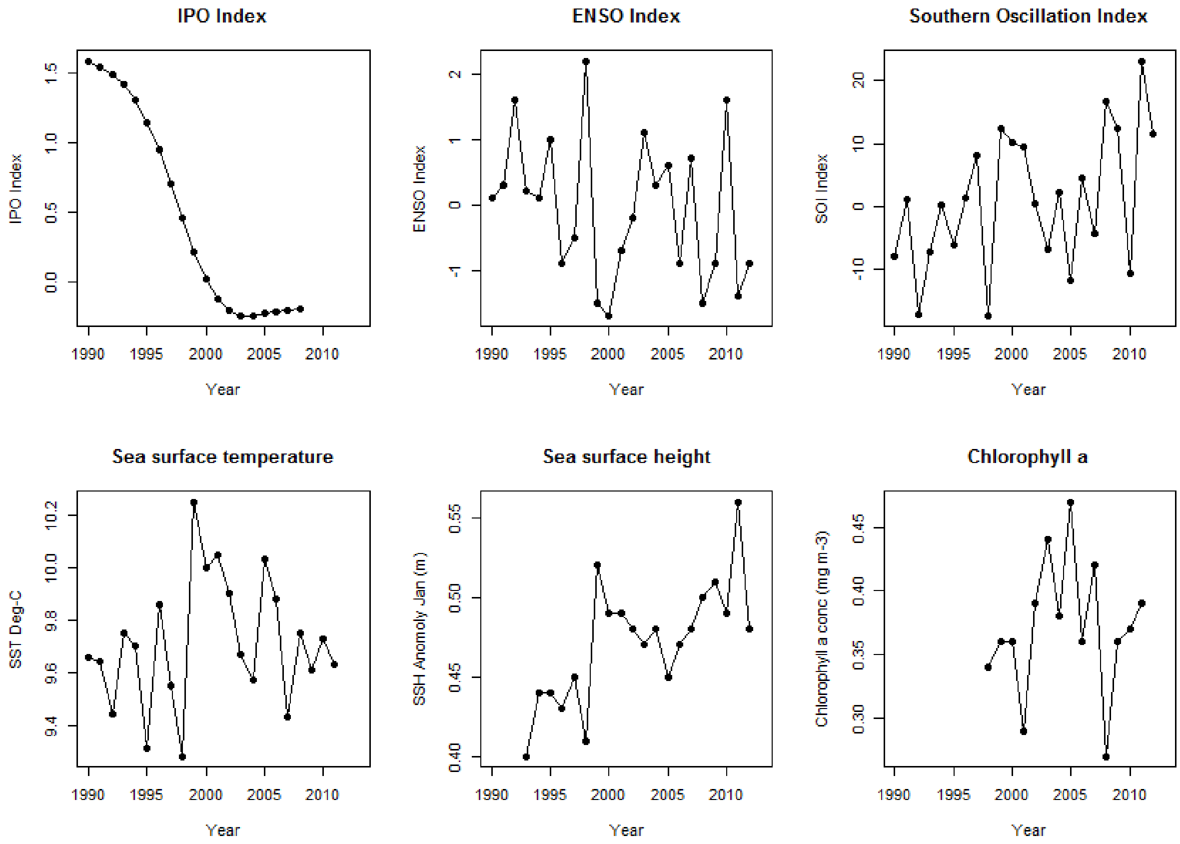

Figure A-9: Annual values of climate indices and physical measurements used in this assessment. (NOAA, 2012; NOAA, 2013; NASA, 2014).

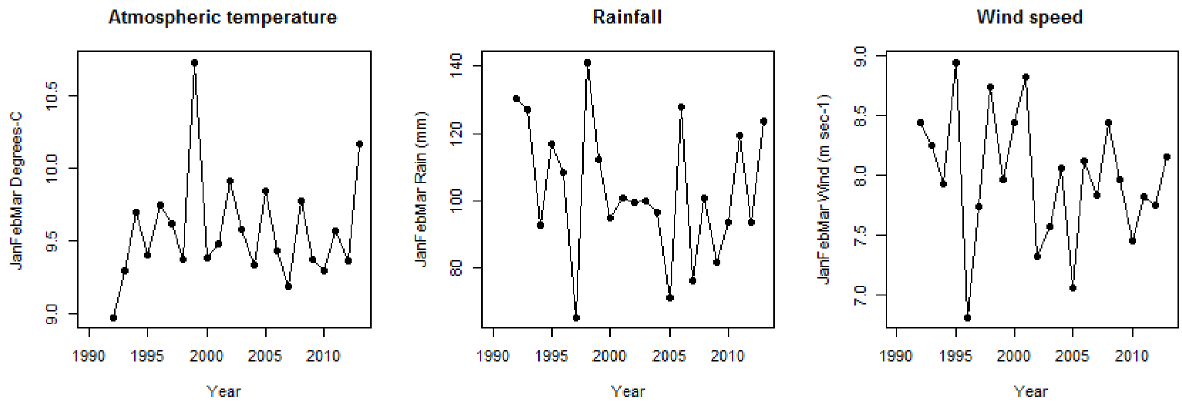

Figure A-10: Annual value of atmospheric climate measurements used in this assessment. National Climate Database (2014).

Fishery-related datasets

Fishery-related datasets include an analysis of catch rate of selected NZ sea lion prey species in commercial trawls within the area bounded by SQU6T North and annual estimates of NZ sea lion interactions and captures in the squid trawl fishery in SQU6T (Table A-4, data sources are listed in the table legend).

Table A-4: Time series of fishery-related datasets used in this assessment. Fishery CPUE = standardised catch per tow of selected NZ sea lion prey species in commercial trawls conducted within the area bounds of SQU6T North (Roberts, unpub. data); and sea lion capture/interactions are estimates for the squid trawl fishery in SQU6T (Thompson & Abraham, 2010).

Year	Fishery CPUE	Sea lion captures/ interactions
1990	Y	
1991	Y	
1992	Y	
1993	Y	
1994	Y	
1995	Y	
1996	Y	Y
1997	Y	Y
1998	Y	Y
1999	Y	Y
2000	Y	Y
2001	Y	Y
2002	Y	Y
2003	Y	Y
2004	Y	Y
2005	Y	Y
2006	Y	Y
2007	Y	Y
2008	Y	Y
2009	Y	Y
2010	Y	Y
2011	Y	Y
2012	Y	Y

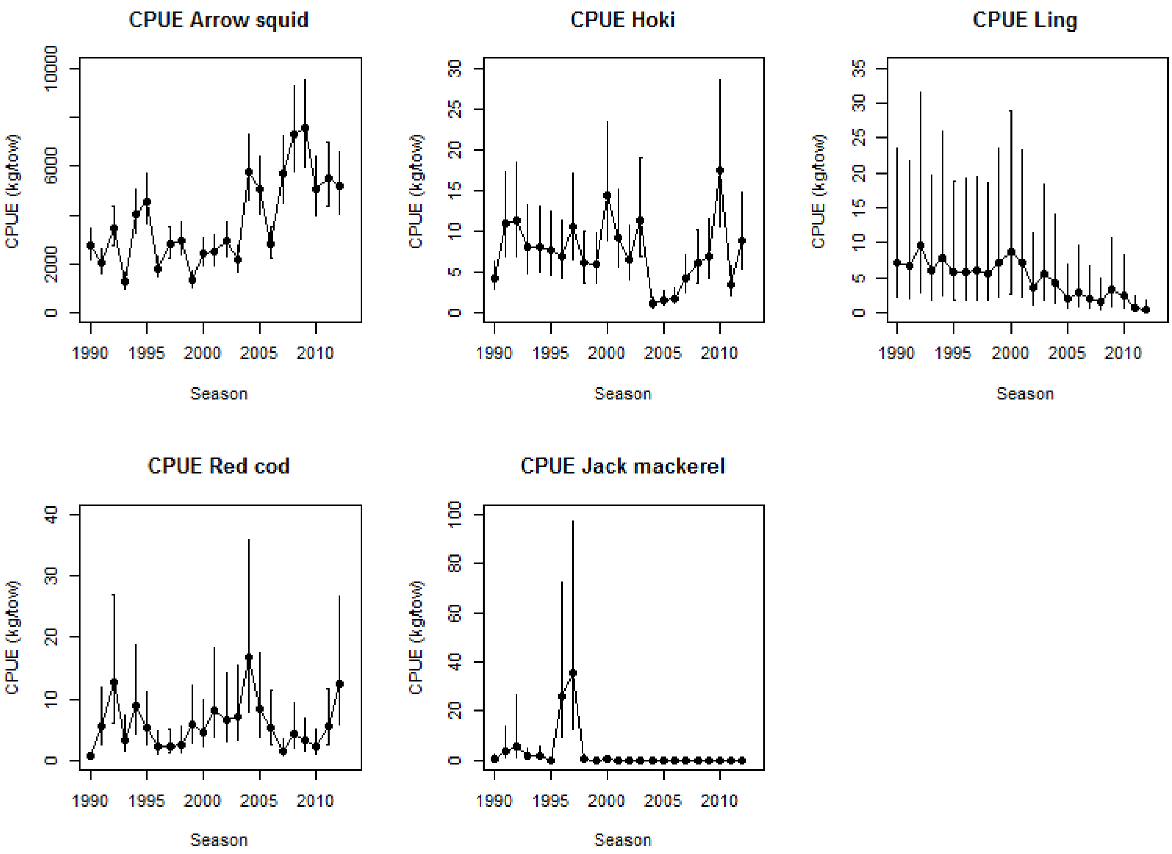

Figure A-11: Standardised catch per tow of selected sea lion prey species in commercial trawls operating within the Auckland Islands Management Area SQU6T North. Roberts, unpub. data.

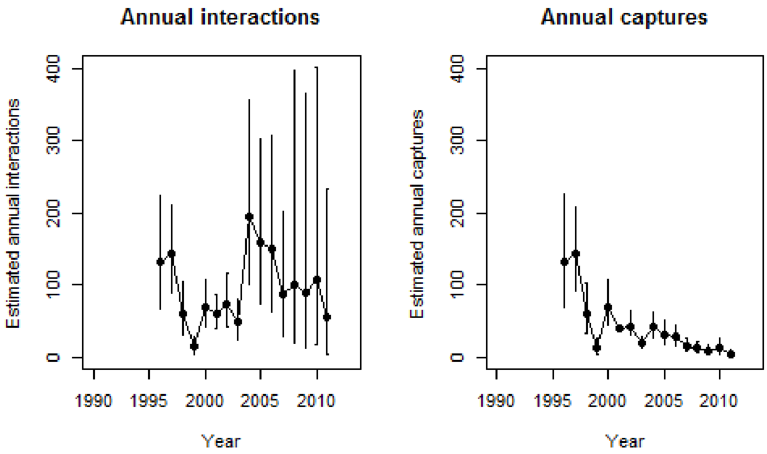

Figure A-12: Annual estimates of NZ sea lion captures and interactions for the squid trawl fishery in SQU6T. (Thompson & Abraham, 2010)

Appendix B Summary of hypothetical models

Hypothetical models were developed that related selected candidate drivers of NZ sea lion population change to biological and demographic responses. These models provided the framework for the correlative assessment aimed at identifying the ultimate causes of demographic and population change in NZ sea lions at the Auckland Islands. Initial model structures were developed at project workshops (Appendix D), with further development guided by a literature review encompassing relevant aspects of mammalian reproductive biology (e.g. Clutton-Brock et al. 1989; Trillmich 1990) (Figure B-1 to Figure B-4).

