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Biometric variability of New Zealand sea lion (*Phocarctos hookeri*) pups at the Auckland Islands and utility for predicting demographic rates

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EXECUTIVE SUMMARY

Roberts, J.O.; Cawthorn, M.W.; Childerhouse, S.J.; Clemens-Seely, K. (2021). Biometric variability of New Zealand sea lion (*Phocarctos hookeri*) pups at the Auckland Islands and utility for predicting demographic rates.

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Biometric measurements including mass and condition are known to be good predictors of early-life survival in multiple pinniped species, including otariids (sea lions and fur seals). Mass and length measurements have been collected from pups born at Auckland Islands rookeries since the early 1980s and these observations were recently collated into a single data set for the first time.

The overall objective of this project was to investigate potential relationships between pup biometric indices with the first-year survival for the Auckland Islands population. The first part of this analysis produced annual indices of pup mass and body condition that were standardised for sex and individual growth through the field season. At Sandy Bay on Enderby Island (the best-studied breeding rookery), strong temporal patterns were obtained in estimated indices through the past 40 years, including: female pup mass, male minus female pup mass, and body condition. These patterns do not appear to be driven by changes in birth date, which had no obvious trend through the study period. The temporal patterns were different for each pup index, and appear to vary with rookery (i.e., compared with Dundas Island, the largest breeding rookery).

A correlative assessment using the outputs of a demographic assessment model found that the female pup mass index was positively correlated with first-year survival at the cohort level (i.e., comparing annual estimates). This was corroborated by a demographic population assessment also produced under this research project (Edwards & Roberts 2021). A simple demographic assessment reported on here found much less support for this relationship when estimating the life history parameters of light versus heavy pups. As such, this suggests that the relationship between pup mass and survival might be stronger at the cohort level rather than at the level of the individual. The potential causes of this apparent contradiction are discussed, though not well-understood.

Mark-resighting effort at Dundas Island is likely to be insufficient to assess the extent to which relatively poor mass of pups here is informative of first year survival. Both the biometric and mark-recapture data are insufficient to assess the southern Figure of Eight Island colony, where the temporal pattern in annual pup production is very different.

The relative mass of males and females was positively correlated with annual pupping rate, e.g., males were not much bigger than females in years with anomalously low pupping rate, in contrast to years with average or above average pupping rates, in which males pups tended to be bigger than females.

In summary, this study supports the use of pup mass as a covariate of first year-survival, which may be informative well in advance of mark-recapture observations, and for cohorts lacking reliable mark-recapture data. However, the extent to which any benefits conferred from elevated pup mass are negated by endemic disease caused by *Klebsiella pneumoniae* (the main cause of death in the early field season) is unknown. The strong temporal patterns in pup mass and condition are likely to relate to external processes, e.g., variable maternal nutrition, prey availability, disease prevalence, and other factors. If confirmed, the relationship between pup mass and survival would facilitate the assessment of the population effects of variable pup mass and its causes.

1. INTRODUCTION

The New Zealand sea lion has an extremely concentrated breeding distribution with 97–98% of annual pup production at the Auckland Islands and Campbell Island, in the New Zealand Sub-Antarctic region (Chilvers 2019, DOC 2019, Foo & Weir 2019, Fyfe 2019) (Figure 1). The largest breeding population at the Auckland Islands was estimated to have declined by about 40% between the late 1990s and the 2008/09 field season (seasons hereafter referred to by the end year, i.e., 2009), although annual pup production estimates appear to have stabilised since then (DOC 2019, Roberts 2019). Known threats to the Auckland Islands population include deaths relating to commercial fisheries at the Auckland Islands, including southern arrow squid and scampi trawl fisheries, *Klebsiella pneumonia* infection-related mortality of pups, and indications of variable and/or limited prey availability and consequent nutritional stress (Augé 2010, Large et al. 2019, Meyer et al. 2015, Roberts et al. 2018, Roberts & Doonan 2016, Roe et al. 2015, Stewart-Sinclair 2013).

The Auckland Islands population of New Zealand sea lions exhibits multiple indicators of nutritional stress including: delayed age at first breeding, years with low pupping rate, and the poor condition of mothers and pups — all relative to the small, but growing population on the mainland of New Zealand (Augé 2010, Fyfe 2019, Roberts & Doonan 2016). However, the effects of nutritional stress on demographic rates and population growth of New Zealand sea lions, and other marine mammal species, remain poorly understood, which limits the population risk assessment of threats that impact on prey availability (Roberts 2019, Roberts & Doonan 2016).



Figure 1: (left) Location of New Zealand sea lion breeding populations, including the Auckland Islands population that is the subject of this assessment. (right) Map of the Auckland Islands showing the locations of the New Zealand sea lion colonies where pups were measured: Sandy Bay (on Enderby Island, Southeast Point also on Enderby Island, though not highlighted), Dundas Island, and Figure of Eight Island. Grey lines represent the 200 m, 500 m, and 1000 m bathymetric contours. A Threat Management Plan was recently developed for New Zealand sea lion populations (MPI/DOC 2017), which was informed by a population model of female sea lions breeding at the Auckland Islands (Roberts & Doonan 2016). This population model identified variable pup survival as a key driver of changing breeder numbers through time (Roberts & Doonan 2016). For example, an abrupt and sustained decline in first year (pup) survival from around 80% down to around 40% since 1994 preceded the protracted decline in breeders since the late 1990s (Roberts & Doonan 2016). More recent estimates of pup survival were weakly identifiable because females rarely attend the main study sites prior to attaining breeding age (approximately half have bred by age five at the Auckland Islands). This is an issue for risk assessments based on projected population size where recent demographic rates are sampled (Roberts & Doonan 2016).

The reproductive success (including birth rates and early survival of offspring) of marine megafauna species (including marine mammals) may be influenced by:

- Intrinsic bio-demographic factors, such as breeder age or genetics (Ozgul et al. 2009, Postma et al. 2013);
- Changes in prey availability which impact on maternal foraging efficiency and condition (Georges & Guinet 2001, Kraus et al. 2013); and
- Other biotic or abiotic external factors which impact on foraging efficiency, reproductive success or the survival of offspring (e.g., predation, disease or changes to habitat) (Roberts & Doonan 2014).

New Zealand sea lion pup measurements including length mass and axial girth have been collected at the main study breeding rookery at Sandy Bay, Auckland Islands since the early 1980s and according a highly standardised and consistent approach since 1994 (DOC 2019). Variable mass and body condition have been demonstrated to be good predictors of early-life survival in multiple otariid and phocid pinniped species (DeLong et al. 2017, Harding et al. 2005, Hastings et al. 2011). An initial study of New Zealand sea lion pup mass at Sandy Bay found no evidence for a year trend, though was limited to a period of population decline only and, so, lacked observations from contrasting conditions (Chilvers 2012). Pup mass has increased in recent years, coincident with a period of stabilisation in breeder numbers at the Auckland Islands (DOC 2019). Older pup biometric data have since been obtained from 1980 to 1993 field seasons, including at least three cohorts estimated to have relatively high first-year survival (1991 to 1993) (Roberts & Doonan 2016). Most of the pups that were measured were also marked with flipper tags, injected with microchips, branded, or a combination of these mark types, such that the fate of individual sea lions can be related to biometric measurements.

The overall objective of this project is to investigate the likely causes of differential New Zealand sea lion reproductive success (focusing on pup survival) and implications for population and risk assessment modelling. The specific research objectives of this research were to:

- 1. Explore the factors which affect year-varying pup mass and, ultimately, produce a pup mass series standardised for nuisance factors such as date of measurement;
- 2. Explore the relationships between pup measurements (or derived condition indices) with their survival rate to older age, including consideration of other factors known to impact on pup survival at the Auckland Islands such as bacterial disease; and
- 3. Examine the effects (on fits and population projections) of incorporating pup measurement covariates into updates of the Auckland Islands New Zealand sea lion risk assessment model described by Roberts & Doonan (2016) to develop biodemographic models for this population (i.e., simultaneously fitting to both biometric and demographic observations).

This report addresses research objectives 1 and 2 (above), i.e., the standardisation of pup mass and preliminary exploration of relationships to demographic rates, focussing on first-year survival. This is

followed by a discussion of potential drivers of temporal patterns in pup mass and body condition indices.

The subsequent incorporation of a pup mass covariate (from this analysis) into a female demographic assessment model for female New Zealand sea lions at the Auckland Islands is described in a separate report by Edwards & Roberts (2021).

2. METHODS

2.1 Field methods for measuring pups

All available pup biometric measurements were collated across field seasons from 1979/80 to 2018/19. Pups were sampled at Sandy Bay (the best-studied rookery at the Auckland Islands) in nearly all years through this time period, about half of these years at Dundas Island (the largest breeding rookery for the species), with more patchy sampling at both Southeast Point and Figure of Eight Island (see Table A1-1). Single measurements of a pup within a year were collected at the time a pup was marked for an ongoing mark-recapture study of Auckland Islands rookeries. In addition, some pups were measured multiple times within a field season, to estimate annual variability in growth rates and to assess the effects of variable growth on early-life survival (Chilvers et al. 2007).

