



## Sea lion population modelling and management procedure evaluations

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## EXECUTIVE SUMMARY

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This report describes population modelling of the New Zealand or Hooker's sea lion (*Phocarctos hookeri*) population and evaluating the population consequences of alternative bycatch control rules for the SQU 6T squid fishery around the Auckland Islands.

This report describes the model evolution from its inception in 2000 through 2012. The model is age-structured but not sex-specific, implemented as a Bayesian model in AD Model Builder. It was fitted to data sets from sea lion population studies, bycatch estimates and fishing effort. The joint posterior distribution of estimated parameters, estimated with Markov chain – Monte Carlo simulation (McMC), formed the basis of an operating model used to evaluate alternative bycatch control rules. Diagnostics of the fitting and for the McMC are shown.

In the basic study, six alternative operating models for projection were developed, including the base case, varying in how they treated density-dependence and pupping rate. These were all used to evaluate two families of bycatch control rules, using seven different assumptions about the survival of sea lions that encounter nets with sea lion exclusion devices. Evaluations involved a variety of population and fishery indicators, including four key criteria developed by the Ministry of Fisheries (now the Ministry for Primary Industries) and the Department of Conservation.

This report presents and discusses the evaluation results and also presents sensitivity results from earlier modelling. Current bycatch management assumes a value (discount rate) for the survival of animals that exit a trawl net through a sea lion exclusion device (SLED). The currently assumed value for the discount rate implies that restriction of fishing, so long as fishing effort does not increase and SLEDs are used, is not necessary to meet agreed management criteria.

In 2013 the model was reviewed by a panel of independent experts. The review identified some key modelling choices that needed exploration, and additional sensitivity trials were made during the review and used to evaluate management procedures. These results are presented in a discrete section. Implications for future work are discussed.

## 1. INTRODUCTION

The commercial trawl fishery for arrow squid (*Nototodarus sloanii*), also called Wellington flying squid (FAO 2005; Sakai & Taro 2005) incidentally catches some endemic New Zealand or Hooker's sea lions (*Phocarctos hookeri* Gray 1844). Because *Phocarctos hookeri* is one of the two most rare sea lions (Campbell et al. 2006) and has a threat classification (Baker et al. 2013), the bycatch is treated as a serious conservation problem (Wilkinson et al. 2003). For each year from 1992, the Minister for Primary Industries<sup>1</sup> has set a bycatch limit (fisheries-related mortality limit or FRML). For 1992–2003 these were based on an estimate of the population size, in turn based on annual pup birth estimates and the Gales & Fletcher (1999) model. The population estimate was used in a formula described by Wade (1998). From 2004, the FRML has used control rules evaluated in modelling of the type described here (Breen et al. 2003a; Breen & Kim 2006a; Breen & Kim 2006b).

A large biological programme, part of the Conservation Services Programme administered by the Department of Conservation (DoC) and funded through fishing industry levies, collects annual data on the sea lion population at the Auckland Islands. Pup births are estimated at each of the four rookeries; female pups are tagged; previously tagged female resightings are recorded and pups from these females are recorded (Gales & Childerhouse 1999; Chilvers et al. 2007). Earlier census results are described by Cawthorn (1986; 1993). Pup survival is monitored at all four rookeries through to mid-January, and at Sandy Bay through the end of February (e.g. Chilvers 2009a); causes of pup mortality are well studied (e.g. Castinel et al. 2007). A very high pup mortality was observed in 1998 (Baker 1999).

Foraging behaviour has been extensively studied with satellite tags, and the foraging areas for lactating females overlap the areas trawled for squid (Chilvers 2008; Chilvers 2009b; Chilvers & Wilkinson 2009; Chilvers et al. 2005). The fidelity of females to their natal rookery appears to be high (Chilvers & Wilkinson 2008), and females display an unusual two-phase behavioural pattern on the rookery (Augé et al. 2009). Diving behaviour is thought to be extreme (Gales & Mattlin 1997; Costa & Gales 2000; Costa et al. 2001; 2004) and some authors suggest that this has ecological implications (e.g. Chilvers et al. 2006b; Chilvers & Wilkinson 2009). Feeding ecology has been studied (Childerhouse et al. 2001; Meynier 2009; Meynier et al. 2008; 2009).