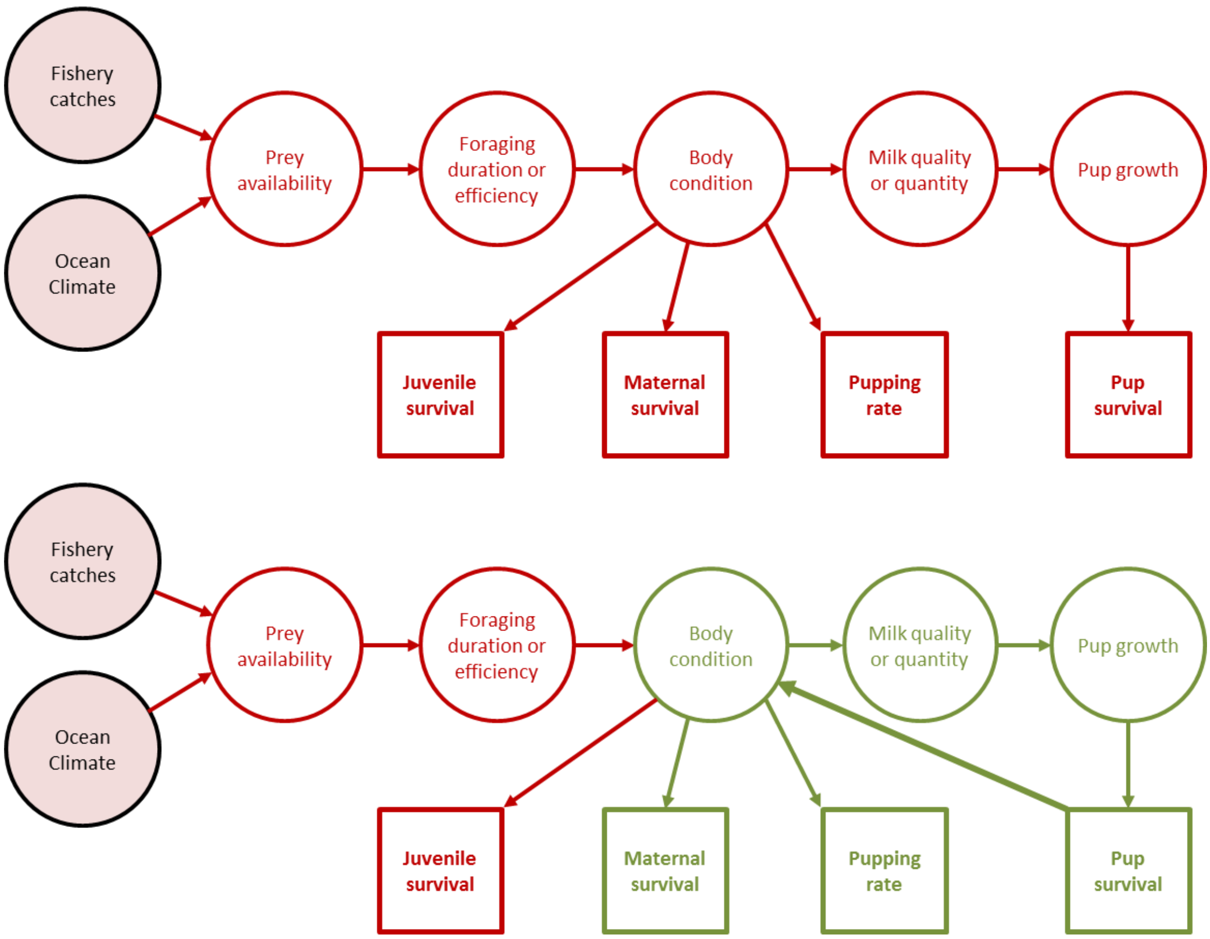

Figure B-1: Hypothetical biological and demographic responses to a reduction in prey availability. Top figure shows negative effects up to the end of the nursing period; bottom figure shows positive biological and demographic effects associated with early pup mortality; Candidate drivers of population change (shaded circles; were related to biological responses (open circles) and demographic rates (open squares); Negative effects highlighted in red; positive effects in green.

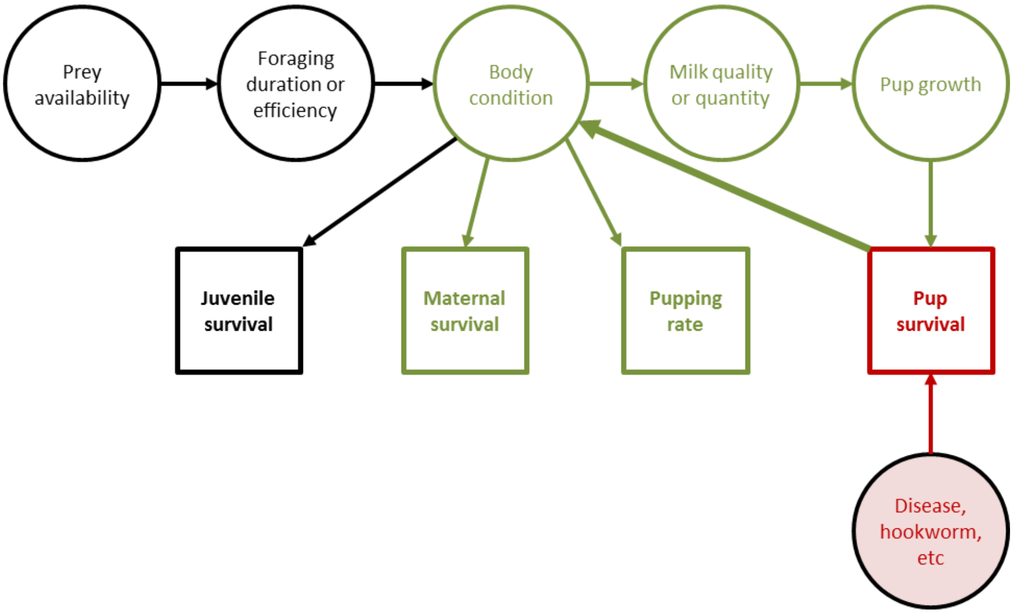

Figure B-2: Hypothetical biological and demographic responses to pup mortality, including disease-related mortality. Candidate drivers of population change (shaded circles; were related to biological responses (open circles) and demographic rates (open squares); Negative effects highlighted in red; positive effects in green.

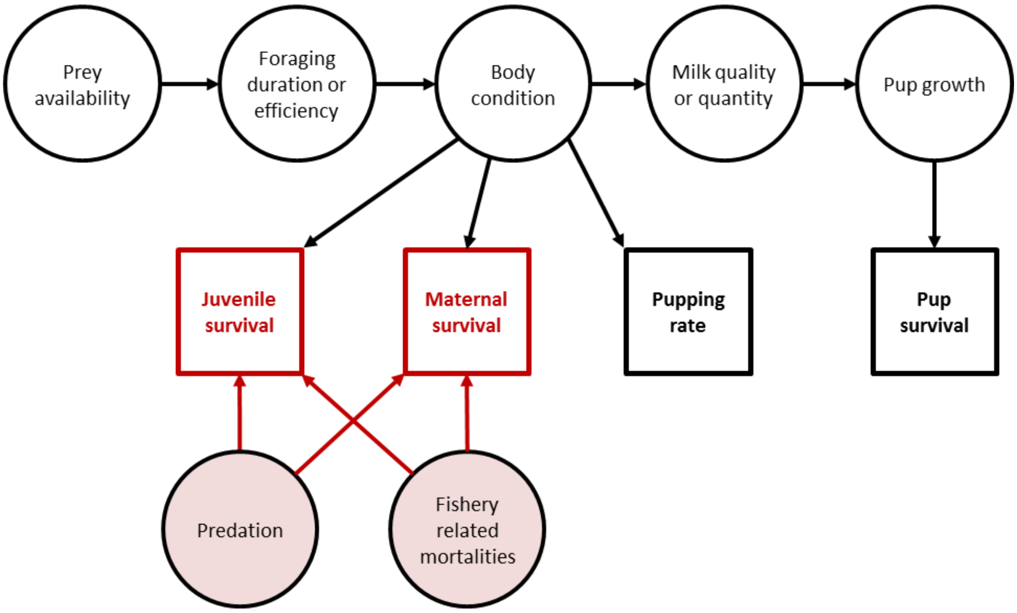

Figure B-3: Hypothetical demographic responses to direct fishery interactions or predation. Candidate drivers of population change (shaded circles; were related to biological responses (open circles) and demographic rates (open squares); Negative effects highlighted in red; positive effects in green.

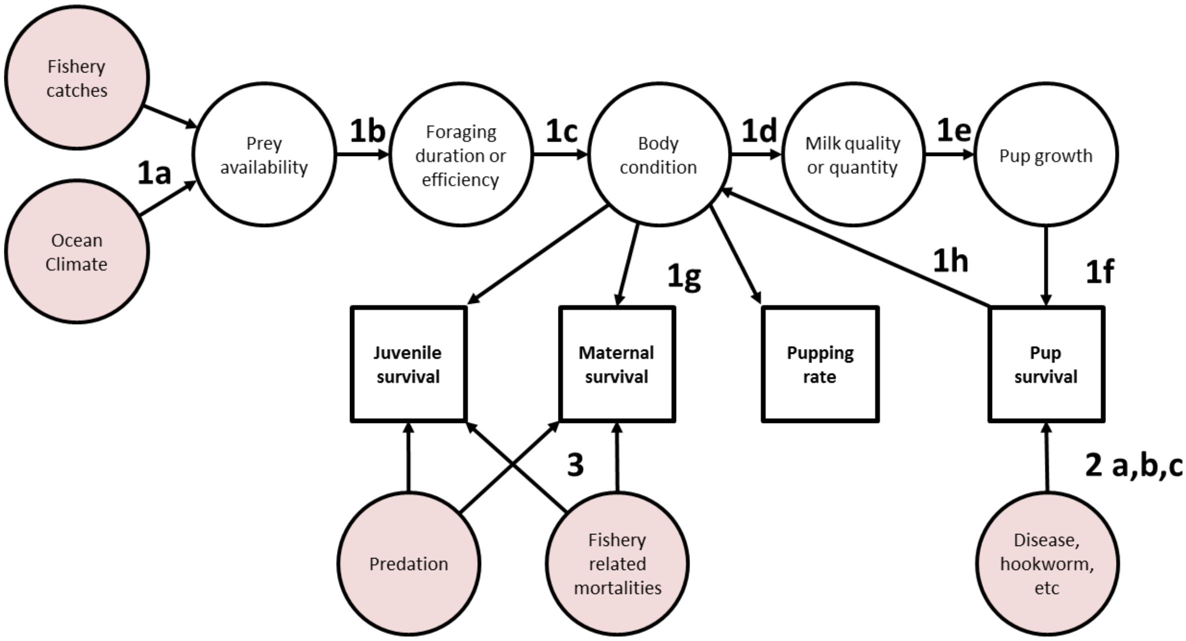

Figure B-4: Hypothetical model relating selected candidate drivers of demographic change in NZ sea lions to associated biological and demographic responses. Model relationships relating to changes in prey availability (1a-g); relating to pup mortality (2a-c); and relating to direct fishery interactions or predation (3). Candidate drivers of population change (shaded circles; were related to biological responses (open circles) and demographic rates (open squares); Negative effects highlighted in red; positive effects in green.

Table B-1: Summary of hypothetical biological/demographic responses to drivers of population change.