At Sandy Bay, the field methods for collecting pup size measurements have been highly standardised and consistent since the 1994/95 field season, with overlap in the composition of field teams to ensure that a consistent methodology has been applied through time. Each year, 100 pups (50 of each sex) were both flipper-tagged and measured on a single day, for 15–17 January. At Dundas Island, 50 individuals of each sex were measured in most years since 1998/99, with some gaps, which could relate to no measurements being taken or failure to obtain the field data for this analysis. In recent years Dundas pups were tagged and measured from 18 to 21 January, though this was done later in January in preceding years (see Figure A1-1 in Appendix A). Sampling has been more sporadic at the other rookeries of Southeast Point (a now extinct breeding rookery located on the other side of Enderby Island from Sandy Bay) and Figure of Eight Island, located towards the south of the Auckland Islands (Figure 1).

At all rookeries, pups were randomly selected with effort spread evenly throughout the colonies, and any sickly and/or small pups were included if selected. Pups were physically captured and weighed in specifically designed bags using Salter hanging scales (either 30 kg or 50 kg). Scales were regularly checked and calibrated using items of known mass. The mass of the weighing bag was checked regularly and used to zero the scales during the course of weighing. Since 2015/16, standard length (cm) was also collected; this was defined as the straight-line measurement from the tip of the nose to the end of the tail with the pup laid flat on a measuring board. Axial girth measurements were also taken on the exhale, just posterior of the pectoral flippers. However, girth observations were not summarised or used by this analysis, because the relationship between length and mass is considered a superior measure of pup condition (Trites & Jonker 2000). At Sandy Bay, longitudinal pup growth studies from 1998/99 to 2003/04 collected multiple measurements from the same individuals, through until the end March for the longest-running season (2002/03). These longitudinal data were made available to this analysis, except the 2003/04 data (Chilvers et al. 2007), which could not be located by the authors.

Sampling was more sporadic and opportunistic prior to 1994/95, with greater variability in the date of measurement. However, the basic approach of pup selection and measurement was broadly consistent with the later period, i.e., field teams systematically measured all pups within pods, as well as singletons on the beach or sward, until it was considered that all pups had been marked; and pups were selected regardless of size, condition, and health status. Pups were weighed in weighing bags, using 20 kg Salter scales, which were calibrated using two or four litre bottles filled with fresh water the night before measurement. The scales were zeroed to exclude the mass of the pup weighing bag, or the bottle when

calibrating the scales. A fiberglass 1-m tape was used to take standard length measurements of pups held in a straight position on the ground. Repeat mass and length measurements (of the same individual within a season) were undertaken in 1983/84 and 1991/92 and were used by this analysis.

2.2 Processing biometric observations

The pup mass and standard length data were groomed to remove a small number of major outliers that probably resulted from mis-recording at the time of measurement; and measurements that result in a highly improbable mass-length relationship given that observed across the sampled population. For a comparatively much larger number of records, it was clear that mass and standard length measurements had been inverted, and these were corrected accordingly. The groomed dataset of New Zealand sea lion pup measurements at Auckland Islands rookeries has recently been collated by the authors of this report and submitted to the Department of Conservation.

Where both body mass and standard length were recorded for the same individual on the same date, the body condition index (BCI) — the relative mass given body length — was calculated. This is essentially an indirect measure of an individual's somatic condition, or relative 'fatness' for a given length. The calculation of BCI followed the approach of Roberts & Neale (2016). Briefly, an individual's mass was regressed on standard length, across all data for Auckland Islands rookeries, and the respective BCI was then calculated as the residual of each measurement to this regression (i.e., the mass relative to the mean at a given length). Alternative linear/curvilinear relationships were explored and selected based on model Akaike Information Criterion (AIC) (Akaike 1974). Note that standard length was not routinely collected for a large number of years (compare Table A1-1 and Table A1-2), such that the sample for calculating BCI was more limited relative to that of pup mass.

2.3 Standardisation of pup measurements

Mixed effects models were used to estimate annual time series of male and female pup mass and female body condition indices, which were standardised for variability in the date of measurement through time (and the effects of individual growth). A secondary objective of this modelling approach was to explore other factors affecting pup mass, including sex and breeding rookery. Generalised Additive Mixed Models (GAMMs) were developed to produce annual pup size and condition indices, using the 'mgcv' *R* package (R Core Team 2019, Wood 2011). GAMMs allow nested structures (e.g., of random effects within fixed effects) and the modelling of non-linear responses (e.g., to represent non-linear growth through time).

For both mass and condition standardisation models, field season ('year') was fixed as the first model term to obtain a standardised time series. Other terms offered to mass standardisation models included:

- The date of measurement ('day'). This was specified as an integer of the number of days since December 26 (the peak pupping date) (Chilvers et al. 2007), such that measurements prior to this date had a negative value, and those after were positive. A spline was used to allow for non-linear growth through time, with the basis dimension term (*k*) fixed to equal 3, to prevent biologically unrealistic shapes.
- A random slope against 'day' for each sea lion pup ('ID'), representing individual variability in growth rate (initial exploration found this to be more optimal than a random intercept, based on model AIC). Individual variability in growth was primarily informed by longitudinal studies in some seasons that took repeated measurements from certain individuals (e.g., see Figure 2).
- Individual sex ('sex') was offered as:
 - \circ an interaction term with 'year' to estimate annual sex-differences in mass; and
 - o an interaction term with 'day' to account for sex differences in daily growth rate.

For the body condition model, only female measurements were used, and sex was not included as a model term. In addition, sea lion ID was offered as a random slope with respect to date of measurement. A male body condition index could also have been produced from the data, though this was deemed to be less useful for predicting demographic rates due to both the relatively short time series of observations, and the absence of a pre-existing demographic model for male New Zealand sea lions.

Pup mass or condition models were fitted using a normal error distribution, and conformance to the assumed normal error structure was assessed through visual inspection of quantile-quantile plots. In addition, diagnostic plots of residual variance were produced using scaled Pearson residuals to evaluate model fits to pup measurements. Model selection was carried out by comparing the model AIC of different forms including various combinations of the explanatory variables described above.

2.4 Exploration of bio-demographic relationships

Demographic assessments were undertaken using the outputs of the standardisation described in this report, to assess the strength of potential relationships between pup mass/condition indices and key life history rates. Two different approaches were taken, and both used modifications of a pre-existing demographic assessment model for female New Zealand sea lions at the Auckland Islands (Roberts 2019):

- 1. An exploratory correlative assessment of standardised pup mass and condition indices with estimates of annual estimates of first year (pup) survival and annual pupping rate probabilities from a demographic model that was modified to produce long time series of annual estimates; and
- 2. The estimation of fecundity-related demographic rates using a simplified parameterisation of the demographic model fitted to subsets of relatively light, intermediate-mass, and heavy pups, based on the outputs of the standardisation of pup measurements.

Approach 1

Approach 1 related demographic assessment estimates of annual first-year survival and annual pupping rate with standardised pup mass and condition indices from this assessment. The 'full' demographic assessment model parameterisation was used to generate the annual demographic rate estimates, using the SeaBird demographic assessment software (e.g., Roberts & Doonan 2016). The base model by Roberts (2019), using the '8+ partitioning', was modified to produce annual estimates of first-year survival (*Surv*₀) and annual pupping probability (*Pr*_P). Owing to time constraints of doing MCMC runs using this model, only Maximum Posterior Density (MPD) runs were undertaken. The estimates for the final two years (2017 and 2018 for first-year survival; 2018 and 2019 for annual pupping rate) were excluded from the analysis, because these will be less well-informed by the mark-resighting data. The strength of the linear relationship between annual pup measurement indices and demographic rates was assessed by calculating the Pearson product-moment correlation coefficient (*r*).

Approach 2

Approach 2 assessed the relationships between the relative mass of an individual as a pup and its subsequent life history. This analysis focused on fecundity related parameters (e.g., breeding rate and offspring survival), which tend to be most responsive to changes in population health (Gaillard et al. 2000). This required the linking of pup mass estimates to individual resighting histories. This was only possible for pups that were both measured and marked and was achieved using an array of sources (e.g., field notes and excel spreadsheets obtained for some field seasons) to determine flipper tag/chip/brand identification numbers recorded at the time of measurement. Once the mark ID was obtained for an individual, it was then attributed with the sea lion unique identification code used by the database of New Zealand sea lion demographic observations belonging to the Department of Conservation and maintained by Dragonfly Data Science (Dragonfly Data Science 2019).

The 'simple' demographic assessment model parameterisation was used to estimate demographic rates contingent on pup mass (Approach 2), also using SeaBird. This model was a simplification of the assessment model for female New Zealand sea lions at the Auckland Islands, developed by Roberts (2019) and based on Roberts & Doonan (2016). See Roberts & Doonan (2016) for a full description of model structure and parameter estimation. The likelihood calculation for the mark-recapture observations was a generalisation of that used in the Cormack-Jolly-Seber model (Cormack 1964). A description of all model estimated parameters is given in Table A3-1. All parameters, except those of interest – first year (pup) survival (*Surv*₀), annual pupping rate (*Pr*_P), which was year-invariant, and relative pupping rate at ages four (*Mat*₄) and age five (*Mat*₅) – were fixed to the base case model estimates of Roberts (2019). Branded pups (1999/00 only) were not used due to issues with parameter estimation.