Sea lion biology and the history of exploitation are described by Childerhouse & Gales (1998) and Wilkinson et al. (2003). Since 1993, from 1500 to 3020 pups have been born annually at the four rookeries on the Auckland Islands. In 2003, 385 pups were seen at Campbell Island (Childerhouse et al. 2005), and in 2008 a minimum estimate of 583 was made at Campbell Island (Maloney et al. 2009). A very few have been born on the South Island (McConkey et al. 2002). Sea lions were killed for their hides in the early nineteenth century, were depleted and then rebounded, but pre-exploitation numbers and severity of exploitation cannot be estimated (Childerhouse & Gales 1998; Maloney et al. 2009). The species was classified as “endangered” by the International Union for the Conservation of Nature (Chilvers 2015) and the current New Zealand threat classification is “nationally critical” (Baker et al. 2013).

The Auckland Islands squid fishery (the area-defined stock is SQU 6T) begins in early February each year and is usually finished by June. Sea lions sometimes enter the trawl nets; some of those are caught and drowned. The squid fishing industry is excluded from fishing closer than 12 nautical miles (22.2 km) from the Auckland Islands; it uses sea lion exclusion devices (SLEDs) (Clement et al. 2008) in the nets and uses a Code of Practice (Maunder et al. 2000). Although few mortalities are now observed in the SQU 6T fishery even with high observer coverage<sup>2</sup>, the bycatch remains a cause for concern.

The MPI bycatch management strategy is to use a suitable “bycatch control rule”, currently based on one that changes the bycatch limit up and down as annual pup births<sup>3</sup> (pup production) track up and down. Candidate rules can be tested with an operating model, which is a numerical population model fitted to population and fishery data and then projected forward, using a bycatch control rule to

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<sup>1</sup> Or previously the Minister of Fisheries

<sup>2</sup> none by early May 2016, none in 2015, two in 2014

<sup>3</sup> “pup births”, “pup production” and “pup counts” are used interchangeably

determine the annual bycatch limit. This is the approach used in this report and also by Breen et al. (2003a) and Breen & Kim (2006a; 2006b); it is an “operational management procedure” approach.

The use of management procedures (MPs) in fisheries management was reviewed by Butterworth (2007) and examples are provided by Edwards & Dankel (2016). An MP specifies the input to a formula that provides a specific management recommendation such as a TAC or bycatch limit. The harvest or bycatch control rule in an MP has been extensively simulation-tested, using an appropriate operating model, to ensure that it will deliver specified management goals with high probability. In New Zealand, the MP approach is used for rock lobsters in seven stocks (Breen et al. 2016).

This report describes the results of evaluations from the last (revised 2009) model, incorporating additional runs requested by MPI in 2011. Some information is also adduced on model sensitivity from the 2008 study. Because the modelling has evolved, an overview of this evolution is appropriate and helpful to understanding the 2009 model.

The model was reviewed in 2013 by a panel of independent experts (Bradshaw et al. 2013). The review identified some key modelling choices that required exploration, and additional sensitivity trials were made during the review and used to evaluate management procedures. These results are presented here in a discrete section. In the Discussion, key issues that have been discussed or have arisen are discussed and their implications for future work are discussed.

## 1.1 Modelling in 2000–01

The first Hooker’s sea lion modelling was conducted by Woodley & Lavigne (1993), who estimated very low rates of population increase and suggested that sea lions would not be resilient to bycatch. This was not the conclusion of Maunder et al. (2000), who suggested that bycatch management had a much greater effect on squid catch than on the sea lion population. For completeness we mention the optimal control approach of Wilson & Soboil (2006).

A group that included the Maunder et al. (2000) authors developed a Bayesian population model that was used, after modification, in 2000–2001 by Breen et al. (2003a) to evaluate bycatch control rules. For a discussion of Bayesian techniques in protected species problems see Hoyle & Maunder (2004). This was a simple deterministic population model, partially age-structured, with density-dependent pup production; it was fitted to observed annual pup counts at four Auckland Islands rookeries and used sea lion bycatch estimates. Results were then used as the basis for forward projections, with stochastic variation in fishing effort and catchability among years and stochastic variation in age-specific annual survival among years and ages. Random catastrophic events were also modelled, with varying probability and severity, which were designed to test the alternative bycatch control rules in a variety of benign and challenging environments.

At that time, the bycatch management approach used by the Ministry of Fisheries was a simple rule based on the formula for Potential Biological Removals (PBR) described by Wade (1998):

$$\text{Eq. 1} \quad FRML_y = 0.5N_{\min}R_{\max}F_r$$

where  $FRML_y$  is the fishing-related mortality limit<sup>4</sup> in year  $y$ ,  $N_{\min}$  is a conservative estimate of population size,  $R_{\max}$  is the maximum rate of population increase, and  $F_r$  is a “recovery factor”. The recovery factor allocates the proportion  $F_r$  of this surplus production to allowable bycatch mortality.