Response variable	Predation or fishery captures	Nutritional stress (climate or fishery driven)	Pup disease (but non-nutritional stress driven)
Adult condition	No variation	Will vary in response to changing resources & reproductive success in yr-1	Will increase in response to reduced reproductive success in yr-1
Adult survival	Affects age classes vulnerable to fishery captures or predation	Will vary in response to changing resources & reproductive success in yr-1	Increases adult survival in response to reduced reproductive success in yr-1
Pupping rate (includes age at first pupping)	No variation	Will vary in response to changing resources & reproductive success in yr-1	Increased pupping rate in response to reduced reproductive success in yr-1
3-week pup mass (pup growth)	Reduced pup mass/growth of pups affected by mortality of mother	Will vary in response to changing resources & reproductive success in yr-1	No effect prior to infection
Milk quality	No variation	Will vary in response to changing resources & reproductive success in yr-1	Will vary in response to reproductive success in yr-1
Pup/post-weaning survival	Reduced survival of pups affected by mortality of mother	Will vary in response to pup growth rate & resources available to pup on weaning (disease may be a consequence)	Reduced pup or post-weaning survival of affected cohort

Appendix C Outputs of correlative assessment

Summary of outputs

Table C-1: List of hypothetical relationships between datasets assessed in this study and degree of correlation obtained. Relationships supported by correlative assessment bolded. In addition, relationships 1d, 1e and 1g were inferred by the results of the assessment.

Candidate driver of population change	Relationship ID	Relationships assessed	Correlation
Nutritional stress	**1a**	**Climate and diet**	**Yes (SSH, IPO)**
	1b	Prey abundance and diet	Only one prey species
	1c	Diet and maternal condition	Only one prey species
	1d	Diet and milk quality	Only one prey species
	1e	Maternal condition/milk quality and pup mass	Yes – maternal condition and pup mass
	1f	**Pup mass and pup/yearling survival**	**Yes**
	1g	Maternal condition and maternal survival/pupping rate	No
	1h	**Pup/yearling survival and demographic response in yr+1**	**Yes between pup/yearling survival and adult survival as well as pup mass**
Disease-related pup mortality	2a	Pup mortality at 3/7 weeks and pup/yearling survival	No
	2b	Pup mortality by cause and pup/yearling survival – all sampling	No
	2c	**Bacterial disease-related mortality and pup/yearling survival**	**Yes**
Direct fishery-related mortality	3	Estimated fishery interactions/captures and juvenile/adult survival	No

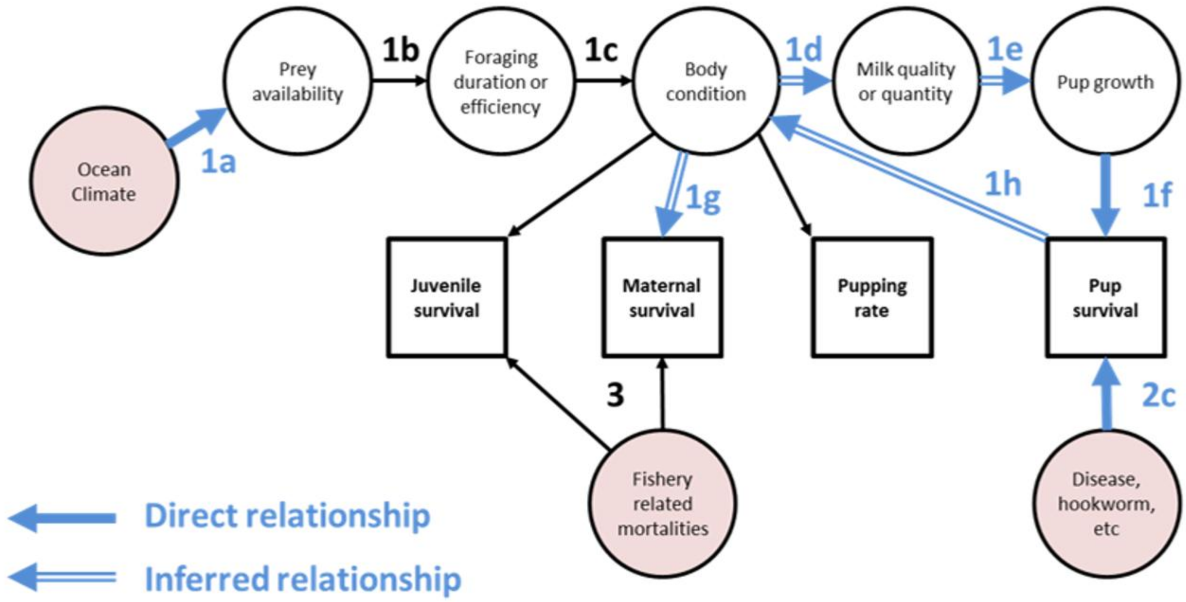

Figure C-1: Hypothetical model highlighting relationships that were supported by the correlative assessment. Relationships denoted with identifier e.g. "1a", listed in Table 4-2.

Plots of selected relationships

Climate and diet (1a)

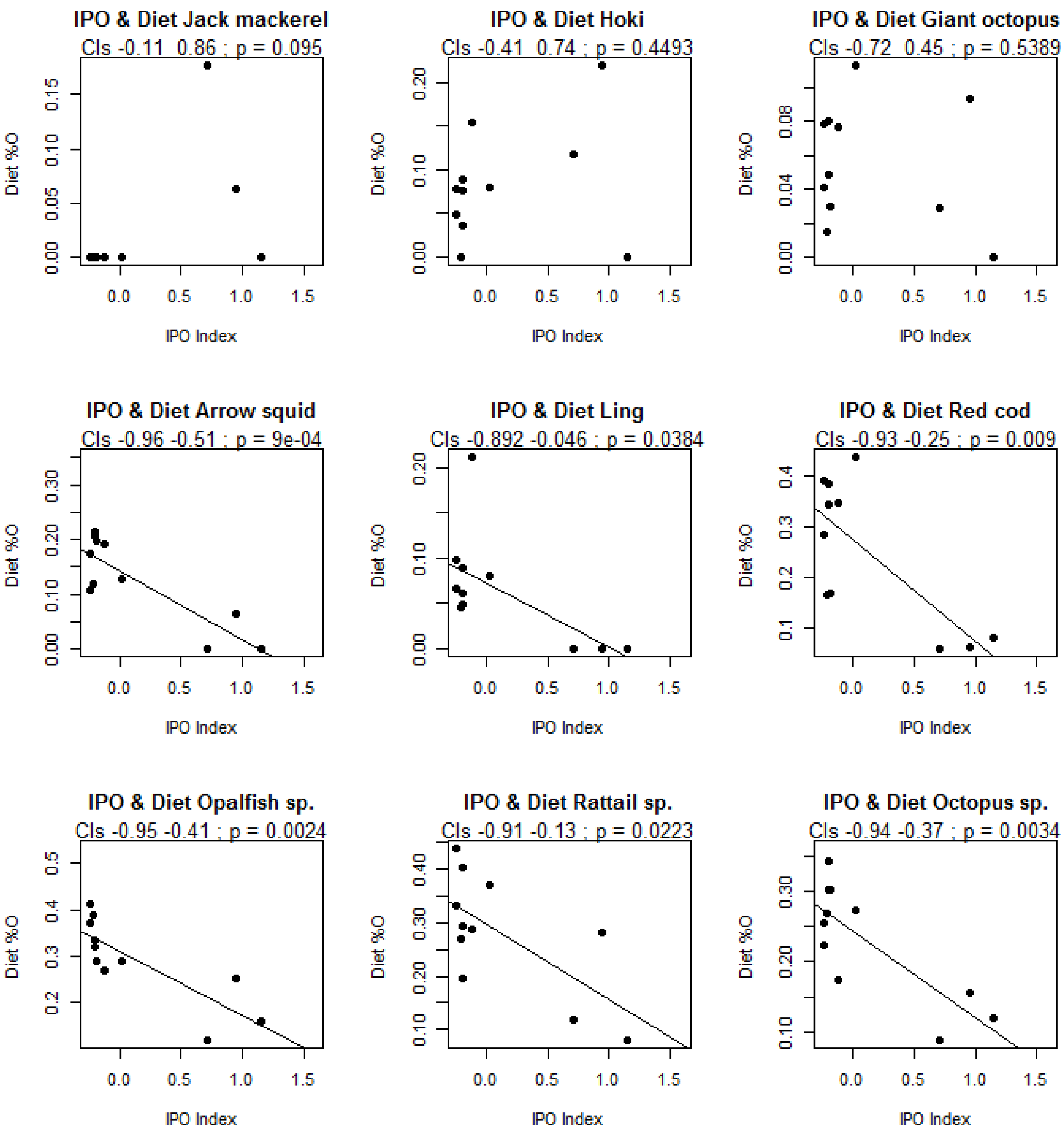

Figure C-2: IPO index and occurrence of selected prey species in the diet of NZ sea lions at Sandy Bay. (Childerhouse et al., 2001; Stewart-Sinclair, 2013).

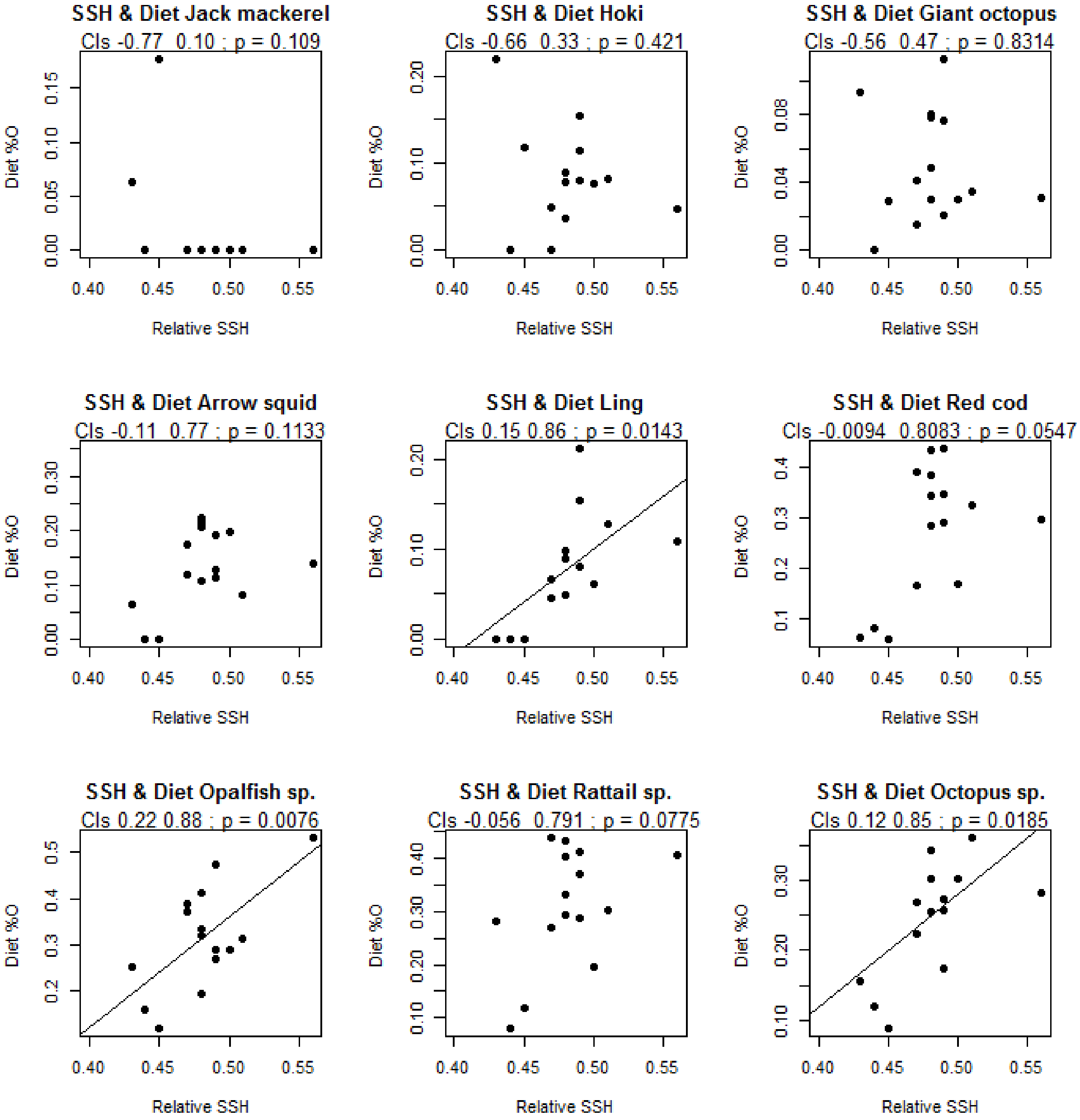

Figure C-3: **Sea surface height (SSH) and occurrence of selected prey species in the diet of NZ sea lions at Sandy Bay. (Childerhouse et al., 2001; Stewart-Sinclair, 2013).**