The models were fit to subsets of light, intermediate-mass, or heavy pups (i.e., a total of three model runs). The relatively small number of marked individuals used meant that MCMC runs were relatively straightforward to do. Samples were taken every 10 iterations, across a total chain length of 20 000 iterations, giving a total of 2000 samples. The covariance matrix was then recalculated from these samples, and the chain restarted (following the approach of Roberts & Doonan 2016). All the resulting chain was then used to calculate the posterior distributions of each parameter, discarding the portion used to recalculate the covariance matrix.

3. RESULTS

3.1 Characterisation of pup biometrics

The Sandy Bay rookery is the best and longest studied of the Auckland Islands, with few gaps in sampling since the 1979/80 field season (1982/83, 1986/87 to 1988/89, and 1993/94). Mass measurements were taken in all years with sampling, though length sampling has been much more sporadic, with large gaps through time (e.g., no sampling from 1993/94 to 1998/99, and from 2005/06 to 2014/15), precluding the estimation of body condition in these years (Table A1-1 and Table A1-2).

Any inter-annual variability in raw (unstandardised) mass and length estimates will be confounded with variability in the date of measurements when comparing early years and later years in the series (Figure A1-1 and Figure A1-2). Pup mass was higher nearer the beginning of the sampling time series for both sexes (e.g., not below 13.3 kg for females and 15.1 kg for males from 1979/80 to 1983/84). Pup mass has been relatively low since 1994/95 (not higher than 12.5 kg for females and 13.9 kg for males). There are also clear patterns in the difference between male and female mass at Sandy Bay: males were not less than 1.4 kg heavier than females from 1979/80 to 1985/86; whereas males were less than 1 kg heavier than females in several years from 2001/02 to 2018/19 (Table A1-3).

The mean standard length of both sexes was less variable through time, though was also consistently high in the first years of sampling (e.g., at least 81 cm for females and 83 cm for males from 1979/80 to 1981/82), with several years of much shorter pups since then (i.e., under 80 cm and 82 cm for females and males, respectively). Temporal trends in male minus female length were less evident than for mass, with intermittent high periods (e.g., 1981/82 to 1984/85, and 1991/92 to 2004/05) though no long-term trend across the full time series (Table A1-4).

Biometric sampling at the other three Auckland Islands rookeries had been comparatively patchy through time, with most consistent sampling at Dundas Island, compared with Southeast Point and Figure of Eight Island. Unstandardised means indicate that pup mass at Dundas Island was much greater in the early 1990s than since 1998/99 (Table A1-3), though sampling was later in the season in these earlier years (Figure A1-1). Boxplots of mass and length measurements by sex and rookery are shown in Figure A1-3 and Figure A1-4.

Except for 2014/15, raw pup mass was consistently lower at Dundas Island than at Sandy Bay in the period from 2007/08, despite measurements at Dundas Island occurring a few days later in all these years (Table A1-3). This would be consistent with pups at Dundas Island being relatively small across the last 10 or so years. Also, there was a general lack of correspondence, comparing rookeries, in the periods in which males were comparatively larger than females, e.g., males were relatively heavy at Dundas Island from 2004/05 to 2009/10, when they were relatively small at Sandy Bay (Table A1-3, Figure A1-5). Sampling was too sporadic to assess for changes in comparative male and female length at any rookery (Figure A1-6).

Summary plots of measured mass and length with respect to date of measurement are shown for both sexes at each rookery in Figure A1-7 and Figure A1-8. A non-linear trend is apparent from the plots for Sandy Bay (top two plots of each figure), which has the greatest coverage of sampling by date. The plots of the other rookeries indicate that the coverage of dates with measurements is insufficient for the robust estimation of growth separately for these rookeries. Plots of size with date of measurement are shown separately for individuals with repeat measurements within a season (Figure 2 and Figure 3). These confirm the non-linear shape of growth in terms of mass and length and indicate that the gain in mass is minimal around the pupping period.

In terms of AIC, a non-linear model was optimal for deriving BCI for individual sea lions; this had the equation mass ~ $0.000287 * \text{length}^{2.429}$ (model AIC of 10 364.7, compared with 10 393.7 for the linear model). The model fits to the data were reasonably good, with no evidence for a trend in residuals with increasing length (Figure A1-9). Plots of BCI by year and day are shown in Figure A1-10, and Figure A1-11 shows BCI by sample date for individuals with repeat measurements within a season. These plots suggest that BCI increased with sample date in some seasons (e.g., 2002/03) but not others (e.g., 1999/2000).

3.2 Standardised pup mass and condition time series

The optimal model for producing standardised pup mass indices included: year, day of the year (before/after 26 December — the date of peak pupping), interaction terms between year and sex (difference between male and female pup mass) as well as day of the year and sex (sex differences in growth rate), and a normal random slope relating to the response to day of the year for each sea lion (individual variability in growth rate). The optimal model structure ('mgam1') produced a model AIC of 30 units below that of the next best model ('mgam2') and explained 92.5% of the total deviance (Table 1). The quantile-quantile plots for the optimal model (Figure A2-1) and the random effect (Figure A2-2, right) indicate that the assumption of a normal error structure was met in both cases. A good model fit was obtained to observed pup mass, in both males and females (Figure A2-3). A curvilinear relationship was obtained in the response of pup mass to day of the year, with slower growth (in terms of pup mass gain per day) prior to an inflection point around 25th January (i.e., approximately one month after the date of peak pupping) (Figure A2-2, left). There was no apparent trend in the residuals with respect to year or day (Figure A2-3).

The optimal model produced two pup mass time series:

- 1. An index of female pup mass, presented as kilograms relative to the minimum annual estimate (of 13.61 kg in 1996); and
- 2. An index of male minus female pup mass (also in relative kilograms).

High inter-annual variability and temporal trends were obtained in both time series (Figure 4). The period from 1980 to 1993 was characterised by relatively high female pup mass (annual averages ranging from 1.12–3.62 kg greater than the annual minimum). This was followed by a period of alternating low (even years) and moderate estimates (odd years) from 1995 to 2004, then a period of building pup mass from 2004 to 2010, followed by decline (2010–2015), then increase up to the final year (2015–2019).

The temporal pattern in the difference between male and female pup mass was not so pronounced (Figure 4, middle). The years in which male pup mass estimates were closest to that of females were all in the period since 2008 (2008, 2009, 2016, and 2018) (also see the right-hand column of Table A2-1).



Figure 2: Individual growth in terms of <u>mass</u> of New Zealand sea lion pups at Sandy Bay, Auckland Islands, for which multiple measurements were made within a field season. Females are shown on the top row and males on the bottom row; a different colour is used for each individual.



Figure 3: Individual growth in terms of <u>standard length</u> of New Zealand sea lion pups at Sandy Bay, Auckland Islands, for which multiple measurements were made within a field season. Females are shown on the top row and males on the bottom row; a different colour is used for each individual.

The optimal model ('bgam2') for estimating the standardised time series of body condition index included: year, and a normal random slope relating to the response to date of measurement for each sea lion (representing individual variability in the change in body condition index through time). This model

explained 74.8% of the total deviance (Table 2). The quantile-quantile plots for the optimal model indicated a slightly heavy-tailed distribution (Figure A2-5) (a model using the scaled *t* distribution was trialled, though convergence issues were experienced). The analogous plot of the random effect (Figure A2-6) indicated that the assumption of a normal error structure was met. No trends in the residuals were detected for this model (Figure A2-7).

The standardised series of annual estimates obtained from the body condition model indicated a drop in female BCI between the early to mid-1980s (around 2–3 BCI units, indicating that a pup of corresponding length was then 2–3 kg lighter), which then remained close to or slightly below the average BCI until the present day (Figure 4, bottom). The drop in BCI was driven by a decrease in mass (comparing years) without a corresponding decrease in the standard length of the sample population (Table A1-3 and Table A1-4). Conversely, the drop in pup mass after 1993 was accompanied by a drop in standard length, so that body condition did not alter appreciably (pups decreased in size, though maintained the same level of condition) (Table A1-3 and Table A1-4).

Table 1:Summary of candidate models for estimating a standardised time series of annual mass for New
Zealand sea lion pups at Sandy Bay, Auckland Islands. Model terms are labelled as follows:
'mass' = measured pup mass, 'year' = field season end year of measurement (e.g., 2014/15 =
2015), 'sex' = sex of measured pup, 'day' = day of the year (relative to 26st Dec), 'ID' = unique
identifier of measured pup. A random slope for day of the year was estimated for each sea lion
pup. Models are ranked in ascending order of model AIC, with the optimal model ('mgam1')
at the top.

Model label	Model structure	d.f.	Deviance explained	AIC	d-AIC
mgam1	$mass \sim year + year:sex + s(day) + day:sex + s(ID day)$	3 720.5	92.5%	29 183.2	0.0
mgam2	mass ~ year + year:sex + $s(day) + s(ID day)$	3 714.2	92.5%	29 212.8	29.6
mgam4	mass ~ year + s(day) + day:sex + s(ID day)	3 641.5	92.1%	29 473.4	290.2
mgam5	mass ~ year + $s(day) + s(ID day)$	3 857.4	92.4%	29 517.9	334.7
mgam3	mass ~ year + year:sex + $s(ID day)$	3 951.6	91.0%	31 150.1	1 966.9
mgam6	mass ~ year + $s(ID day)$	4 042.4	91.0%	31 323.3	2 140.2

Table 2:Summary of candidate models for estimating a standardised time series of annual body
condition index for female New Zealand sea lion pups at Sandy Bay, Auckland Islands. Model
terms are labelled as follows: 'mass' = measured pup mass, 'year' = field season end year of
measurement (e.g., 2014/15 = 2015), 'day' = day of the year (relative to 26st Dec), 'ID' = unique
identifier of measured pup. A random slope for day of the year was estimated for each sea lion
pup. Models are ranked in ascending order of model AIC, with the optimal model ('bgam2') at
the top.