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<sup>4</sup> in documents of the time this was called a MALFiRM (maximum allowable fishing-related mortality), but later the term FRML was adopted because of the special legislative meaning of MALFiRM in New Zealand.

Values used to apply this formula in New Zealand were 0.08 for  $R_{\max}$ , for reasons discussed below, and 0.15 for  $F_r$ . These were agreed by a Technical Working Group in 1996 (unpublished document held by Dr. Rob Mattlin). With respect to  $R_{\max}$  the group concluded (paragraph 10.15; punctuation and other problems are from the original):

*“The NMFS [National Marine Fisheries Service] model suggests a default value for  $R_{\max}$  of 0.12 for seal species if no data are available on which to estimate this parameter. At the Technical Workshop in October 1996 discussion was held on an appropriate value for  $R_{\max}$  for the New Zealand sea lion. An invited participant, Dr. Paul Wade (one of the NMFS scientists most closely involved with the development and application of the NMFS model) showed that for several species of pinnipeds the actual  $R_{\max}$  is likely to be lower than the default value and suggested a value of 0.08 for the New Zealand sea lion. This is particularly the case for species that have not shown a demonstrable rapid increase in population abundance (such as the New Zealand sea lion). For example the  $R_{\max}$  for the northern fur seal has been set at 0.08 and the Hawaiian monk seal has an  $R_{\max}$  of 0.06.”*

$N_{\min}$  was estimated as the lower 20th quantile of a population estimate obtained from observed pup counts using a model (Gales & Fletcher 1999) that used assumptions about pupping and survival rates. The population estimate was averaged over the two years preceding the fishing season for which the FRML was to apply<sup>5</sup>. For several years following an unusually high pup mortality event,  $N_{\min}$  was arbitrarily reduced further to make the calculation more conservative. This bycatch control rule was never satisfactorily named and here it will be referred to as the “New Zealand Wade rule”.

The 2000–01 work of Breen et al. (2003a) used a family of bycatch control rules based on the New Zealand Wade rule. Pup counts, averaged over the preceding two years, were used to drive the rule, and one member of the family – rule 310 – was intended to replicate the New Zealand Wade rule. An exact replication was not possible because modelling could not use the Gales-Fletcher model to make population estimates and because of a complication involving Campbell Island pups: these were used in the Gales & Fletcher model procedure but could not be used in the Auckland Islands modelling.

Other members of the rule family gave FRMLs that were multiples of those produced by rule 310; viz. rule 305 gave half and rule 330 gave three times the FRML of rule 310. Conclusions from this work were that the population might be near its carrying capacity,  $K$ , that bycatch had a small effect on future population states, and that simple alternatives to the New Zealand Wade rule gave better performance in both cost and risk indicators.

The 2000–01 work was funded initially by the fishing industry (at that time the Squid Fishery Management Company Ltd., now part of the Deepwater Group), later by DoC, and final work and publication were funded directly by NIWA. The work was overseen and coordinated by a technical working group convened and funded by DoC.

## 1.2 Modelling in 2003

A revised modelling project was contracted by the Ministry of Fisheries in 2003 (Breen & Kim 2006a; 2006b). The earlier model was re-written to simplify the code and made fully age-structured to age 20.

The model was extended to fit to sea lion population data provided by DoC: the new data sets were resightings data from females tagged as pups in a number of years and from some breeding females branded in one year, observed pups from the branded females, the ages of bycaught animals autopsied,

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<sup>5</sup> for instance, the FRML that limited bycatch in the 2000 season was based on observed pup counts in 1999 and 1998. When fishing began in 2000, a pup count for 2000 was actually available, but could not be incorporated into management action within the consultation and decision-making timetables.

the age structure of breeding females (Childerhouse et al. 2004), and survival of pups through to mid-January. An objective way to weight the datasets was adopted from other stock assessment practice (Breen et al. 2003a): this involves iteratively adjusting weights so that the standard deviation of normalised residuals is close to 1.

The model remained deterministic in the minimisation phase, but projections incorporated stochastic variation in survival and pupping rates and observation error on pup counts.

The random catastrophic mortality simulated in 2000 was abandoned in the 2003 study. The bycatch control rules evaluated included the rule 300 series. Although the maximum rate of population increase,  $R_{\max}$ <sup>6</sup>, was not an estimated but a derived parameter, a prior was placed on it, with mean 0.08 and a variance determined arbitrarily. Estimated  $R_{\max}$  was substantially less than the prior mean.