CPUE and diet (1b)

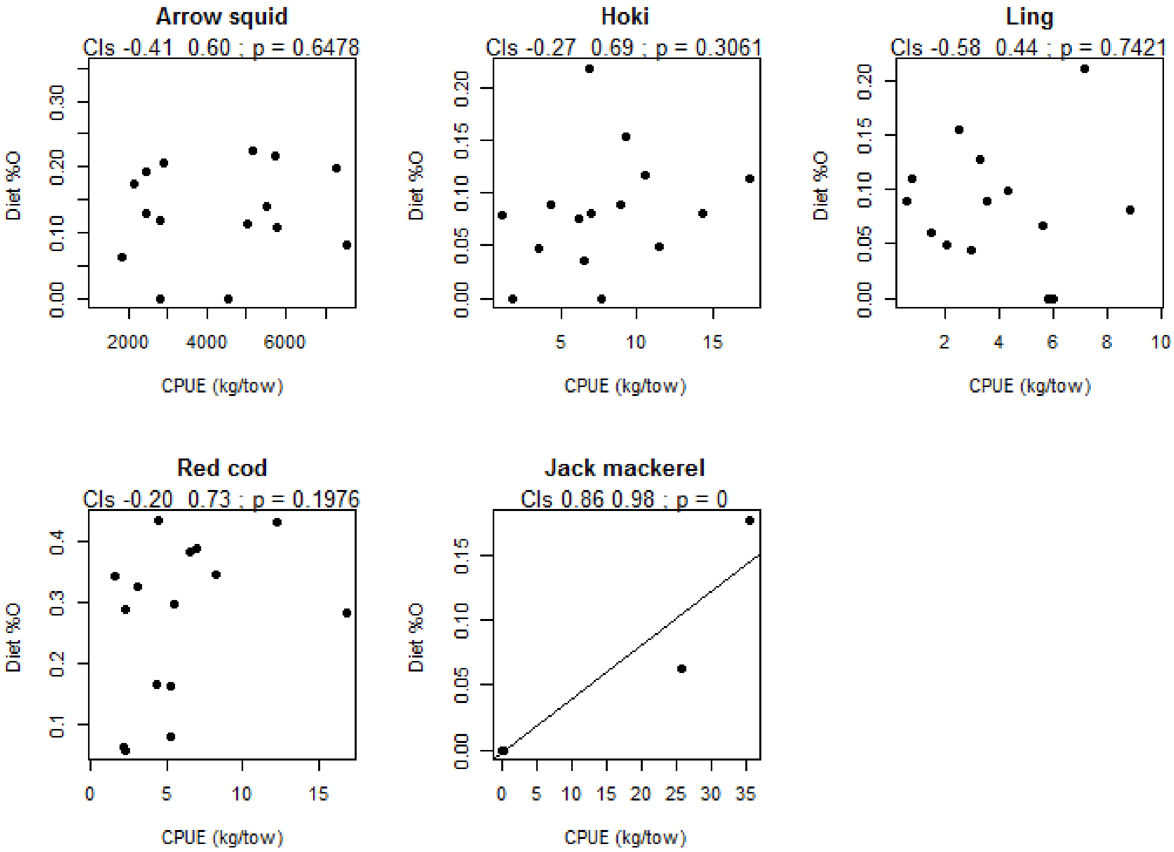

Figure C-4: Standardised catch per tow of selected prey species in commercial trawl fisheries and their occurrence in the diet of NZ sea lions at Sandy Bay. (Childerhouse et al., 2001; Roberts, unpub. Data; Stewart-Sinclair, 2013).

Diet and maternal condition (1c)

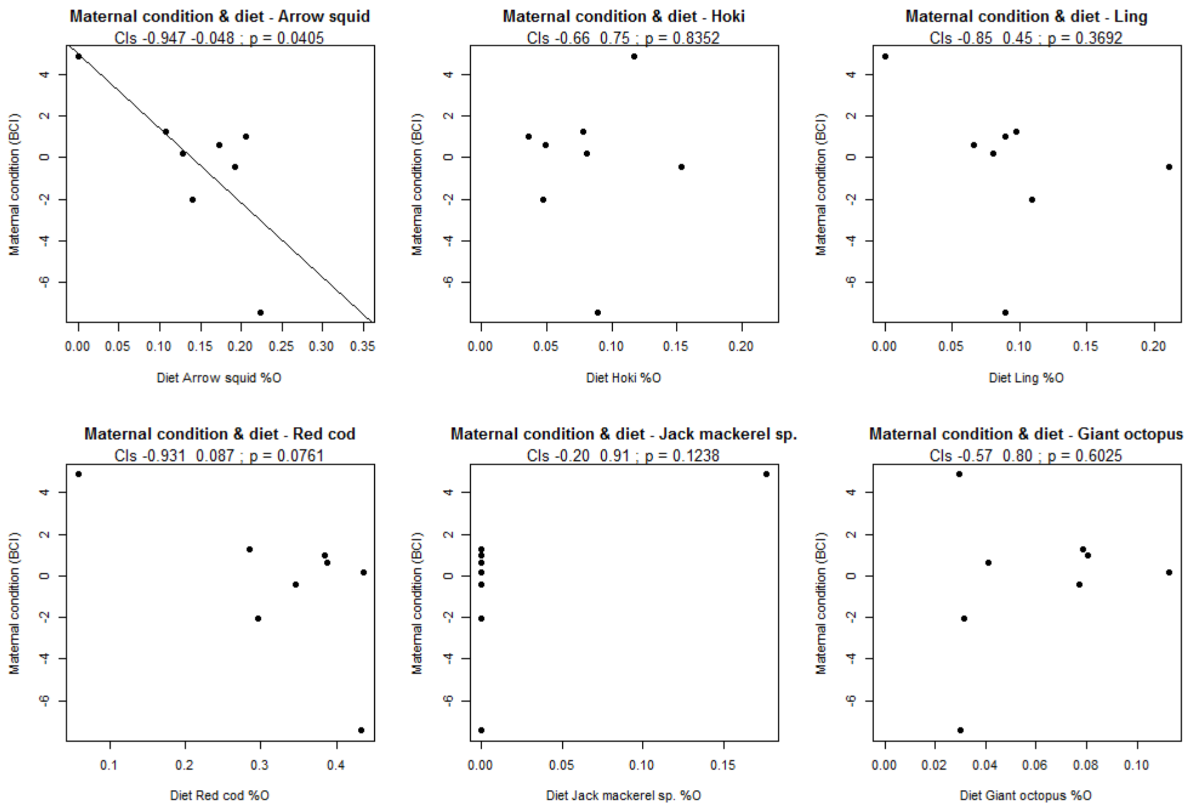

Figure C-5: Maternal condition and occurrence of selected prey species in the diet of NZ sea lions at Sandy Bay. (Childerhouse et al., 2001; Riet-Sapriza et al., 2012; Stewart-Sinclair, 2013).

Diet and milk quality (1d)

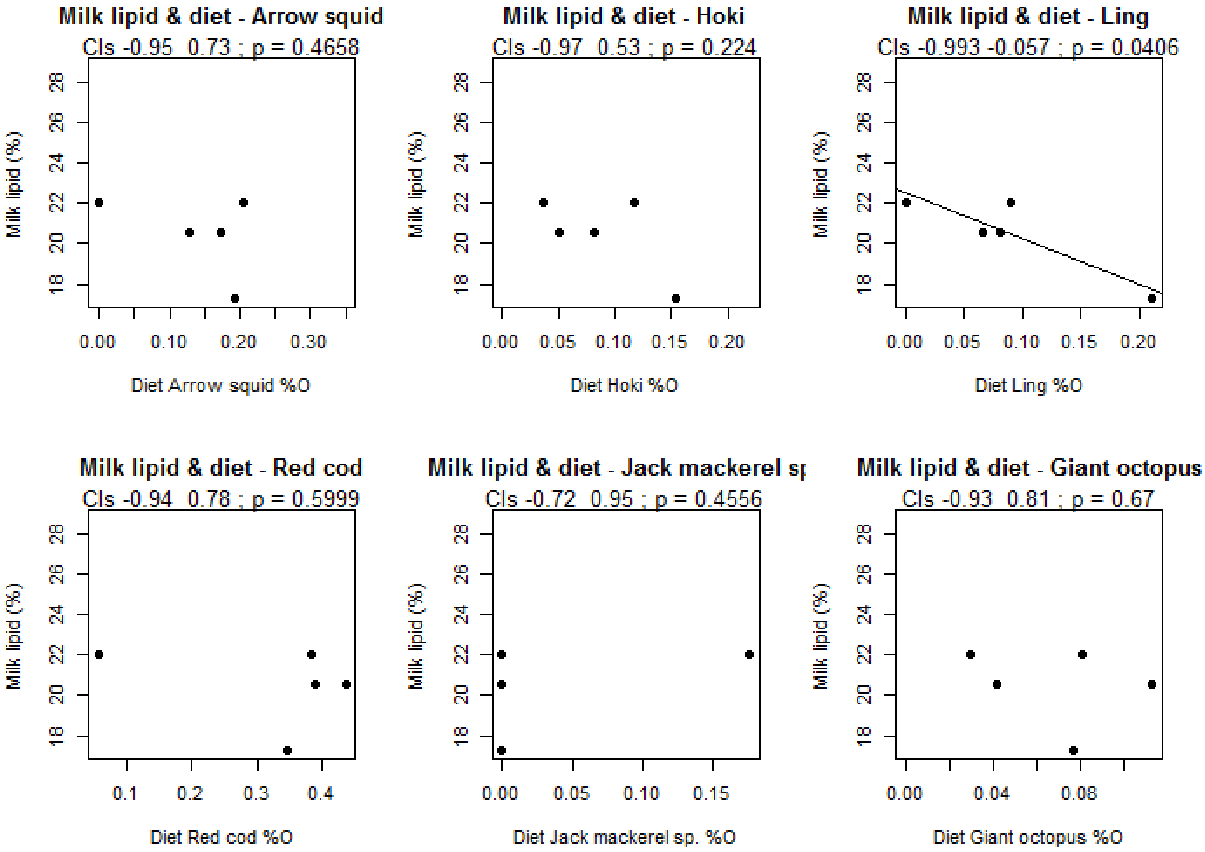

Figure C-6: Milk quality and occurrence of selected prey species in the diet of NZ sea lions at Sandy Bay. (Childerhouse et al., 2001; Riet-Sapriza et al., 2012; Stewart-Sinclair, 2013).