Model label	Model structure	d.f.	Deviance explained	AIC	d-AIC
bgam2	mass ~ year + $s(ID day)$	671.9	74.8%	6 096.6	0.0
bgam1	mass ~ year + $s(day) + s(ID day)$	644.1	74.0%	6 097.5	0.9







Year



Figure 4: Standardised time series indices of female mass (top), male minus female mass (middle), and female body condition index (bottom) of New Zealand sea lion pups measured at Sandy Bay, Auckland Islands. Pup mass estimates were predicted by model 'mgam1', and the body condition index was predicted by model 'bgam2'. The female pup mass index was rescaled to be relative to the 1996 estimates, which was the minimum for any year. Points are model estimates for each year, bars are 95% confidence intervals. Horizontal dashed lines are shown to facilitate the visual comparison of estimates between years.

3.3 Relating pup biometrics and demographic rates

3.3.1 Annual pup biometrics and demographic rates (Approach 1)

All parameter estimates from the 'full' demographic model, with year-varying first-year survival and annual pupping rate are shown in Table A3-2. As with previous assessments using other versions of this model (Roberts & Doonan 2016), the estimated probability of surviving the first year was higher for all cohorts born in 1990 to 1993 (all > 0.7) than in all subsequent years (all < 0.6). Annual estimates of pupping probability were obtained for the years 1999 to 2019 and were generally higher at the beginning and end of this time series.

Both female pup mass (Pearson product-moment correlation, r = 0.72, p < 0.001, df = 20) and female body condition index (r = 0.69, p < 0.05, df = 8) were significantly positively correlated with the firstyear survival of females. Male minus female pup mass was also positively correlated with annual pupping rate (r = 0.59, p < 0.01, df = 17). None of the other assessed pup size/condition and demographic rate pairings were found to be significantly correlated (Figure 5).





3.3.2 Life history contingent on pup mass (Approach 2)

The class boundaries used to delineate individuals into 'light', 'intermediate', and 'heavy' pups was designed to give approximately equal numbers of pups in each category. This was achieved using 11 kg as a maximum to delineate light from intermediate mass pups, and 13 kg as the minimum to delineate heavy pups (Figure 6). This resulted in 586, 1045, and 290 pups in 'light', 'intermediate', and 'heavy' mass categories that could be linked to a mark ID and were fitted to by the 'simple' demographic assessment model, and were used to estimate demographic rates contingent on pup mass (Table A3-3).



Figure 6: Distribution of model predicted female New Zealand sea lion pup mass on January 16 across all years (model run 'gam1'). Red lines delineate 'light', 'intermediate', and 'heavy' pup mass categories used in the exploration of demographic rates contingent on pup mass category.

Mixing was good for all MCMC model runs, based on the visual inspection of trace plots (Figure A3-1). The precision of all demographic rate estimates was poor, such that only a very strong effect of pup mass would have resulted in non-overlapping credible intervals. Even so, the MCMC run estimates were similar for all estimated life parameters, including first-year (pup) survival (*Surv*₀) for all year-ranges (1990–93, 1998–2005, and 2006–18), annual pupping rate (*Pr*_P), and relative pupping rate at ages 4 and 5 (*Mat*₄ and *Mat*₅, respectively).

Focusing on pup survival, the expected increase with increasing pup mass category was observed for the 1990–1993 cohorts only, though with majorly overlapping 95% credible intervals. The 2006–2018 pup mass estimate was best informed by the data (based on precision) and produced near-identical estimates for all three mass categories (median estimate of 0.35 for all mass categories) (Table 3).

Annual pupping rate was the best-informed breeding parameter and was remarkably consistent across the three pup mass categories (median estimates ranged from 0.75 to 0.77). The precision of relative breeding rate estimates at ages 4 and 5 were too low to say anything about the effects of mass, although there do not appear to be any future breeding advantages associated with being heavy.

Table 3:Median and 95% credible intervals of MCMC runs of demographic models fitted to subsets of
light, intermediate and heavy pups. ' $Surv_0$ ' = first year survival within a year block (e.g., $Surv_0$
= first year survival in 1990-1993); ' Mat_4 ' and ' Mat_5 ' = relative pupping rate ages 4 and 5,
respectively; and ' Pr_P ' = annual pupping rate.

_		First-year surviva	al by year block	Relative puppin	ig ages 4 and 5	Annual pupping
Pup mass	<i>Surv</i> 0 ₉₀₋₉₃	Surv0 ₉₈₋₀₅	<i>Surv</i> 0 ₀₆₋₁₈	Mat ₄	Mat ₅	$Pr_{\rm P}$
-	0.87 (0.71 -	0.35 (0.17 -	0.35 (0.24 -	0.11 (0.02 -	0.31 (0.10 -	0.75 (0.69 -
Heavy	0.98)	0.58)	0.48)	0.33)	0.64)	0.81)
Tata and a diata	0.84 (0.72 -	0.44 (0.34 -	0.35 (0.29 -	0.17 (0.08 -	0.66 (0.51 -	0.75 (0.71 -
Intermediate	0.96)	0.54)	0.42)	0.29)	0.83)	0.79)
T : -1-4	0.77 (0.52 -	0.39 (0.29 -	0.33 (0.25 -	0.09 (0.03 -	0.40 (0.22 -	0.77 (0.69 -
Light	0.97)	0.49)	0.42)	0.22)	0.60)	0.84)

4. DISCUSSION

4.1 Limitations of analysis

The standardisation of pup measurements does not account for any potential change in the precision in measurements that might have occurred through time. This is unlikely to be an issue when comparing estimates since 1994/95, when methods were highly standardised though time, though any bias could affect comparability with earlier measurements. Based on the description of field methods, the approach to measuring pups appears consistent before and since 1994/95 (the authors led the field team in a number of years in the pre and post 1994/95 periods). However, the approach to selecting pups was different: prior to 1994/95 an attempt was made to measure all pups at Sandy Bay, and, since then, has been based on a random sample of 50 pups of each sex. This difference would only affect comparability if the sampling in the later period was in fact not completely random, e.g., the sample contained a greater proportion of smaller pups (e.g., Trites 1993), or more gregarious pups were selected. No attempt was made to estimate or reconcile any bias associated with field methods that may affect comparability.

Pup mass and condition estimates were primarily standardised for between-season variability in the date of measurement, which was likely to be the main potential source of bias affecting comparability, due to the rapid growth of pups (Trites 1993). This was achieved by estimating the daily growth of individual pups (represented by the 'day' parameter used in optimal models) (Table 1 and Table 2). The non-linear shape of New Zealand sea lion mass gain following birth, as reported by Chilvers et al. (2007), was represented by a curved spline which was assumed to be the same for all years (Figure A2-2). This is largely dependent on repeat measurements of an individual (within a season), because daily growth could otherwise be confounded with inter-annual variation in pup mass by date. Repeat measurements were made in 1983/84, 1991/92, and 1998/98 to 2002/03, and growth rates comparing years appear similar from visual inspection (Figure 2), though growth rate was not estimated separately for each year.

Repeat measurements were much too sparse at Dundas Island, the largest breeding rookery for the species, to estimate growth here with any confidence. This is a limitation for standardising pup mass and condition observation at this rookery, given changes in the date of measurement at this rookery, and the lack of information about relative growth rate compared with Sandy Bay. There are also few years of pup size information from Figure of Eight Island; this rookery appears to have a different pup production trajectory through time, compared with Sandy Bay and Dundas Island (DOC 2019).

4.2 Changing pup size and condition through time

Standardised pup mass and body condition estimates were only produced for the best-studied Sandy Bay rookery, for which rookery-specific individual growth in mass or body condition could be estimated. Contrary to the findings of Chilvers (2012), this analysis obtained considerable variability in the mass of pups in a comparison of cohorts, and evidence for trends through time (Figure 4). Female pup mass was estimated to be highest at the beginning of the time series (from 1979/80 to 1992/93) before reaching a low in 1995/96 and then going through phases of increase (until 2009/10), decline (until 2014/15), and then another period of increasing mass through to the final year (2018/19). A broadly similar temporal pattern was estimated for first-year survival (see Table A3-2). The complexity of this pattern indicates that the positive correlation with pup mass (Figure 5) was not due to chance.

Strong temporal patterns were also observed in male minus female mass and body condition index that were not well-correlated with the female mass time series. The abrupt drop in body condition since the early 1980s is more extreme than the drop in female pup mass through the same time period (Figure 4). The continued collection of length data would allow a more robust assessment of relationships of body condition with pup survival and other demographic rates than is currently possible (Figure 5), although female mass may be an adequate predictor of first-year survival and is available over a longer time period.