The 2003 work was overseen by the Aquatic Environment Working Group (AEWG), a technical working group convened by MFish (and now MPI). An important change was that the AEWG defined two management objectives against which bycatch control rule performance could be compared. The first was that the population should be maintained at either at least 90% of  $K$  or at least 90% of the population size that would be obtained in the absence of fishing, in 90% of years. The second was that the population should average at least 90% of  $K$  in the long term.

The 2003 work concluded that the management criteria were achieved by rules with 9 times the FRML of the New Zealand Wade rule, hence that the then-current management approach was likely overly conservative. Sensitivity trials were made only at the minimisation phase – estimated  $R_{\max}$  was sensitive to the prior – and rule performance sensitivity was not explored.

As a result of this work, the Squid Fishery Management Company Ltd. challenged the 2004 FRML, which had been generated by the New Zealand Wade rule. The Court of Appeal<sup>7</sup> overturned the Operational Plan on the understanding that the industry would abide by a FRML based on rule 320. Subsequent FRMLs were based each year on the rule 300 family, although Ministers tended to “choose” a different rule each year (thus there was not a true management procedure approach).

The 2003 model was subsequently used in work contracted by DoC to provide various pieces of advice (e.g. Breen & Kim 2005). It was reviewed by Dr. Dan Goodman (unpublished report) of the University of Montana.

### 1.3 Modelling in 2007–08

Another modelling project was contracted jointly by MFish and DoC in 2007 to make revisions to the model. The project involved:

- collating and reviewing all the data available on Hooker’s sea lions relevant to modelling the Auckland Islands population
- updating and revising the 2003 model “to incorporate all relevant data and address model uncertainties including ... those identified by the AEWG”
- fitting the revised model and testing sensitivity and
- testing a range of management procedures (rules) with the model to determine if they met agreed management criteria.

Issues that had been identified by the AEWG as potential problems included (quoted from the tender):

- *the 2006 pup counts are lower than the minimum pup indicators assumed in the existing model; this creates uncertainties about the ability of high-numbered harvest control rules to achieve the management criteria;*

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<sup>6</sup> In older documents this was incorrectly called *lambda* ( $\lambda$ ); this has been changed in this document.

<sup>7</sup> available at <http://www.nzlii.org/nz/cases/NZCA/2004/132.html>

- *the existing model fits only to early-season pup mortality data, not to late-season pup mortality data;*
- *only the SQU6T fishery was represented in the existing model; other fisheries associated with the Auckland Islands Shelf region that take sea lions as bycatch were excluded;*
- *the existing model does not take in to account pups that die as a consequence of their mother's death as bycatch;*
- *the very low [Rmax] predicted by the existing model suggests there may be some mis-specification of density-dependence; and*
- *the existing model does not address uncertainties associated with bycatch and fishing effort data.*

A wide variety of changes were made. These included:

- the model code was re-written and carefully tested,
- the minimisation phase of the model was changed from deterministic to stochastic by estimating annual survival rate deviations in appropriate periods (to address bullet point one above),
- the end-February pup mortality data set was obtained from DoC, and the model was parameterised to fit to this (addressing bullet point 2 above),
- bycatch from fisheries other than SQU 6T was reviewed, and an estimate of this “background bycatch” was included (addressing bullet point 3 above),
- model dynamics were revised to simulate the mortality of pups whose mothers had died in the bycatch (addressing bullet point 4 above),
- density-dependence was changed from pupping rate to pup survival (addressing bullet point 5 above),
- estimated fishing effort was reviewed and updated (addressing bullet point 6 above),
- data sets that had not been provided by DoC in 2003 were identified, obtained and used in model fitting: these are described below,
- all the bycatch estimates and fishery data were revised as described below,
- independent analyses of pupping rate were considered,
- ages from bycatch autopsies were collated by year for fitting instead of being aggregated; similarly for the breeding female ages,
- fitting to proportions-at-age was changed to multinomial likelihood,
- ageing error was addressed for the breeding female ages, as described below,
- “attempted fishing effort” (see below) was resampled rather than synthesised in projections,
- the logic of predictions of resightings of tagged females and pups from tagged females was reworked,
- survival rate was re-parameterised,
- the implementation model was extensively changed to mimic the current bycatch management,
- at industry request, an additional bycatch control rule family with fixed FRML was evaluated (the rule 200 series).

The 2007–08 work was again overseen by the AEWG. A wide range of sensitivity trials were made for the performance of bycatch control rules, and the work was used to advise the Minister of Fisheries in his “choosing a rule” to set the FRML for the 2009 season (he chose rule 320). After the FRML decision had been made, a small error was discovered in the projection model: the FRML for year  $y$  had been based on pup counts in years  $y$  and  $y-1$  instead of years  $y-1$  and  $y-2$ . A single sensitivity trial (unpublished data) suggested that this error was not consequential.