Maternal condition and pup growth (1e)

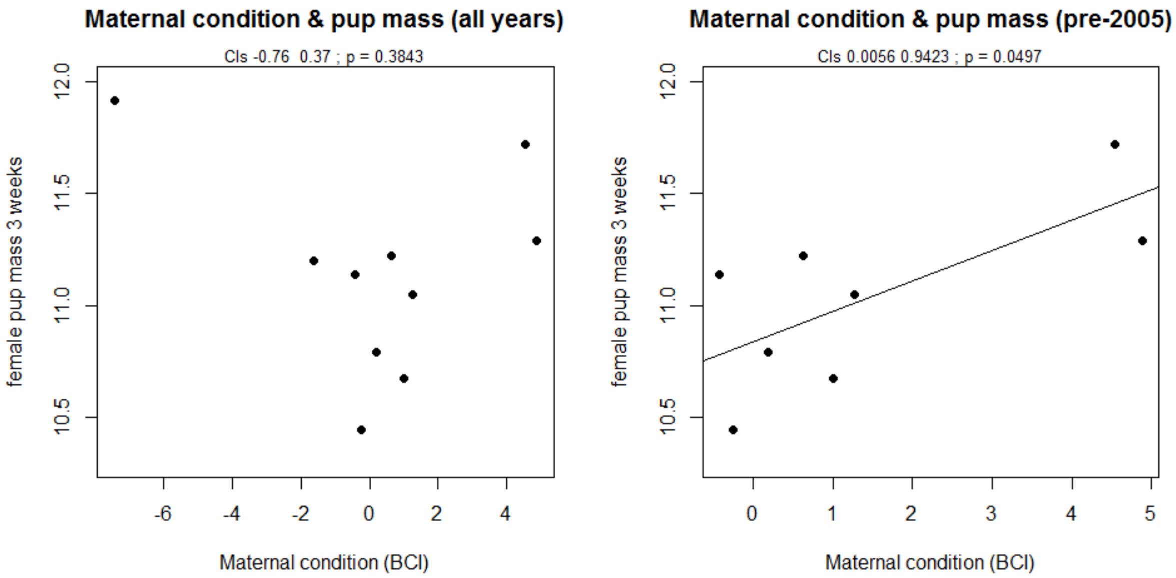

Figure C-7: Maternal condition and 3-week pup mass of NZ sea lions at Sandy Bay. (Cawthorn, unpub.data, Childerhouse et al., 2013; Chilvers, 2012; Riet-Sapriza et al., 2012).

Pup mass and pup/yearling survival (1f)

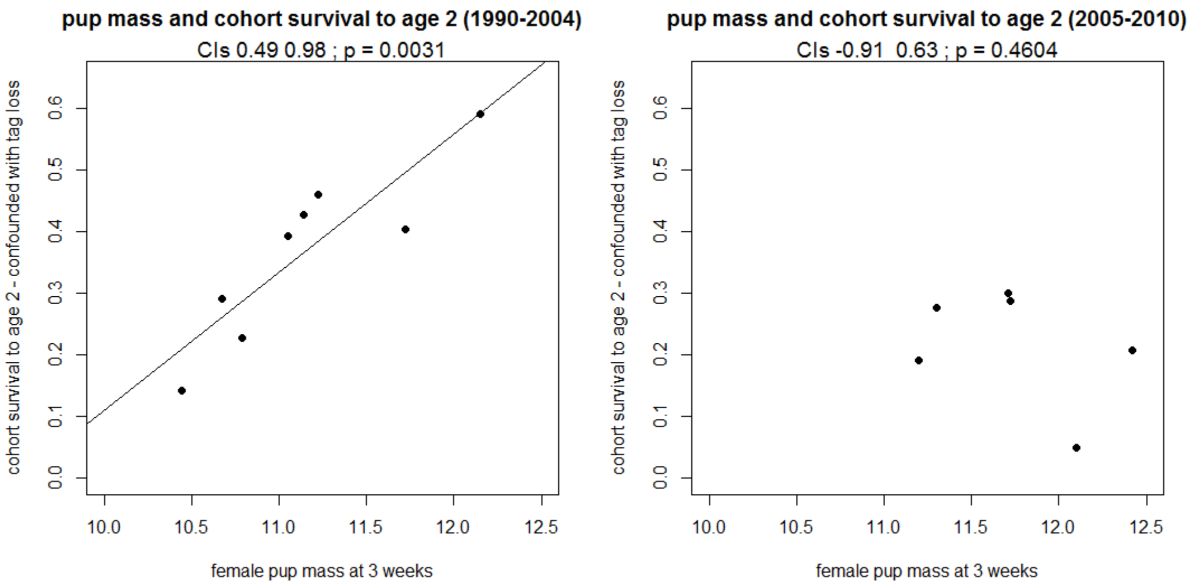

Figure C-8: Annual pup mass of females and demographic modelling estimate of pup and yearling survival. Estimation of survival confounded with tag loss; Regression line shown for significantly correlated datasets; Cawthorn, unpub.data, Childerhouse et al., 2013; Chilvers, 2012.

Pup yearling survival in year and adult survival in year+1 (1h)

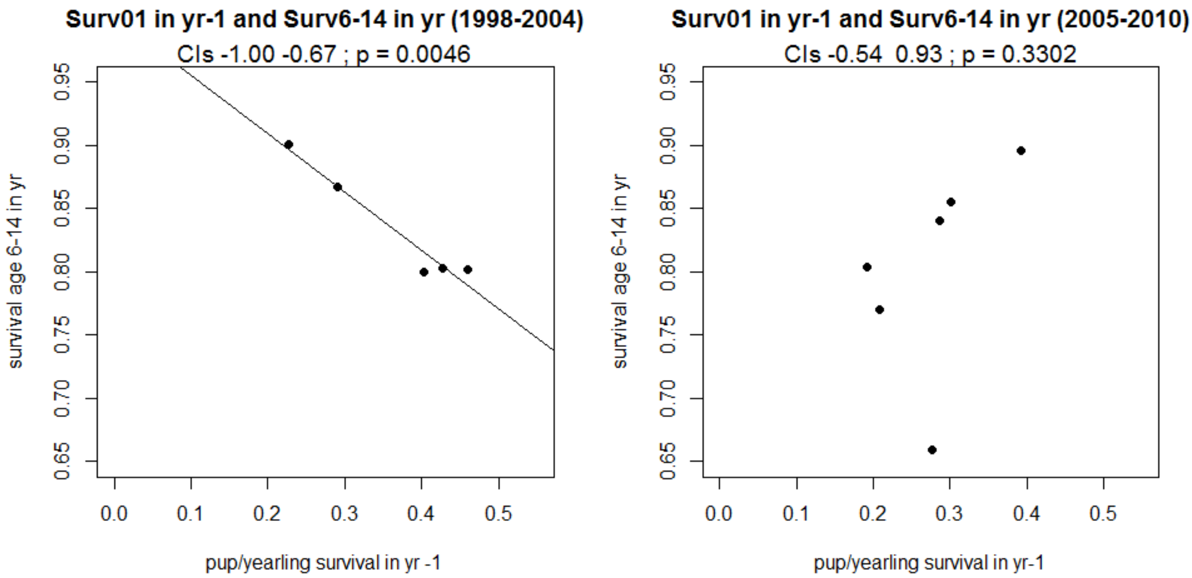

Figure C-9: Annual survival at age 6-14 (Surv6-14) in year plotted against pup/yearling (Surv01) survival in the previous year. Regression line shown for significantly correlated datasets; survival estimates confounded with tag loss rate.

Maternal condition, adult survival and pupping rate (1g)

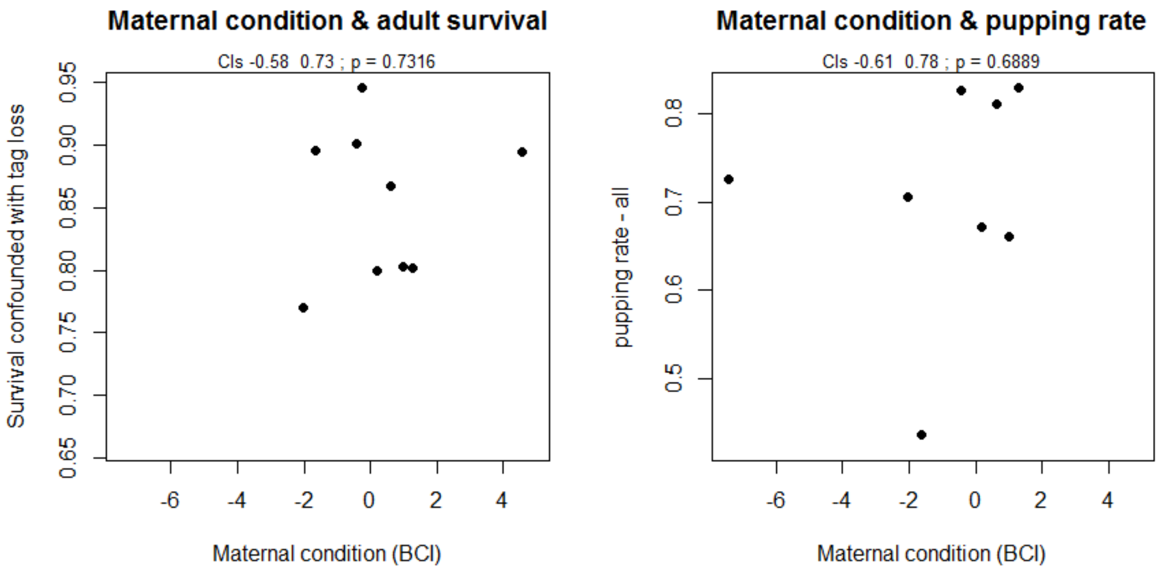

Figure C-10: Maternal condition and estimated survival at age 6-14 (Surv6-14) or pupping rate. Regression line shown for significantly correlated datasets. Survival estimates confounded with tag loss rate.

Early pup mortality and pup yearling survival (2a)

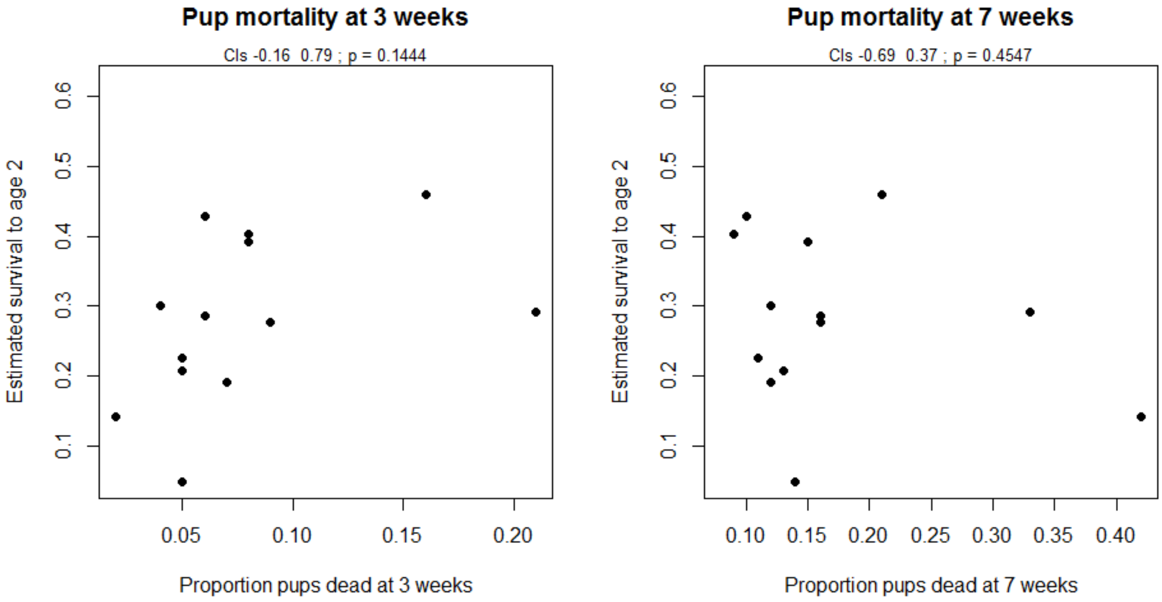

Figure C-11: Three and seven-week pup mortality rate and estimated cohort survival to age 2. Chilvers (2012); survival estimates confounded with tag loss rate.