4.3 Pup size effects on life history

The demographic consequences of variable pup mass and condition in sea lion and fur seal species (otariids) are perhaps better understood than the underlying causes. This is likely to be because the life histories of marked individuals can be monitored in the months and years after measurement. Whereas, the potential causes, e.g., disease or changes in maternal nutrition (which could also have multiple drivers) are more complex and difficult to monitor.

Positive correlations have been obtained between the relative pup mass or body condition and first-year survival in multiple pinniped species (Craig & Ragen 1999, DeLong et al. 2017, Hastings et al. 2011, Maniscalco 2014). The bio-demographic assessment developed by Edwards & Roberts (2021) also obtained a positive relationship between mass of female New Zealand sea lion pups at the Auckland Islands and estimates of first-year survival, from a comparison of annual estimates (cohorts). Notably, pups born on the Otago Coast of New Zealand tend to be larger for a given age and have relatively high rates of first-year survival (Augé 2010, Roberts & Doonan 2016).

This analysis corroborated this relationship when comparing cohorts, although this relationship was not evident on an individual basis (i.e., comparing the demographic histories of light versus heavy pups, across cohorts). The potential causes of this apparent contradiction are not known. For example, the extent to which any benefits conferred from elevated pup mass are confounded with disease is not understood. Infection with the bacterium *Klebsiella pneumoniae* caused ~ 60% of pup deaths during the field season at Enderby Island from 2013 and 2018 (Michael et al. 2019, Roe et al. 2015). However, preliminary blubber depth data up to the 2014 field season indicated that pups dying from *Klebsiella* infection were in comparatively good condition relative to pups dying from other causes (preliminary data from W. Roe, unpublished, Fisheries New Zealand 2020). This is a potential mechanism by which the life history benefits of high pup mass and condition might be negated on an individual level, although cohort-level effects might also be expected.

The subsequent breeding rates of light and heavy pups were remarkably similar (Table 3). This suggests that any advantages associated with high pup mass are dissipated with age. DeLong et al. (2017) found that the survival of California sea lion (*Zalophus californianus*) cohorts after age one depended as much on timing relative to major climate oscillations as cohort-specific pup mass. However, this study found evidence that the annual breeding rate of New Zealand sea lions at the Auckland Islands was positively correlated with male minus female pup mass. Although this does not point to a demographic consequence of pup mass, it does indicate that this quantity might be informative of annual pupping rate.

4.4 Causes of variable pup size and condition

Potential causes of variable pinniped pup mass and condition include:

- Changes in the mean date of pupping relative to the date of measurement (Reijnders et al. 2010);
- Changes in the size and age composition of breeding females (Arnbom et al. 1994); and
- Changes in maternal mass, nutritional status, and prey availability (Arnbom et al. 1994, Harding et al. 2018, Kauhala et al. 2017).

A previous analysis by Chilvers (2012) found no evidence for any long-term shift in the mean date of pupping at Sandy Bay, with mean birth date always falling either on 26, 27, or 28 December. However, this analysis was limited to the period from 1998 to 2010. Based on the exploration of daily pup counts since the early 1980s (Department of Conservation, unpublished data), there was some evidence of temporal variability in the timing of pupping, though no long-term trends that could explain the patterns in estimated pup mass and condition indices.

Differential investment in male and female pups has been observed in a number of pinniped species, evidenced by changes in birth sex ratio, and the relative growth rates of male and female pups (Arnbom et al. 1994; Bradshaw et al. 2003). This can be driven by changes in prey availability impacting on maternal nutrition, or changes in the age structure of breeding females, where relatively fewer male births and slower-growing male pups are symptomatic of adverse maternal nutritional status or a younger breeding population (Bradshaw et al. 2003). For New Zealand sea lions at Sandy Bay, the relatively strong cohort born in 1990–1993 (see Table A3-2) will have matured by around the year 2000 and become a relatively dominant component of the breeding population in subsequent years. As such, changes in breeding female age structure are a plausible driver of trends in pup mass indices through time. If this was the case, then the very different patterns observed at Sandy Bay and Dundas Island would be indicative of differing age structure of the two largest breeding rookeries at the Auckland Islands (Figure A1-5). This was corroborated by the analysis of age composition of lactating females at these rookeries (Childerhouse et al. 2010).

All sea lion and fur seal species are income breeders, such that their offspring are dependent on the mother for their nutrition for a protracted period – typically at least ten months for New Zealand sea lions (Gales 1995). A study of lactating New Zealand sea lions at Sandy Bay found that milk lipid content declined with decreasing maternal mass and BCI (Riet-Sapriza et al. 2012). Furthermore, dietary studies of sea lions at the Auckland Islands and associated prey species have found evidence for long-term shifts in diet composition that could be driven by changes in prey availability through time (Roberts et al. 2018, Stewart-Sinclair 2013). As such, variable pup mass could plausibly be driven by changes in maternal nutrition, though this relationship remains untested.

Variability in New Zealand sea lion pup condition has anecdotally been observed when comparing colonial versus non-colonial pups. Non-colonial 'bush' pups were noted to be larger at both the Auckland Islands and Campbell Island and may have been more common in the early years of field work at the Auckland Islands (unpublished observations of Martin Cawthorn and Andy Maloney). As such, population-level variability in pup mass through time could possibly be driven by changes in the proportions of colonial versus non-colonial pups. Possible mechanisms for this include changes in breeding population size, as well as changes in terrestrial habitat or habitat use by breeding females though time.

5. IMPLICATIONS FOR MANAGEMENT

The primary conclusions of this research are as follows:

- Strong temporal patterns were obtained in female pup mass, the difference between male and female pup mass, and in body condition through the past 40 years at the Sandy Bay rookery. The patterns were different for each index.
- Pup mass and potentially body condition index at Sandy Bay were positively correlated with first-year survival at the cohort level (i.e., comparing annual estimates). The relationship with pup mass was corroborated by demographic assessment modelling by Edwards & Roberts (2021), which used the outputs of this analysis.
- Male minus female mass appears to be positively correlated with annual pupping rate, e.g., males were not much bigger than females in years with anomalously low pupping rate.
- Biometric measurements of marked pups are sparse for estimating potential differences in the demographic rates of heavy versus light pups. However, it appears that the relationship between pup mass and survival might be stronger at the cohort level rather than at the level of the individual. The reasons for this are not understood, though it is suspected that the relationship between pup mass and survival might be confounded with other processes, e.g., relating to the ongoing, endemic infection and mortality of pups from *Klebsiella pneumonia*, which appears to kill light and heavy pups.

• The sparsity of repeat measurements at Dundas Island (the largest rookery) precluded a robust standardisation of pup mass for this rookery. Pups measured here were consistently smaller than Sandy Bay pups in recent years, despite being measured a few days later in the season.

The implications for management are as follows:

- Pup mass appears to be a useful covariate of first year-survival. If collected in a standardised way, or with sufficient coverage to allow for standardisation, pup mass may have utility for predicting cohort survival years in advance of mark-recapture observations being informative.
- The difference between male and female mass may also have utility for predicting annual breeding rate. It is suspected that this will also relate to changes in sex ratio at birth, although this was not assessed.
- Resighting levels of pups already marked at Dundas Island and Figure or Eight Island are likely to be too sparse to assess the strength of the pup mass and survival relationship at the other Auckland Islands rookeries, which may have contrasting population trajectories through time.
- Although not explored by this assessment, strong year-trends were identified in pup mass and condition that may relate to external processes e.g., variable maternal nutrition, climate, or disease prevalence. If a mechanistic relationship between pup mass and first year survival is established, then we may be able to assess the population effects of any identified driver(s) via first-year survival.

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APPENDIX 1: CHARACTERISATION OF PUP BIOMETRIC DATA SUPPLEMENTARY OUTPUTS

Table A1-1: Sample size of Auckland Islands New Zealand sea lion pups for which a <u>mass</u> measurement was taken, by field season and rookery. Counts of pups with multiple measurements within a field season are shown in parentheses.

_				Rookery
		Southeast	Dundas	Figure of
Field season	Sandy Bay	Point	Island	Eight Island
1979/80	176 (1)	-	_	_
1980/81	333	_	_	_
1981/82	336	_	_	_
1982/83	_	_	_	_
1983/84	351 (151)	_	_	_
1984/85	149	_	_	_
1985/86	73	_	_	_
1986/87	_	_	_	_
1987/88	_	_	_	_
1988/89	_	_	_	_
1989/90	311	7	_	_
1990/91	366 (8)	4	102	_
1991/92	467 (95)	21	33	_
1992/93	200	24	_	_
1993/94	_	_	_	_
1994/95	100	_	_	_
1995/96	100	_	_	_
1996/97	100	_	_	_
1997/98	110	_	-	_
1998/99	163 (22)	_	228 (14)	_
1999/00	505 (82)	14 (14)	238 (12)	_
2000/01	123 (20)	3 (3)	102	_
2001/02	137 (37)	_	_	_
2002/03	142 (47)	_	_	_
2003/04	101	39	100	_
2004/05	140 (1)	_	100	_
2005/06	100	_	100	_
2006/07	100	_	98	_
2007/08	100	_	100	_
2008/09	100	_	100	_
2009/10	100	_	102	_
2010/11	100	_	_	_
2011/12	100	_	101	_
2012/13	100	_	100	_
2013/14	102	_	103	_
2014/15	101	_	101	40
2015/16	90	_	100	49
2016/17	139	_	100	47
2017/18	100	_	100	_
2018/19	101	_	100	_

Table A1-2: Sample size of Auckland Islands New Zealand sea lion pups for which a <u>standard length</u> measurement was taken, by field season and rookery. Counts of pups with multiple measurements within a field season are shown in parentheses.