## 1.4 Modelling in 2009

In 2009, the Auckland Islands pup count fell from 2175 in 2008 to 1501, by far the largest drop in either numbers or percentage that had been observed in the data series. For the 2009 season the industry voluntarily reduced the FRML to what would have been the FRML had the 2008 and 2009 pup counts been used.



The low observed pup count in 2009 was below the 5th quantile of the distribution of projected pup counts from the 2008 modelling results (unpublished data). Questions arose about the 2008 operating model: was variation in survival and pupping rate too narrow? In addition, MFish had a desire to see further sensitivity analyses. MFish contracted an additional modelling project to update, revise and document the model, with these specifications (portions in italics are quoted from the tender):

- *the existing model structure will be used except that the lag in the model's management procedure will be made equal to that in the real procedure [i.e. correcting the small error]*
- *the revised model will be fitted to the 2009 pup counts and pup mortality estimates but not to any other new data [because there was insufficient time for DoC to update the other data sets].*
- *the assumed bycatch outside SQU 6T will be increased based on Ed Abraham's most recent work. This information will be provided*
- *four cases will be fitted assuming 0%, 20%, 35% and 50% survival of sea lions in nets with SLEDS; none will be called the base case*
- *projections will include increased stochasticity in adult survival and pupping rate sufficient to generate pup counts at least as low as those observed in 2009*
- *the four cases will be run with the same priors as used in the existing Breen-Fu-Gilbert model*
- *a set of sensitivity runs will be run for each of the four cases assessing the effect of:*
  - *the prior on [Rmax] (including no prior)*
  - *the assumed shape of the density dependent response, z*
  - *fixing the maximum pupping rate to the level estimated by Dave Gilbert*
- *for each case and each sensitivity run, both the 200 series (fixed FRML) and 300 series (FRMLs based on pup counts) rules will be evaluated against the same criteria as used for project IPA2006/09 [the 2008 modelling].*

All these specifications were met and the model and results are reported in this document.

## **1.5 Modelling in 2011**

In late 2011, MPI requested further runs with discount rates of 65%, 75% and 85% (discount rates are explained below). These were done and the results are incorporated in this report. The 2011 work did not change the model or the data used; it simply used the 2009 operating models to make further projections.

## **1.6 Modelling in 2013**

In 2013, MPI commissioned a review of this modelling with three international reviewers. In the course of the review, some key items were identified and additional runs were made, either to address these items or at the request of the reviewers. These results are described in Section 6.

## **2. BIOLOGICAL DATA**

### **2.1 Background: sea lion population data**

Sea lion biological data were obtained from DoC's Conservation Services Programme (CSP), which has been conducting field studies at the Auckland Islands since 1996 (Pugsley 2004) during the sea lion breeding season. Some of these data had been made available to Breen & Kim (2006a; 2006b) for the 2003 modelling; some had not.

For the 2008 project, NIWA met with DoC to discuss what data were available from the CSP and whether and how they could be used by the project. DoC and NIWA agreed formally on handling protocols for data to be supplied by DoC to NIWA. Because of these protocols, examples of all the

data sets were shown to the AEWG (and later to the 2013 reviewers), But the data were reported to MFish in a Confidential Appendix to one of the interim reports (Breen 2008). In the present report, only the publically available data are shown in full: pup counts and pup mortality, ageing from autopsies and ageing from breeding females. Other data sets are described but not shown. Where data have changed over the course of the project, only the 2009 data are shown.

The data comprised the following data sets. There are other population data, for instance numbers of females ashore at Sandy Bay during the breeding season (Chilvers 2009a), and some information on males, that were not used for this project. Chilvers (pers. comm.) advised that tag-recapture data on males were not suitable for estimating mortalities (but see Chilvers & McKenzie 2010).

## **2.2 Pup counts**

This data set represented the estimated number of births at each rookery. Methodology for the pup counts was described by Chilvers et al. (2006a), and results have been made available annually (e.g. Chilvers 2007). Scientists make tag-resighting estimates of pups, using temporary tags, at the Sandy Bay and Dundas rookeries, and they make less involved estimates at the other rookeries.

Earlier methodology is described by Cawthorn (1986; 1993), whose estimates were included in the DoC data set. The pup count data comprised 96 records, each with rookery, year, number of pups and reliability code (from 1 – a good, modern estimate, to 4 – a poor estimate). Of these, 13 records had reliability codes 3 or 4 and were not used. The data are shown in Table 1.