Pup mortality rate by diagnosis and pup yearling survival (2b)

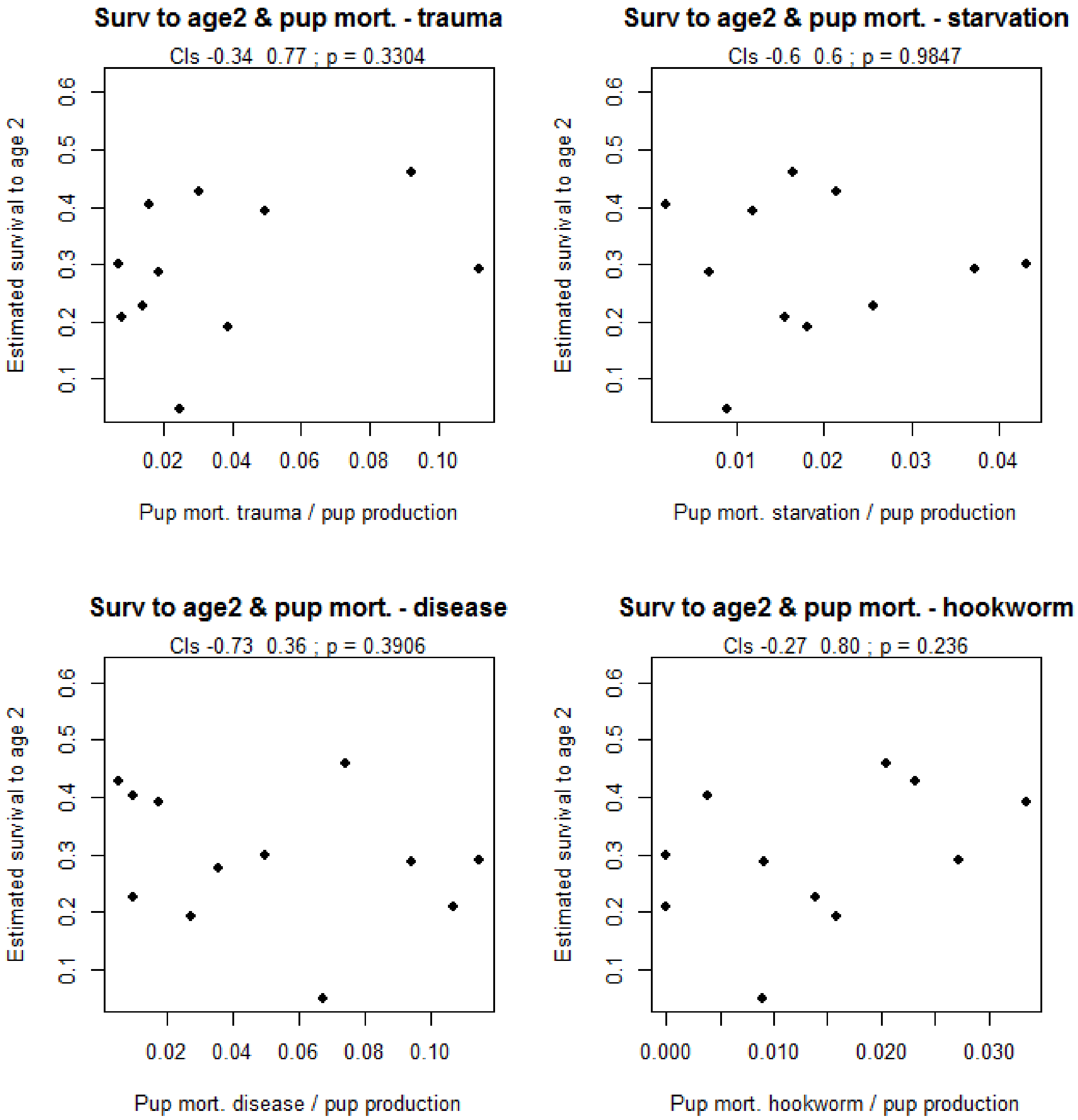

Figure C-12: Pup mortality rate by diagnosis and estimated cohort survival to age 2. Pup mortality as a proportion of estimated pup births, Castinel et al. (2007); Roe (2012); Roe unpub. data; regression line shown for significantly correlated datasets; survival estimates confounded with tag loss rate.

Bacterial disease-related pup mortality rate by sample week and pup yearling survival (2c)

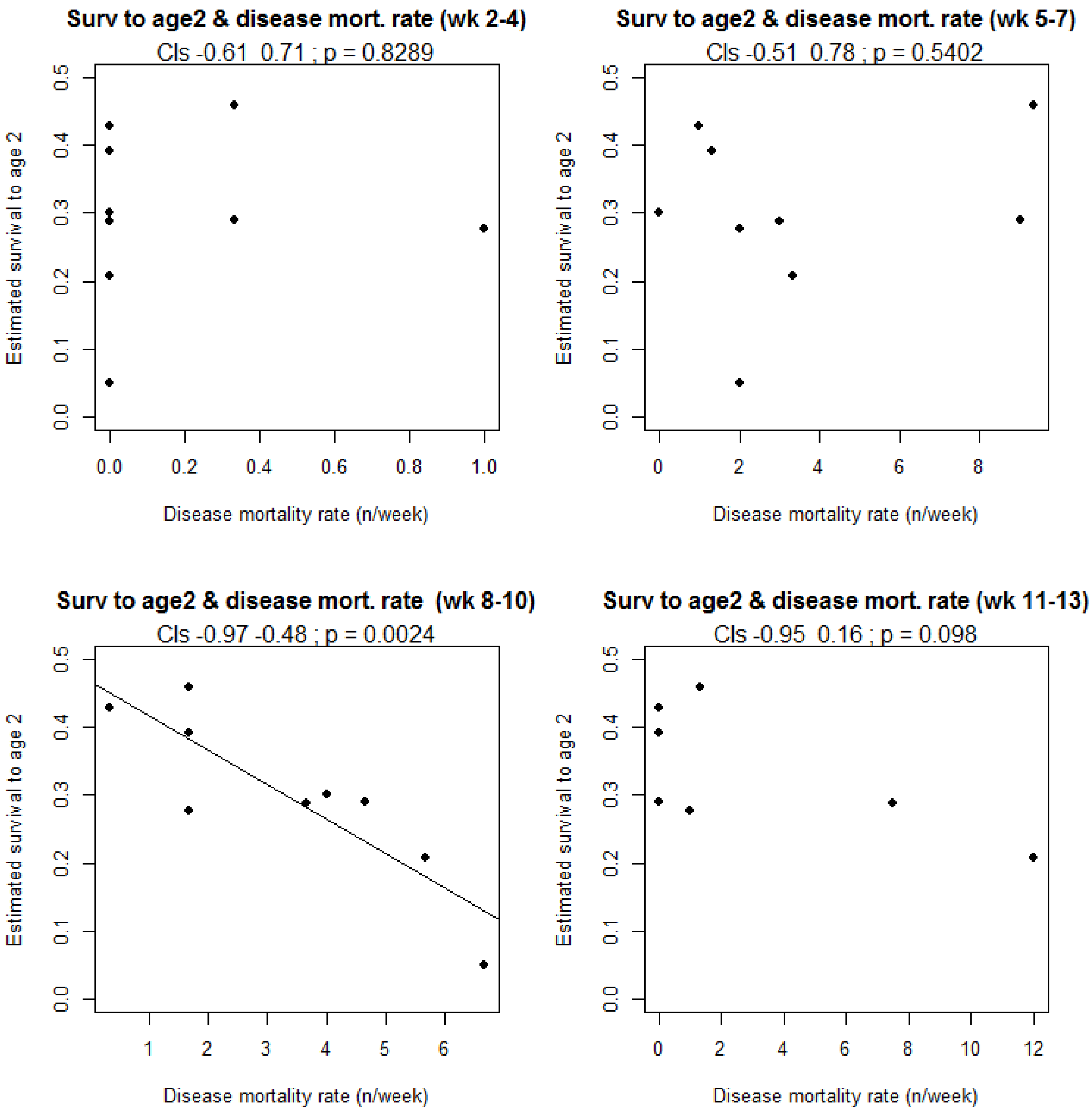

Figure C-13: Pup disease related mortality rate and estimated cohort survival to age 2. Number of pups diagnosed as disease-related mortality per week with sampling effort, Castinel et al. (2007); Roe (2012); Roe unpub. data; regression line shown for significantly correlated datasets; survival estimates confounded with tag loss rate.

Captures/interactions with commercial fishery trawls and survival at vulnerable age (3)

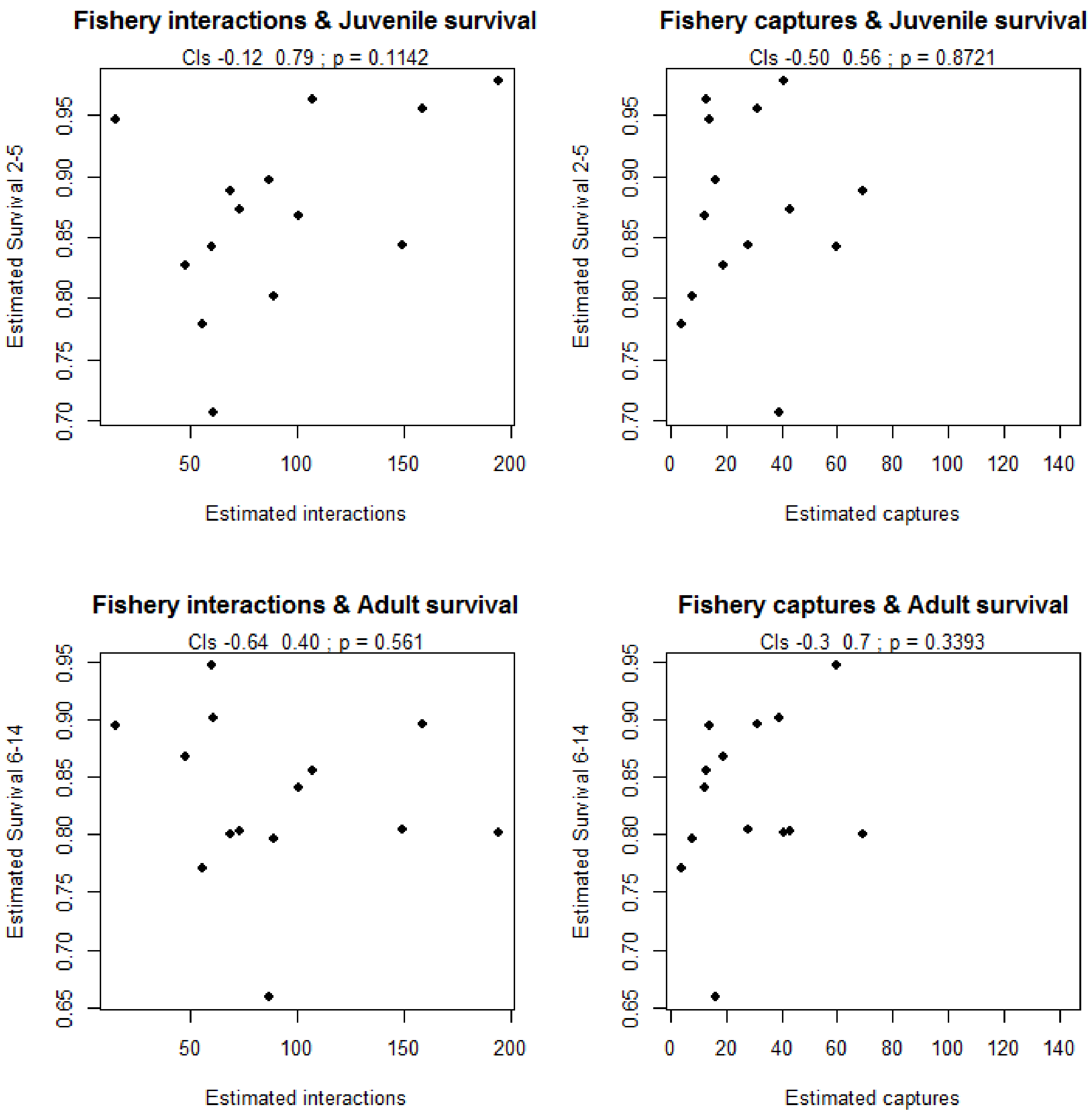

Figure C-14: Estimated captures and interactions with squid fishery trawls (SQU6T) and estimated cohort survival at vulnerable ages. Thompson & Abraham (2010); survival estimates confounded with tag loss rate.