				Rookery
		Southeast	Dundas	Figure of
Season	Sandy Bay	Point	Island	Eight Island
1979/80	176 (1)	_	_	_
1980/81	333	—	_	—
1981/82	335	_	_	_
1982/83	_	_	_	_
1983/84	348	_	_	_
1984/85	149	_	_	_
1985/86	72	_	_	-
1986/87	_	_	_	38
1987/88	_	_	_	_
1988/89	_	_	_	_
1989/90	312	7	_	_
1990/91	366 (8)	4	196	23
1991/92	466 (1)	21	33	_
1992/93	395	24	_	_
1993/94	_	_	_	_
1994/95	_	_	_	_
1995/96	_	_	_	_
1996/97	_	_	_	_
1997/98	_	_	_	_
1998/99	_	_	_	_
1999/00	55 (37)	14 (14)	_	_
2000/01	116 (20)	3 (3)	_	_
2001/02	36 (25)	_	_	_
2002/03	47 (47)	_	_	_
2003/04	_	_	_	_
2004/05	45	_	_	_
2005/06	_	_	_	_
2006/07	_	_	_	_
2007/08	_	_	_	_
2008/09	_	_	_	_
2009/10	_	_	_	_
2010/11	_	_	_	_
2011/12	_	_	_	_
2012/13	_	_	_	_
2013/14	_	_	_	_
2014/15	_	_	_	_
2015/16	90	_	100	_
2016/17	139	_	100	47
2017/18	100	_	100	_
2018/19	102	_	100	_

Table A1-3: Mean (unstandardised) mass of New Zealand sea lion pups by rookery, year and sex. 'F'
denoted females, 'M' males, and 'M - F' is the mean for males minus the mean for females. A blank row
delineates contiguous year blocks with estimates. These values are from measurements taken at the time of
tagging (i.e., excluding longitudinal growth studies) in order to aid comparability.

											R	ookery
		San	dy Bay	S	outheas	st Point		Ι	<u>)undas</u>	Fi	igure of	f Eight
Season	F	Μ	M - F	F	Μ	M - F	F	Μ	M - F	F	Μ	M - F
1979/80	14.77	16.37	1.60	_	_	_	_	_	_	_	_	-
1980/81	15.08	16.60	1.52	_	_	_	_	_	_	_	_	-
1981/82	13.39	15.22	1.83	_	_	_	_	_	_	_	_	_
1982/83	_	_	_	_	_	_	_	_	_	_	_	_
1983/84	13.40	15.09	1.70	_	_	_	_	_	_	_	_	_
1984/85	12.62	14.62	2.00	_	_	_	_	_	_	_	_	_
1985/86	10.98	12.40	1.42	_	_	-	_	_	_	-	_	_
1989/90	10.72	11.61	0.89	*	*	*	_	_	_	_	_	_
1990/91	12.31	13.22	0.91	*	*	*	15.59	17.66	2.07	_	_	_
1991/92	12.78	14.61	1.83	*	13.94	*	14.75	15.91	1.16	_	_	_
1992/93	11.81	13.15	1.34	12.00	13.09	1.09	_	_	_	_	_	_
1993/94	_	_	_	_	_	_	_	_	_	_	_	_
1994/95	11.69	12.89	1.21	_	_	_	_	_	_	_	_	_
1995/96	10.30	11.92	1.62	_	_	_	_	_	_	_	_	_
1996/97	11.29	12.89	1.60	_	_	_	_	_	_	_	_	_
1997/98	10.44	12.01	1.57	_	_	_	_	_	_	_	_	_
1998/99	11.72	13.53	1.81	_	_	_	11.67	12.63	0.96	_	_	_
1999/00	10.74	12.30	1.56	_	_	_	_	_	_	_	_	_
2000/01	11.18	12.84	1.66	_	_	_	11.51	12.87	1.36	_	_	_
2001/02	10.52	11.40	0.89	_	_	_	_	_	_	_	_	-
2002/03	11.22	12.34	1.12	_	-	_	_	-	_	_	_	-
2003/04	11.05	12.51	1.45	10.99	11.94	0.95	11.18	12.33	1.15	_	_	-
2004/05	11.34	12.39	1.05	_	_	_	11.66	13.99	2.33	_	_	-
2005/06	11.36	12.32	0.96	_	_	_	11.06	12.59	1.53	_	_	_
2006/07	11.72	12.89	1.18	_	_	_	12.27	13.89	1.62	_	_	_
2007/08	12.07	12.71	0.65	_	_	_	11.56	13.35	1.79	_	_	_
2008/09	11.71	12.03	0.32	_	_	_	11.37	13.25	1.88	_	_	_
2009/10	12.42	13.67	1.25	_	-	_	11.66	13.33	1.67	_	_	-
2010/11	12.10	13.10	1.00	_	_	_	_	_	_	_	_	_
2011/12	11.93	13.08	1.15	_	_	_	11.40	12.79	1.39	_	_	_
2012/13	11.73	13.23	1.49	_	_	_	11.10	11.97	0.87	_	_	_
2013/14	11.09	12.59	1.51	_	_	_	10.17	11.61	1.44	_	_	_
2014/15	10.59	12.05	1.46	_	_	_	11.42	12.27	0.85	10.43	11.72	1.28
2015/16	11.74	12.48	0.73	_	_	_	10.00	11.29	1.30	10.18	10.97	0.79
2016/17	11.29	12.99	1.70	_	_	_	11.09	11.98	0.88	12.14	13.43	1.29
2017/18	11.78	12.32	0.54	_	_	_	10.82	12.38	1.55	_	_	_
2018/19	12.24	13.82	1.58	_	_	_	12.11	13.87	1.77	_	_	_

* Mean not shown where based on fewer than 10 measurements

Table A1-4: Mean (unstandardised) <u>standard length</u> of New Zealand sea lion pups at the time of tagging, by rookery, year and sex. 'F' denoted females, 'M' males, and 'M - F' is the mean for males minus the mean for females. Blank rows delineate contiguous year blocks with estimates. These values are from measurements taken at the time of tagging (i.e., excluding longitudinal growth studies) in order to aid comparability.

											R	ookery
		San	dy Bay	S	outheas	st Point		Ι	Dundas	F	igure o	f Eight
Season	F	Μ	M - F	F	Μ	M - F	F	Μ	M - F	F	Μ	M - F
1979/80	81.35	83.20	1.84	_	_	_	_	_	_	_	_	_
1980/81	82.22	83.48	1.26	_	_	_	_	_	_	_	_	_
1981/82	82.25	85.18	2.93	_	_	_	_	_	_	_	_	_
1983/84	80.11	82.76	2.66	_	_	_	_	_	_	_	_	_
1984/85	82.30	85.85	3.55	_	_	_	_	_	_	_	_	_
1985/86	79.40	81.26	1.86	_	_	_	_	_	_	_	_	_
1986/87	87.49	91.46	3.96	_	_	_	_	_	_	76.55	80.50	3.95
1989/90	77.39	79.33	1.94	*	*	*	_	_	_	_	_	_
1990/91	79.94	81.64	1.70	*	*	*	87.44	88.78	1.34	_	_	_
1991/92	83.83	86.90	3.07	*	87.06	*	88.69	90.94	2.25	77.86	*	*
1992/93	81.36	83.52	2.16	80.15	83.09	2.94	_	_	_	_	_	_
2000/01	79.12	83.09	3.97	_	_	_	_	_	_	_	_	_
2004/05	83.28	85.50	2.22	_	_	_	_	_	_	_	_	_
2015/16	80.16	81.73	1.57	_	_	_	79.35	82.35	2.99	_	_	_
2016/17	79.36	82.71	3.35	_	_	_	80.82	83.52	2.70	80.75	84.61	3.86
2017/18	80.24	81.92	1.68	_	_	_	79.38	82.26	2.88	_	_	_
2018/19	79.90	81.55	1.65	_	-	_	77.36	80.94	3.58	_	_	_

* Mean not shown where based on fewer than 10 measurements

_							Re	ookery
_	San	dy Bay_	Southeast	t Point	D	undas	Figure of	f Eight
Season	BCI	N	BCI	N	BCI	N	BCI	N
1979/80	2.18	84	_	_	_	_	_	_
1980/81	2.14	156	_	_	_	_	_	_
1981/82	0.44	153	_	-	_	_	_	_
1983/84	1.26	170	_	_	_	_	_	_
1984/85	-0.34	50	_	_	_	_	_	_
1985/86	-0.95	30	_	_	_	_	_	_
1989/90	-0.43	141	*	6	_	_	_	_
1990/91	0.21	190	*	1	0.61	37	_	_
1991/92	-0.78	242	*	5	-0.79	16	_	_
1992/93	-0.47	84	-0.15	13	_	_	_	_
1999/00	-0.99	87	-0.87	45	_	_	_	_
2000/01	-0.93	116	*	6	_	_	_	_
2001/02	-0.48	44	_	_	_	_	_	_
2002/03	0.58	52	_	_	_	_	_	_
2004/05	-1.52	25	_	_	_	_	_	_
2015/16	-0.38	50	_	_	-1.85	48	_	_
2016/17	-0.55	72	_	_	-1.29	50	-0.24	28
2017/18	-0.4	50	_	_	-1.05	50	_	_
2018/19	0.21	51	_	_	0.97	50	_	_

Table A1-5: Mean (unstandardised) <u>body condition index (BCI)</u> and associated samples size (N) of female New Zealand sea lion pups at the Auckland Islands, by rookery and field season. Blank rows delineate contiguous year blocks with estimates.