## **2.3 Pup mortality data**

Pup mortality to mid-January was reported annually (e.g. Chilvers 2007). At Sandy Bay only, pup mortality was also reported from the end of February. These two data sets are shown in Table 2.

## **2.4 Resightings of females tagged as pups**

Female pups were tagged in 12 years (1987, 1990–93 and 1998–2004), for a total of 2464 tagged pups. Resightings were made in 17 years (1988–2007), for a total of 2331 re-sightings in 121 cohort/year records. Most resightings were made after 1998.

After modelling was completed in 2009, DoC advised that some pups had been branded, not tagged in the same way as the others. This information had not been made available during the NIWA/DoC data meetings in 2008. Had it been available, the project would have calculated predictions differently for the branded animals.

## **2.5 Pups from females tagged as pups**

Records of pups born to females that had been tagged as pups were made in 12 years (1996–2007), in 100 year/cohort combinations (some were zero) involving 908 pups. The model made a prediction for numbers of pups only when at least one tagged female from a cohort was resighted in a year, giving 62 records for fitting. Three records from before 1999 were discarded because the search effort had obviously been very low.

## **2.6 Breeding females tagged as adults in 1999**

DoC tagged 97 randomly chosen breeding females in 1999 and aged each one from a tooth removed under anaesthetic. Some of these females had been tagged as pups and their true age was therefore

known (Table 3). Ages ranged from 4 to 19. Resightings of 207 animals were made in 2000–2007, and the model was fitted to 128 cohort/year combinations (16 ages in each of 8 years).

## **2.7 Pups from females tagged as adults in 1999**

DoC recorded pups born to the adults tagged in 1999. Each sighted female was scored by DoC as having a pup, possibly having a pup, or not having a pup, to which scores we attached the values 1, 0.5 and 0 respectively. The total pups from these females in each year was estimated as the sum of these codes. A total of 85.5 pups were “sighted”. We could make predictions for each parental age, but only when at least one female within an age cohort was sighted in a year, giving 85 records for model fitting. [These data were not fitted in the model for reasons described below.]

## **2.8 Breeding females tagged as adults in 2001**

DoC tagged 64 randomly chosen females that bred in 2001 and aged each one from a tooth removed under anaesthetic; some had been tagged as pups and their true age was known (Table 3). Ages ranged from 5 to 23. Resightings of 95 animals were made in 2002–2007 and the model was fitted to 108 cohort/year combinations (19 ages in each of 6 years, minus 6 combinations that exceeded the model’s maximum age).

## **2.9 Pups from females tagged as adults in 2001**

DoC recorded sightings of pups from the adults tagged in 2001. Each sighted female was scored by DoC as having a pup, maybe having a pup or not having a pup, to which scores we attached the codes 1, 0.5 and 0 respectively. A total of 28.5 pups were sighted. We could make predictions for each age, but only when at least one female within an age cohort was sighted in a year, giving 56 records for model fitting. [These data were not fitted in the model for reasons described below.]

## **2.10 Breeding females branded in 2000**

DoC branded 117 randomly chosen females that bred in 2000 and aged each one from a tooth removed under anaesthetic; some had been tagged as pups and their true age was known (Table 3). Ages ranged from 4 to 22. Resightings of 498 animals were made in 2001–2007, and the model was fitted to 127 cohort/year combinations.

## **2.11 Pups from females branded in 2000**

DoC provided data on sightings of pups from the adults branded in 2000. Each sighted female was scored by DoC as having a pup, possibly having a pup or not having a pup, to which scores we attached the codes 1, 0.5 and 0 respectively. A total of 388 pups were “sighted”. We could make predictions for each age, but only when at least one female within an age cohort was sighted in a year, giving 97 records for model fitting. [These data were not fitted in the model for reasons described below.]

## **2.12 Catch at age**

Age estimates from bycatch autopsies were obtained from the reports by Duignan (2003), Duignan & Jones (2003; 2004; 2006; 2007), Duignan et al. (2003a; 2003b; 2006) and Roe (2006; 2007). These comprised 105 female age estimates from eight years, 1996–2005, ranging from 1 to 12 years old. Only female ages were fitted by the model. Where there was a choice of method, the “dentine GLG” estimate

was used. Where an age range was given, the rounded average was used; where age was given as “n+”, “n” was used. This data set is shown in Table 4.