Table C-2: Results of correlation analyses – all tests in this assessment. r = Pearson product moment correlation coefficient; df = degrees of freedom; p = p-value; */**/*/. = significance at 10%, 5%, 1% or 0.1% level, respectively.**

Relationship	variable 1	variable 2	df	r	p	
1a i climate and prey abund	CLIMATE atmospheric rain	CPUE arrow squid	19	-0.38	0.088	.
	CLIMATE atmospheric rain	CPUE hoki	19	-0.08	0.738	
	CLIMATE atmospheric rain	CPUE red cod	19	0.03	0.881	
	CLIMATE atmospheric rain	CPUE ling	19	0.26	0.255	
	CLIMATE atmospheric rain	CPUE jack mackerel	19	0.03	0.881	
	CLIMATE atmospheric temperature	CPUE arrow squid	19	-0.27	0.239	
	CLIMATE atmospheric temperature	CPUE hoki	19	-0.23	0.310	
	CLIMATE atmospheric temperature	CPUE red cod	19	-0.11	0.629	
	CLIMATE atmospheric temperature	CPUE ling	19	0.01	0.967	
	CLIMATE atmospheric temperature	CPUE jack mackerel	19	0.07	0.761	
	CLIMATE atmospheric wind	CPUE arrow squid	19	0.01	0.974	
	CLIMATE atmospheric wind	CPUE hoki	19	0.08	0.734	
	CLIMATE atmospheric wind	CPUE red cod	19	0.09	0.703	
	CLIMATE atmospheric wind	CPUE ling	19	0.36	0.105	
	CLIMATE atmospheric wind	CPUE jack mackerel	19	-0.34	0.131	
	CLIMATE Chlorophyll a	CPUE arrow squid	12	-0.05	0.863	
	CLIMATE Chlorophyll a	CPUE hoki	12	-0.18	0.548	
	CLIMATE Chlorophyll a	CPUE red cod	12	0.13	0.657	
	CLIMATE Chlorophyll a	CPUE ling	12	-0.22	0.454	
	CLIMATE Chlorophyll a	CPUE jack mackerel	12	-0.19	0.516	
	CLIMATE ENSO	CPUE arrow squid	21	-0.04	0.843	
	CLIMATE ENSO	CPUE hoki	21	0.18	0.421	
	CLIMATE ENSO	CPUE red cod	21	0.05	0.808	
	CLIMATE ENSO	CPUE ling	21	0.16	0.470	
	CLIMATE ENSO	CPUE jack mackerel	21	-0.12	0.596	
	CLIMATE IPO	CPUE arrow squid	17	-0.35	0.144	
	CLIMATE IPO	CPUE hoki	17	0.32	0.188	
	CLIMATE IPO	CPUE red cod	17	-0.18	0.465	
	CLIMATE IPO	CPUE ling	17	0.62	0.005	**
	CLIMATE IPO	CPUE jack mackerel	17	-0.18	0.465	
	CLIMATE sea surface height	CPUE arrow squid	18	0.42	0.068	.
	CLIMATE sea surface height	CPUE hoki	18	-0.03	0.886	
	CLIMATE sea surface height	CPUE red cod	18	0.14	0.568	
	CLIMATE sea surface height	CPUE ling	18	-0.38	0.096	.
	CLIMATE sea surface height	CPUE jack mackerel	18	-0.30	0.200	
	CLIMATE sea surface temp	CPUE arrow squid	20	-0.33	0.135	
	CLIMATE sea surface temp	CPUE hoki	20	-0.01	0.965	
	CLIMATE sea surface temp	CPUE red cod	20	0.05	0.837	
	CLIMATE sea surface temp	CPUE ling	20	0.04	0.857	
	CLIMATE sea surface temp	CPUE jack mackerel	20	-0.09	0.702	
	CLIMATE SOI	CPUE arrow squid	21	0.25	0.251	
	CLIMATE SOI	CPUE hoki	21	-0.12	0.576	
	CLIMATE SOI	CPUE red cod	21	0.03	0.895	
	CLIMATE SOI	CPUE ling	21	-0.31	0.148	
	CLIMATE SOI	CPUE jack mackerel	21	0.06	0.780	

Relationship	variable 1	variable 2	df	r	p	
1a ii climate and diet	CLIMATE atmospheric rain	DIET arrow squid	14	0.24	0.373	
	CLIMATE atmospheric rain	DIET hoki	14	-0.45	0.079	.
	CLIMATE atmospheric rain	DIET ling	14	-0.07	0.791	
	CLIMATE atmospheric rain	DIET red cod	14	-0.06	0.832	
	CLIMATE atmospheric rain	DIET jack mackerel	14	-0.48	0.060	.
	CLIMATE atmospheric rain	DIET giant octopus	14	-0.11	0.673	
	CLIMATE atmospheric rain	DIET opalfish sp.	14	0.31	0.239	
	CLIMATE atmospheric rain	DIET rattail	14	0.10	0.713	
	CLIMATE atmospheric rain	DIET Octopus sp.	14	0.05	0.856	
	CLIMATE atmospheric temperature	DIET arrow squid	14	0.43	0.100	
	CLIMATE atmospheric temperature	DIET hoki	14	-0.16	0.543	
	CLIMATE atmospheric temperature	DIET ling	14	-0.25	0.342	
	CLIMATE atmospheric temperature	DIET red cod	14	-0.03	0.898	
	CLIMATE atmospheric temperature	DIET jack mackerel	14	0.16	0.565	
	CLIMATE atmospheric temperature	DIET giant octopus	14	0.16	0.542	
	CLIMATE atmospheric temperature	DIET opalfish sp.	14	-0.14	0.609	
	CLIMATE atmospheric temperature	DIET rattail	14	0.01	0.980	
	CLIMATE atmospheric temperature	DIET Octopus sp.	14	0.03	0.924	
	CLIMATE atmospheric wind	DIET arrow squid	14	0.02	0.937	
	CLIMATE atmospheric wind	DIET hoki	14	-0.40	0.128	
	CLIMATE atmospheric wind	DIET ling	14	0.18	0.501	
	CLIMATE atmospheric wind	DIET red cod	14	0.03	0.917	
	CLIMATE atmospheric wind	DIET jack mackerel	14	-0.29	0.272	
	CLIMATE atmospheric wind	DIET giant octopus	14	-0.19	0.483	
	CLIMATE atmospheric wind	DIET opalfish sp.	14	-0.22	0.419	
	CLIMATE atmospheric wind	DIET rattail	14	-0.44	0.088	.
	CLIMATE atmospheric wind	DIET Octopus sp.	14	-0.08	0.778	
	CLIMATE Chlorophyll a	DIET arrow squid	9	-0.06	0.863	
	CLIMATE Chlorophyll a	DIET hoki	9	-0.41	0.213	
	CLIMATE Chlorophyll a	DIET ling	9	-0.38	0.248	
	CLIMATE Chlorophyll a	DIET red cod	9	0.46	0.154	
	CLIMATE Chlorophyll a	DIET jack mackerel	9	NA	NA	
	CLIMATE Chlorophyll a	DIET giant octopus	9	-0.02	0.943	
	CLIMATE Chlorophyll a	DIET opalfish sp.	9	0.44	0.176	
	CLIMATE Chlorophyll a	DIET rattail	9	0.70	0.016	*
	CLIMATE Chlorophyll a	DIET Octopus sp.	9	0.19	0.580	
	CLIMATE ENSO	DIET arrow squid	13	-0.12	0.661	
	CLIMATE ENSO	DIET hoki	13	-0.15	0.605	
	CLIMATE ENSO	DIET ling	13	-0.02	0.956	
	CLIMATE ENSO	DIET red cod	13	-0.01	0.969	
	CLIMATE ENSO	DIET jack mackerel	13	-0.10	0.730	
	CLIMATE ENSO	DIET giant octopus	13	-0.32	0.247	
	CLIMATE ENSO	DIET opalfish sp.	13	0.13	0.640	
	CLIMATE ENSO	DIET rattail	13	0.03	0.919	
	CLIMATE ENSO	DIET Octopus sp.	13	-0.20	0.479	

Relationship	variable 1	variable 2	df	r	p	
1a ii climate and diet	CLIMATE IPO	DIET arrow squid	9	-0.85	0.001	***
	CLIMATE IPO	DIET hoki	9	0.25	0.449	
	CLIMATE IPO	DIET ling	9	-0.63	0.038	*
	CLIMATE IPO	DIET red cod	9	-0.74	0.009	**
	CLIMATE IPO	DIET jack mackerel	9	0.53	0.095	.
	CLIMATE IPO	DIET giant octopus	9	-0.21	0.539	
	CLIMATE IPO	DIET opalfish sp.	9	-0.81	0.002	**
	CLIMATE IPO	DIET rattail	9	-0.68	0.022	*
	CLIMATE IPO	DIET Octopus sp.	9	-0.80	0.003	**
	CLIMATE sea surface height	DIET arrow squid	13	0.43	0.113	
	CLIMATE sea surface height	DIET hoki	13	-0.22	0.421	
	CLIMATE sea surface height	DIET ling	13	0.62	0.014	*
	CLIMATE sea surface height	DIET red cod	13	0.51	0.055	.
	CLIMATE sea surface height	DIET jack mackerel	13	-0.43	0.109	
	CLIMATE sea surface height	DIET giant octopus	13	-0.06	0.831	
	CLIMATE sea surface height	DIET opalfish sp.	13	0.66	0.008	**
	CLIMATE sea surface height	DIET rattail	13	0.47	0.078	.
	CLIMATE sea surface height	DIET Octopus sp.	13	0.60	0.018	*
	CLIMATE sea surface temp	DIET arrow squid	12	0.41	0.146	
	CLIMATE sea surface temp	DIET hoki	12	0.32	0.259	
	CLIMATE sea surface temp	DIET ling	12	0.44	0.119	
	CLIMATE sea surface temp	DIET red cod	12	0.33	0.248	
	CLIMATE sea surface temp	DIET jack mackerel	12	-0.14	0.634	
	CLIMATE sea surface temp	DIET giant octopus	12	0.60	0.023	*
	CLIMATE sea surface temp	DIET opalfish sp.	12	0.13	0.668	
	CLIMATE sea surface temp	DIET rattail	12	0.42	0.136	
	CLIMATE sea surface temp	DIET Octopus sp.	12	0.09	0.751	
	CLIMATE SOI	DIET arrow squid	13	0.15	0.592	
	CLIMATE SOI	DIET hoki	13	0.04	0.896	
	CLIMATE SOI	DIET ling	13	0.19	0.501	
	CLIMATE SOI	DIET red cod	13	0.08	0.785	
	CLIMATE SOI	DIET jack mackerel	13	0.06	0.833	
	CLIMATE SOI	DIET giant octopus	13	0.08	0.784	
	CLIMATE SOI	DIET opalfish sp.	13	0.01	0.973	
	CLIMATE SOI	DIET rattail	13	0.00	0.989	
	CLIMATE SOI	DIET Octopus sp.	13	0.25	0.369	