* Mean not shown where based on fewer than 10 measurements



Figure A1-1: Boxplots showing the distribution of the date of <u>mass</u> measurements (relative to 26 December, the approximate date of peak pupping; highlighted wish horizontal dashed lines) by year and rookery.



Figure A1-2: Boxplots showing the distribution of the <u>date</u> of <u>standard length</u> measurements (relative to 26 December, the approximate date of peak pupping; highlighted wish horizontal dashed lines) by year and rookery.



Figure A1-3: Boxplots of individual <u>mass</u> by <u>field season of measurement</u> (end year of a field season is displayed, e.g. 2017/18 = '2018') for female (left, red boxes) and male (right, blue boxes) New Zealand sea lion pups at Auckland Islands rookeries (from top to bottom).



Figure A1-4: Boxplots of individual <u>standard length</u> by <u>field season of measurement</u> (end year of a field season is displayed, e.g. 2017/18 = (2018)) for female (left, red boxes) and male (right, blue boxes) New Zealand sea lion pups at Auckland Islands rookeries (from top to bottom).



Figure A1-5: Scatterplots of mean male minus mean female <u>mass</u> of New Zealand sea lion pups at the Auckland Islands, by year and rookery. A LOESS smooth is shown for all rookeries for which the number of years with measurements was sufficient, with a smoothing span of 25%.



Figure A1-6: Scatterplots of mean male minus mean female <u>standard length</u> of New Zealand sea lion pups at the Auckland Islands, by year and rookery.



Figure A1-7: Scatterplots of individual <u>mass</u> by <u>date of measurement</u> for female (left, red points) and male (right, blue points) New Zealand sea lion pups at Auckland Islands rookeries (from top to bottom). Vertical dashed lines highlight 26 Dec (the approximate date of peak pupping) and 16 Jan at Sandy Bay only (the typical date of sea lion tagging at Sandy bay).



Figure A1-8: Scatterplots of individual <u>standard length</u> by <u>date of measurement</u> for female (left, red points) and male (right, blue points) New Zealand sea lion pups at Auckland Islands rookeries (from top to bottom). Vertical dashed lines highlight 26 Dec (the approximate date of peak pupping) and 16 Jan at Sandy Bay only (the typical date of sea lion tagging at Sandy bay).



Figure A1-9: Optimal non-linear model (red line of left-hand plot; mass ~ $0.000287 * \text{length}^{2.429}$) for predicting mass given standard length, used to calculate individual body condition index of female New Zealand sea lions at Sandy Bay, Auckland Islands. A plot of residuals with observed length using this model is shown in the right-hand plot (the unbroken line is a loess smooth fitted to the residuals, with a smoothing span of 50%).



Figure A1-10: Plots of individual <u>body condition index (BCI)</u> by <u>date of measurement</u> (left) and <u>field season</u> <u>of measurement</u> (right) (end year of a field season is displayed, e.g. 2017/18 = '2018') for female New Zealand sea lion pups at Auckland Islands rookeries (from top to bottom). Vertical dashed lines highlight 26 Dec (the approximate date of peak pupping) and 16 Jan at Sandy Bay only (the typical date of sea lion tagging at Sandy bay). All measurements above the horizontal solid line (at BCI = zero) were heavier than average for a given length, and *vice versa*.



Figure A1-11: Individual growth in terms of derived <u>body condition index</u> of female New Zealand sea lion pups at Sandy Bay, Auckland Islands, for which multiple measurements were made within a field season. A different colour is used for each individual.

APPENDIX 2: PUP MASS STANDARDISATION SUPPLEMENTARY OUTPUTS

Table A2-1: Standardised indices of female pup mass, male minus female pup mass and female body condition index of New Zealand sea lion pups at Sandy Bay, Auckland Islands. Female pup mass estimates were scaled relative to the minimum annual estimate of 13.61 kilos in 1995/96 (i.e., the difference in mass relative to that year in kilos). The other indices are absolute values (also in kilos).

Season	Female pup mass index	Male minus female mass index	Female body condition index
1979/80	2.43 (1.72 - 3.13)	0.85 (-0.04 - 1.74)	2.18 (1.81 – 2.55)
1980/81	3.62 (2.93 - 4.31)	0.94(0.34 - 1.54)	2.16 (1.71 – 2.60)
1981/82	2.08 (1.39 - 2.77)	1.15 (0.56 – 1.74)	0.48(0.04-0.93)
1982/83	-	_	_
1983/84	2.69 (2.03 - 3.35)	1.28(0.82 - 1.74)	1.15 (0.73 – 1.58)
1984/85	2.32 (1.53 - 3.11)	1.55 (0.86 – 2.24)	-0.34 (-0.87 – 0.19)
1985/86	1.12 (0.27 - 1.97)	1.09(0.27 - 1.91)	-0.94 (-1.530.35)
1986/87	-	_	_
1987/88	_	_	_
1988/89	_	_	-
1989/90	1.23 (0.57 - 1.89)	0.58(0.20-0.97)	-0.43 (-0.850.01)
1990/91	1.75 (1.10 – 2.40)	0.41 (-0.07 - 0.89)	0.19 (-0.23 – 0.61)
1991/92	2.32 (1.69 - 2.96)	1.33 (0.91 – 1.76)	-0.75 (-1.160.34)
1992/93	2.45 (1.76 - 3.14)	1.16 (0.73 – 1.59)	-0.50(-0.95-0.05)
1993/94	_	_	_
1994/95	1.39 (0.60 - 2.18)	0.76 (-0.03 - 1.54)	-
1995/96	0.00(-0.79-0.79)	$1.17\ (0.39 - 1.95)$	_
1996/97	0.99(0.20 - 1.78)	1.15 (0.37 – 1.93)	-
1997/98	0.24 (-0.53 - 1.01)	1.10(0.36 - 1.83)	-
1998/99	1.49 (0.74 - 2.24)	1.58 (0.90 – 2.26)	_
1999/00	1.06 (0.41 - 1.70)	0.92(0.55 - 1.30)	-1.46 (-1.950.97)
2000/01	1.45 (0.77 – 2.13)	0.43(0.02 - 0.84)	-1.02 (-1.460.57)
2001/02	0.61 (-0.07 - 1.29)	0.55(0.15-0.95)	-0.60 (-1.180.02)
2002/03	1.30 (0.64 - 1.97)	$1.15\ (0.85 - 1.44)$	-0.33 (-0.87 - 0.20)
2003/04	$0.88\ (0.10 - 1.67)$	1.02(0.27 - 1.78)	_
2004/05	1.03 (0.30 - 1.76)	0.66 (-0.01 - 1.33)	-1.52 (-2.170.87)
2005/06	1.06 (0.27 - 1.85)	0.51 (-0.27 - 1.29)	_
2006/07	1.42 (0.63 - 2.21)	0.73 (-0.06 - 1.51)	-
2007/08	1.77 (0.98 - 2.56)	0.20(-0.59-0.98)	_
2008/09	1.41 (0.62 - 2.20)	-0.13 (-0.92 - 0.65)	-
2009/10	2.12 (1.33 - 2.91)	0.80(0.02 - 1.58)	_
2010/11	1.80 (1.01 - 2.59)	0.55 (-0.23 – 1.33)	-
2011/12	1.63 (0.84 - 2.42)	0.70 (-0.08 - 1.49)	_
2012/13	1.17 (0.36 - 1.98)	1.00(0.17 - 1.83)	_
2013/14	$0.79\ (0.00 - 1.57)$	1.06(0.28 - 1.83)	_
2014/15	0.29 (-0.49 - 1.08)	1.01 (0.23 – 1.79)	-
2015/16	1.45 (0.65 - 2.24)	0.28 (-0.54 - 1.11)	-0.38 (-0.91 - 0.15)
2016/17	1.01 (0.28 - 1.75)	1.25 (0.58 - 1.92)	-0.55 (-1.040.07)
2017/18	1.48 (0.69 - 2.27)	0.09(-0.70-0.87)	-0.40 (-0.93 - 0.12)
2018/19	2.07 (1.29 - 2.85)	1.15(0.39 - 1.91)	0.21 (-0.31 – 0.73)



Figure A2-1: Quantile-quantile plot for optimal model ('mgam1') used to predict annual mass indices of male and female New Zealand sea lion pups at Sandy Bay, Auckland Islands.



Figure A2-2: (left) The predicted spline of mass in response to date of measurement and (right) quantilequantile plot for the individual random effect from the optimal model ('mgam1') used to predict annual mass indices of male and female New Zealand sea lion pups at Sandy Bay, Auckland Islands.