### 2.13 Ageing errors in breeding female age data

Age data were supplied by Simon Childerhouse (pers. comm.): these were the data described by Childerhouse et al. (2004). In all, 908 ages were estimated from the four years 1998–2001, ranging from 4 to 23. The data supplied had been modified to account for an estimate of ageing bias (see Childerhouse et al. 2004): a correction had been calculated for each age and applied to the “raw” estimated age. MFish organised a meeting among NIWA, DoC, MFish and the fishing industry organisation, which agreed that ageing error should be addressed by using an ageing error transition matrix in the population model.

A revised data set was provided by Simon Childerhouse (pers. comm.), comprising the estimated ages from tooth sections and the known ages where the females had been tagged as pups (see Table 3).

We fitted a regression to the second ageing data set to estimate parameters describing the ageing error, its relation with age and the relation between ageing variability and age. This was:

$$\text{Eq. 2} \quad \hat{E}_i = a + bi + \varepsilon$$

where  $\hat{E}_i$  is the expected age estimate for an animal with true age  $i$  and  $\varepsilon$  is normally distributed error with mean zero and standard deviation  $\sigma$ . The parameters  $a$ ,  $b$  and  $\sigma$  were estimated by minimising the negative log-likelihood function:

$$\text{Eq. 3} \quad -LL_k = \frac{(O_k - \hat{E}_k)^2}{2\sigma^2} + \ln(\sigma) + 0.5 \ln(2\pi)$$

where  $O_k$  is the observed age estimate for the  $k$ th animal.

Ageing error was examined as described above (Figure 1) and also examined using the first reading only (Table 5) as requested by the AEWG as a sensitivity trial. Using ageing error as described above gave a better fit, with much lower  $\sigma$  and slightly higher intercept with slightly lower slope. Ageing error transition matrices were based on these relations. Plots of the residuals suggested that standard deviation was constant with age.

Age distributions of the randomly selected breeding females from the four years are shown in Table 6. No age estimate was greater than 23.

### 2.14 Fisheries data

Fisheries data used by the model included the annual number of tows, the estimated sea lion bycatch, and an estimate of how many tows would have been made in years where the fishery was closed through the action of sea lion bycatch management.

#### 2.14.1 Tows and attempted tows

Estimated numbers of tows were obtained by year from 1990 onwards from the MPI catch and effort database. Estimated numbers of tows from 1988 and 1989 were also requested from the FSU database held by MPI, but through their agent MPI advised that the 1989 data have been lost. For these two early

years, an estimate of the number of tows was made from MPI estimates of the strike rate<sup>8</sup> and bycatch for those years (e.g. MFish 2002), and estimates were also made in this way for several later years to compare such estimates with the MPI data.

Tows were also estimated by various other authors, and these estimates were tabulated (Table 7). The Deepwater Group and its predecessor supplied estimates as personal communication, as did Paul J. Starr. For the model input, the maximum of the various estimates was used. For 2009, a preliminary estimate was provided by Aoife Martin of MFish (personal communication).

The study required estimates of how many tows would have been made had the fishery not been shut down early through the operation of bycatch management. It was assumed that the average season length was 13 weeks, and tows in years with early closures were extrapolated (Table 7). A 2008 sensitivity trial, shown below, explored the sensitivity to this 13-week assumption.

### **2.14.2 SQU 6T sea lion bycatch**

Bycatch estimates have been reported using a variety of methods over a number of years, but the estimates have been controversial. The Ministry of Fisheries commissioned estimates (e.g. Baird 2005) based on the numbers of caught sea lions observed by observers, taking the number of observed and unobserved tows into account. These estimates, from a large series of reports by Suze Baird and Ian Doonan of NIWA, were summarised in the IPP for 2006–07 (MFish 2006), with small discrepancies from the estimates summarised by Smith & Baird (2005a). Early estimates made by Cawthorn (1989) were not used in this study.

Such observer-based ratio-method estimates were made more difficult by the increasing use of SLEDs. From 2002, many tows (in recent years, virtually all tows) in SQU 6T used SLEDs. Bycatch estimates for 2004 and 2005 were made from detailed trawl reporting forms by Smith & Baird (2007a, 2007b). For this study we compiled the median of the posterior distribution of “attributed catch” from these studies, where “attributed catch” was based on an assumed 20% survival of sea lions that encounter a net with a SLED in circumstances that would drown them in a net without a SLED. This survival rate is called the “discount rate” in the bycatch management procedure, and is an important variable in evaluations. The discount rate is the survival of sea lions that would have drowned in a net without a SLED, not the survival of sea lions that have escaped from a net through the SLED.