Relationship	variable 1	variable 2	df	r	p	
1b prey abundance and diet	CPUE arrow squid	DIET arrow squid	13	0.13	0.648	
	CPUE hoki	DIET hoki	13	0.28	0.306	
	CPUE ling	DIET ling	13	-0.09	0.742	
	CPUE red cod	DIET red cod	13	0.35	0.198	
	CPUE jack mackerel	DIET jack mackerel	13	0.95	0.000	***
1c diet and maternal condition	DIET arrow squid	BIOLOGY body condition index	6	-0.73	0.041	*
	DIET hoki	BIOLOGY body condition index	6	0.09	0.835	
	DIET ling	BIOLOGY body condition index	6	-0.37	0.369	
	DIET red cod	BIOLOGY body condition index	6	-0.66	0.076	.
	DIET jack mackerel	BIOLOGY body condition index	6	0.59	0.124	
	DIET giant octopus	BIOLOGY body condition index	6	0.22	0.602	
	DIET rattail	BIOLOGY body condition index	6	-0.67	0.068	.
	DIET Octopus sp.	BIOLOGY body condition index	6	-0.75	0.033	*
	DIET opalfish sp.	BIOLOGY body condition index	6	-0.10	0.808	
1d diet and milk quality	DIET arrow squid	BIOLOGY milk fat	3	-0.43	0.466	
	DIET hoki	BIOLOGY milk fat	3	-0.66	0.224	
	DIET ling	BIOLOGY milk fat	3	-0.89	0.041	*
	DIET red cod	BIOLOGY milk fat	3	-0.32	0.600	
	DIET jack mackerel	BIOLOGY milk fat	3	0.44	0.456	
	DIET giant octopus	BIOLOGY milk fat	3	-0.26	0.670	
	DIET rattail	BIOLOGY milk fat	3	-0.07	0.908	
	DIET Octopus sp.	BIOLOGY milk fat	3	0.12	0.846	
	DIET opalfish sp.	BIOLOGY milk fat	3	-0.19	0.756	
	DIET arrow squid	BIOLOGY milk protein	3	-0.82	0.091	.
	DIET hoki	BIOLOGY milk protein	3	0.79	0.113	
	DIET ling	BIOLOGY milk protein	3	-0.18	0.768	
	DIET red cod	BIOLOGY milk protein	3	-0.73	0.158	
	DIET jack mackerel	BIOLOGY milk protein	3	0.75	0.141	
	DIET giant octopus	BIOLOGY milk protein	3	-0.20	0.749	
	DIET rattail	BIOLOGY milk protein	3	-0.91	0.031	*
	DIET Octopus sp.	BIOLOGY milk protein	3	-0.80	0.102	
	DIET opalfish sp.	BIOLOGY milk protein	3	-0.91	0.033	*
1d maternal condition and milk quality	BIOLOGY body condition index	BIOLOGY milk fat	5	-0.23	0.626	
	BIOLOGY body condition index	BIOLOGY milk protein	5	0.54	0.215	
1e i diet and pup growth	DIET arrow squid	BIOLOGY pup mass female	14	0.19	0.486	
	DIET hoki	BIOLOGY pup mass female	14	-0.32	0.222	
	DIET ling	BIOLOGY pup mass female	14	0.24	0.381	
	DIET red cod	BIOLOGY pup mass female	14	0.09	0.730	
	DIET jack mackerel	BIOLOGY pup mass female	14	-0.25	0.349	
	DIET giant octopus	BIOLOGY pup mass female	14	-0.75	0.001	***
	DIET rattail	BIOLOGY pup mass female	14	0.02	0.928	
	DIET Octopus sp.	BIOLOGY pup mass female	14	0.36	0.173	
	DIET opalfish sp.	BIOLOGY pup mass female	14	0.27	0.314	
	DIET arrow squid	BIOLOGY pup mass male	14	0.15	0.577	
	DIET hoki	BIOLOGY pup mass male	14	-0.04	0.886	
	DIET ling	BIOLOGY pup mass male	14	0.20	0.455	
	DIET red cod	BIOLOGY pup mass male	14	0.03	0.908	
	DIET jack mackerel	BIOLOGY pup mass male	14	0.00	0.997	
	DIET giant octopus	BIOLOGY pup mass male	14	-0.48	0.061	.
	DIET rattail	BIOLOGY pup mass male	14	-0.03	0.902	
	DIET Octopus sp.	BIOLOGY pup mass male	14	-0.03	0.915	
	DIET opalfish sp.	BIOLOGY pup mass male	14	0.10	0.703	
	DIET arrow squid	BIOLOGY pup mass male-female	14	-0.06	0.833	
	DIET hoki	BIOLOGY pup mass male-female	14	0.41	0.112	
	DIET ling	BIOLOGY pup mass male-female	14	-0.05	0.841	
	DIET red cod	BIOLOGY pup mass male-female	14	-0.09	0.738	
	DIET jack mackerel	BIOLOGY pup mass male-female	14	0.36	0.169	
	DIET giant octopus	BIOLOGY pup mass male-female	14	0.41	0.118	
	DIET rattail	BIOLOGY pup mass male-female	14	-0.08	0.760	
	DIET Octopus sp.	BIOLOGY pup mass male-female	14	-0.56	0.024	*
	DIET opalfish sp.	BIOLOGY pup mass male-female	14	-0.24	0.366	

Relationship	variable 1	variable 2	df	r	p	
1e ii maternal condition/milk quality and pup growth	BIOLOGY body condition index	BIOLOGY pup mass female	9	-0.29	0.384	
	BIOLOGY milk fat	BIOLOGY pup mass female	5	0.04	0.925	
	BIOLOGY milk protein	BIOLOGY pup mass female	5	0.58	0.169	
	BIOLOGY body condition index	BIOLOGY pup mass male	9	-0.29	0.384	
	BIOLOGY milk fat	BIOLOGY pup mass male	5	0.04	0.925	
	BIOLOGY milk protein	BIOLOGY pup mass male	5	0.58	0.169	
	BIOLOGY body condition index	BIOLOGY pup mass male-female	9	0.43	0.182	
	BIOLOGY milk fat	BIOLOGY pup mass male-female	5	-0.55	0.206	
	BIOLOGY milk protein	BIOLOGY pup mass male-female	5	0.78	0.040	*
1f pup growth & pup survival	BIOLOGY pup mass female	DEMOGRAPHIC Cohort surv to age 2	12	0.10	0.729	
	BIOLOGY pup mass female (pre 2005)	DEMOGRAPHIC Cohort surv to age 2 (pre 2005)	6	0.89	0.003	**
	BIOLOGY pup mass female (post 2004)	DEMOGRAPHIC Cohort surv to age 2 (post 2004)	4	-0.38	0.460	
1g maternal condition and pupping rate/maternal survival	BIOLOGY body condition index	DEMOGRAPHIC puppers pupping	6	0.17	0.689	
	BIOLOGY body condition index	DEMOGRAPHIC non-puppers pupping	6	0.28	0.506	
	BIOLOGY body condition index	DEMOGRAPHIC survival age 6-14	7	0.13	0.732	
1h Cohort survival to age 2 & response in year+1	DEMOGRAPHIC Cohort surv to age 2 yr-1	BIOLOGY body condition index yr	5	0.58	0.169	
	DEMOGRAPHIC Cohort surv to age 2 yr-1	DEMOGRAPHIC pp yr	9	0.05	0.877	
	DEMOGRAPHIC Cohort surv to age 2 yr-1	BIOLOGY pup mass female yr	10	-0.16	0.624	
	DEMOGRAPHIC Cohort surv to age 2 yr-1	DEMOGRAPHIC survival age 6-14	3	-0.98	0.005	**
	DEMOGRAPHIC Cohort surv to age 2 yr-1 (post 2004)	DEMOGRAPHIC survival age 6-14 (post 2004)	4	0.48	0.330	
	DEMOGRAPHIC Cohort surv to age 2 yr-1 (pre 2005)	DEMOGRAPHIC survival age 6-14 (pre 2005)	9	0.06	0.863	
2a 3/7-week pup mortality rate and cohort survival to age 2	PUPMORT 3 weeks	DEMOGRAPHIC Cohort surv to age 2	11	0.43	0.144	
	PUPMORT 3 weeks	DEMOGRAPHIC Cohort surv to age 2	11	-0.23	0.455	
2b Pup mortality diagnosis and cohort survival to age 2	PUPMORT stillborn	DEMOGRAPHIC Cohort surv to age 2	9	-0.22	0.511	
	PUPMORT trauma	DEMOGRAPHIC Cohort surv to age 2	9	0.41	0.211	
	PUPMORT starvation	DEMOGRAPHIC Cohort surv to age 2	9	0.08	0.822	
	PUPMORT bacterial infection	DEMOGRAPHIC Cohort surv to age 2	10	-0.24	0.458	
	PUPMORT hookworm	DEMOGRAPHIC Cohort surv to age 2	9	0.45	0.162	
	PUPMORT congenital	DEMOGRAPHIC Cohort surv to age 2	9	-0.15	0.653	
2c Disease mortality rate by sampling week and cohort survival to age 2	PUPMORT bacterial infection 2-4 weeks	DEMOGRAPHIC Cohort surv to age 2	7	0.08	0.829	
	PUPMORT bacterial infection 5-7 weeks	DEMOGRAPHIC Cohort surv to age 2	7	0.24	0.540	
	PUPMORT bacterial infection 8-10 weeks	DEMOGRAPHIC Cohort surv to age 2	7	-0.87	0.002	**
	PUPMORT bacterial infection 11-13 weeks	DEMOGRAPHIC Cohort surv to age 2	5	-0.67	0.098	.
3a Fishery captures/interactions and juvenile/adult survival	FISHERY estimated captures	DEMOGRAPHIC survival age 2-5	12	0.05	0.872	
	FISHERY estimated ineractions	DEMOGRAPHIC survival age 2-5	12	0.44	0.114	
	FISHERY estimated captures	DEMOGRAPHIC survival age 6-14	12	0.28	0.339	
	FISHERY estimated ineractions	DEMOGRAPHIC survival age 6-14	12	-0.17	0.561	
	FISHERY estimated captures (index)	DEMOGRAPHIC survival age 2-5 (index)	8	0.36	0.306	
	FISHERY estimated ineractions (index)	DEMOGRAPHIC survival age 2-5 (index)	8	0.49	0.152	
	FISHERY estimated captures (index)	DEMOGRAPHIC survival age 6-14 (index)	8	-0.15	0.680	
	FISHERY estimated ineractions (index)	DEMOGRAPHIC survival age 6-14 (index)	8	-0.36	0.302	

Appendix D List of attendees at Project Workshops

Workshop 1, NIWA, 4-6 June 2013

- Andrew Trites, University of British Columbia
- Dan Fu, NIWA
- David Thompson, NIWA
- Ian Doonan, NIWA
- Igor Debski, NZ Department of Conservation
- Jim Roberts, NIWA
- Leigh Torres, NIWA
- Mark Hindell, University of Tasmania
- Martin Cryer, NZ Ministry for Primary Industries

Workshop 2, NIWA, 4-5 December 2013

- Andrew Trites, University of British Columbia
- Brittany Graham, NIWA
- David Middleton, Seafood New Zealand
- David Thompson, NIWA
- Ian Doonan, NIWA
- Igor Debski, NZ Department of Conservation
- Jim Roberts, NIWA
- Laureline Meynier, Massey University
- Leigh Torres, NIWA
- Louise Chilvers, NZ Department of Conservation
- Mark Hindell, University of Tasmania
- Martin Cryer, NZ Ministry for Primary Industries
- Michelle Beritzhoff, NZ Ministry for Primary Industries
- Rohan Currey, NZ Ministry for Primary Industries
- Sarah Bury, NIWA