Figure A2-3: Scaled Pearson residuals for the optimal pup mass standardisation model ('mgam1') for females (left) and males (right), with respect to field season (top) and date of measurement (bottom). Points should be centred around zero (the middle dashed lines), with residual values below -2 and above 2 (lower and upper dashed lines) being considered lower or higher variation than expected by the model.



Figure A2-4: Observed (coloured points) and predicted mass (three black lines, representing average and 95% confidence intervals) of the 12 most frequently measured female (left two columns) and male pups (right two columns) in response to day of measurement, obtained from the optimal model for estimating pup mass ('mgam1'). Pup mass (in kilos) is displayed on the y-axis, and day of the year before/after 26^{th} December (the date of peak pupping) is displayed on the x-axis (i.e., days after 1^{st} Jan, so that 1^{st} Jan = 0, all subsequent days in Jan and Feb are positive, and all days in December are negative). Vertical dashed lines highlight 26 Dec (the peak pupping date), and 16 Jan (approximate date of pup tagging and measurement in a standard field season, when only one measurement is typically taken). A separate plot is shown for each sea lion, headed by the sea lion ID.



Figure A2-5: Quantile-quantile plot for the optimal model ('bgam2') used to predict annual body condition index of female New Zealand sea lion pups at Sandy Bay, Auckland Islands.



Figure A2-6: Quantile-quantile plot for the individual random effect for the optimal model ('bgam2') used to predict annual mass indices of male and female New Zealand sea lion pups at Sandy Bay, Auckland Islands.



Figure A2-7: Scaled Pearson residuals for the optimal pup body condition index standardisation model ('bgam2') for females, with respect to field season (top) and date of measurement (bottom). Points should be centred around zero (the middle dashed lines), with residual values below -2 and above 2 (lower and upper dashed lines) being considered lower or higher variation than expected by the model.

APPENDIX 3: DEMOGRAPHIC ASSESSMENT SUPPLEMENTARY TABLES AND PLOTS

 Table A3-1: Summary of all estimated model parameters from the 'full' demographic assessment model for female New Zealand sea lions at the Auckland Islands

Parameter	Description
N1990	Total number of breeders in 1990
$Surv_0$	Annual survival age 0
$Surv_1$	Annual survival age 1
$Surv_2$	Annual survival age 2–5
Surv ₆	Annual survival age 6+
Pr _P	Annual probability of pupping at age 8+
Mat_4	Probability of pupping at age 4 (multiplier of Pr_P)
Mat ₅	Probability of pupping at age 5 (multiplier of Pr_P)
Mat ₆	Probability of pupping at age 6 (multiplier of Pr_P)
Mat_7	Probability of pupping at age 7 (multiplier of Pr_P)
Res_{1-2}	Annual resighting probability at ages 1–2
Res ₃	Annual resighting probability at age 3
Res _N	Annual resighting probability of non-puppers
$Res_{P_{tag_{chip}}}$	Annual resighting probability of puppers that were not branded as pups
T_{1_0}	Annual probability of losing a single tag in the first year
T_{1_a}	Functional form parameter that gives the probability of losing 1 tag in a year (1)
<i>T</i> _{1_b}	Functional form parameter that gives the probability of losing 1 tag in a year (2)
T_2	Annual probability of losing two tags in a year

Parameter	Estimate	Parameter	Estimate	Parameter	Estimate
N_{1990}	1,831	Surv0_1990	0.719	<i>Pr</i> _{P_1990-99}	0.788
$Surv_1$	0.693	Surv0_1991	0.813		
Surv2_1990-2007	0.930	Surv0_1992	0.778		
Surv2_2008-2018	0.941	<i>Surv</i> 0_1993	0.738		
Surv _{6_1990-1999}	0.945	<i>Surv</i> _{0_1994}	0.455		
Surv6_2000-2009	0.865	Surv0_1995	0.319		
Surv6_2010-2018	0.868	Surv0_1996	0.512		
Mat ₄	0.165	Surv0_1997	0.533		
Mat ₅	0.530	Surv0_1998	0.338		
Mat_6	0.852	<i>Surv</i> _{0_1999}	0.496		
Mat ₇	0.900	Surv0_2000	0.374	<i>Pr</i> _{P_2000}	0.739
Res_{1-2}	0.092	<i>Surv</i> _{0_2001}	0.470	$Pr_{P_{2001}}$	0.749
Res ₃	0.426	Surv0_2002	0.371	<i>Pr</i> _{P_2002}	0.648
<i>Res</i> _{N_1999}	0.460	Surv0_2003	0.553	<i>Pr</i> _{P_2003}	0.731
<i>Res</i> _{N_2000-2001}	0.557	Surv0_2004	0.459	<i>Pr</i> _{P_2004}	0.759
<i>Res</i> _{N_2002-2012}	0.644	Surv0_2005	0.320	<i>Pr</i> _{P_2005}	0.637
<i>Res</i> _{N_2013}	0.429	<i>Surv</i> _{0_2006}	0.360	$Pr_{P_{2006}}$	0.636
<i>Res</i> _{N_2014-2015}	0.747	Surv0_2007	0.381	<i>Pr</i> _{P_2007}	0.691
<i>Res</i> _{N_2016}	0.673			<i>Pr</i> _{P_2008}	0.739
<i>Res</i> _{N_2017}	0.379	Surv0_2009	0.581	<i>Pr</i> _{P_2009}	0.549
<i>Res</i> _{N_2018}	0.517	<i>Surv</i> _{0_2010}	0.528	<i>Pr</i> _{P_2010}	0.647
Resp_tag_chip_1999	0.626	<i>Surv</i> _{0_2011}	0.560	$Pr_{P_{2011}}$	0.609
Resp_tag_chip_2000-2001	0.834	<i>Surv</i> 0_2012	0.515	<i>Pr</i> _{P_2012}	0.691
Resp_tag_chip_2002-2012	0.807	<i>Surv</i> _{0_2013}	0.420	$Pr_{P_{2013}}$	0.754
Resp_tag_chip_2013	0.495	<i>Surv</i> 0_2014	0.464	<i>Pr</i> _{P_2014}	0.678
Resp_tag_chip_2014-2015	0.932	<i>Surv</i> _{0_2015}	0.399	<i>Pr</i> _{P_2015}	0.708
Resp_tag_chip_2016	0.779	<i>Surv</i> _{0_2016}	0.465	$Pr_{P_{2016}}$	0.758
Resp_tag_chip_2017	0.534	<i>Surv</i> 0_2017	0.512	<i>Pr</i> _{P_2017}	0.862
Resp_tag_chip_2018	0.766	<i>Surv</i> _{0_2018}	0.489	$Pr_{P_{2018}}$	0.835
T_{1_0}	0.109			<i>Pr</i> _{P_2019}	0.768
T_{1_a}	0.035				
T_{1_b}	0.006				
T_2	0.029				

 Table A3-2: Parameter estimates from the 'full' demographic assessment model for female New Zealand sea lions at the Auckland Islands with year-varying first-year survival and pupping rate probabilities.

Table A3-3: Number of female sea lion pups with mass measurement by mass category ('Light' = less than 11 kg, 'Heavy' > 13 kg), and corresponding number that could be linked to mark-recapture records. Only cohorts used by the 'simple' demographic assessment model are shown (i.e., those born 1989/90 to 2017/18).

	All with mass measurement				With sea lion ID			
Cohort	Light	Intermediate	Heavy	Light	Intermediate	Heavy		
1989/90	41	93	7	37	90	7		
1990/91	30	125	35	30	123	35		
1991/92	15	139	89	14	125	69		
1992/93	0	50	34	0	49	33		
1993/94	_	-	_	-	-	_		
1994/95	12	34	4	_	_	-		
1995/96	41	9	0	-	-	_		
1996/97	21	28	1	_	-	_		
1997/98	36	18	0	36	18	0		
1998/99	10	33	7	10	32	7		
1999/00	36	14	0	0	0	0		
2000/01	25	28	6	25	28	6		
2001/02	31	19	0	0	0	0		
2002/03	24	20	6	24	20	6		
2003/04	20	26	4	20	26	4		
2004/05	28	44	3	28	43	3		
2005/06	21	28	1	21	27	1		
2006/07	11	34	5	11	34	5		
2007/08	10	25	15	10	25	15		
2008/09	14	30	6	14	30	6		
2009/10	6	29	15	6	29	15		
2010/11	8	29	13	8	29	13		
2011/12	12	27	11	12	27	11		
2012/13	16	30	4	16	30	4		
2013/14	28	20	4	28	20	4		
2014/15	36	15	0	36	15	0		
2015/16	14	29	7	14	29	7		
2016/17	27	40	5	27	40	5		
2017/18	13	29	8	2	8	4		



Figure A3-1: MCMC traces for first-year survival probability (*Surv*₀) from the 'simple' model fitted to a subset of light (left; red), intermediate mass (middle; purple) and heavy pups (right, blue) for cohorts born in 1990-93 (*Surv*_{0_1990-1993}), 1998-05 (*Surv*_{0_1998-2005}) and 2006-18 (*Surv*_{0_2006-2018}).



Figure A3-1 continued: MCMC traces for breeding rate parameters from the 'simple' model fitted to a subset of light (left; red), intermediate mass (middle; purple) and heavy pups (right, blue). '*Mat*₄' and '*Mat*₅' = relative pupping rate ages 4 and 5, respectively; and '*Pr*_P' = annual pupping rate.