Estimates from a methodological study for 2000–2004 were provided by Abraham (2008). These are the estimated mortalities assuming no mitigation by SLEDs. For comparability these were converted to “attributed mortalities” by using the ratio of tows with SLEDs, and assuming (because this was the Ministry assumption at that time) that 20% of sea lions encountering a SLED would survive. The adjustment factor is 0.8 times the proportion of nets with SLEDs plus 1 minus that proportion. The text table below shows the relevant data.

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<sup>8</sup> Strike rate is the number of sea lions that would be caught in 100 tows of nets without SLEDs; this is equivalent to 100 times that year’s catchability times the number of vulnerable sea lions.

**Numbers of SQU 6T tows with and without SLEDs, their total, the percentage with SLEDs and the consequent adjustment factor applied to estimated total mortalities estimated by Abraham (2008). Tow data are from Paul J. Starr and the Deepwater Group (personal communication).**

	With SLED	No SLED	Total	%SLED	Factor
2002	835	817	1 652	50.5%	0.899
2003	1 055	328	1 383	76.3%	0.847
2004	2 437	63	2 500	97.5%	0.805
2005	2 606	39	2 645	98.5%	0.803
2006	2 450	0	2 450	100.0%	0.800
2007	1 318	0	1 318	100.0%	0.800

Breen et al. (2005) described an integrated model for simultaneously estimating strike rate, the proportion of sea lions that escaped from the net through SLEDs and the proportion of mortalities that were reported when no observer was on board. This model (the Breen-Kim-Starr or BKS model) was used to estimate bycatch, assuming a 20% discount rate (other discount rates can be used), using data through 2008.

A final estimate can be made using simple assumptions. From 2008 through 2011, a default strike rate of 5.65% was assumed and a discount rate of 35% (MFish 2009) (before 2008 these were 5.3% and 20%). The procedure is described below. Under these two assumptions the bycatch can be calculated from the number of tows: it is 0.0565 times the number of tows made without a SLED and 0.8 times 0.0565 times the number of tows made with a SLED.

The various estimates are shown in Table 8 and Figure 2. For the model input, the mean of the various estimates was used.

### **2.14.3 Bycatch outside SQU 6T**

The model also required an estimate of the sea lions from the Auckland Islands population killed in fisheries other than SQU 6T. This “background bycatch” included squid fisheries outside SQU 6T and other fisheries within the SQU 6T area and elsewhere that are not controlled by the bycatch management measures applied to SQU 6T.

This study used estimates from Thompson & Abraham (2009) but with estimates for the Auckland Islands squid fishery removed. Estimates for the Campbell Island southern blue whiting fishery, were also removed as almost all sea lions are caught east of Campbell Island and are probably from there rather than from the Auckland Islands to the west. Bycatch in the remaining fisheries is shown in Table 9. The background bycatch assumed by the model was set at 20.

### **2.14.4 Strike rate**

For calculating catchability from 2002 onwards, the model uses estimated strike rate, which is the likelihood that a tow will drown a sea lion in the absence of a SLED. Strike rate was estimated with the BKS model using data through 2008 (Table 8). The default value assumed by MFish was used for 2009, 0.0565.

### 3. OPERATING MODEL

#### 3.1 Overview

The model was not sex-specific. Implicitly, it assumed a 50–50 sex ratio and assumed that population parameters such as natural mortality were the same for both sexes. Alternative options were discussed by the AEWG in 2008 and it was agreed that, given the data, nothing was to be gained by having a two-sex model or a female-only model.

The model was age-structured, with ages from 0 to 26 in this study (the number of age classes was a model option). After age 26, sea lions disappeared from the model: there was no plus group. The model explicitly represented four (another model option) sub-populations (= rookeries) within the Auckland Islands population, each sub-population having a constant proportion of the total number; these proportions were estimated parameters of the model.

Natural mortality was age-dependent with estimated parameters  $S_0$ ,  $S_1$ ,  $S_2$ , and  $Surv$ .  $S_0$  described the early survival of pups to mid-January;  $S_1$  was the survival of pups between mid-January and end-February;  $S_2$  was the pup survival for the rest of the year.  $Surv$  was a vector of parameters representing the annual survival rate at specified ages (in this study ages 1, 4, 8, 13, 19 and 26), and survival rates at intermediate ages were determined with linear interpolation.

Survival of pups in their first year was assumed to be density-dependent. The shape of the density-dependent relation was determined by the estimated shape parameter  $z$ . The actual survival varied from year to year through separate annual survival deviations, estimated for pups and mature animals separately.

Bycatch mortality was modelled from the annual bycatch estimates. The model calculated the exploitation rate for each year from bycatch and the model's vulnerable numbers; the latter was a product of vulnerability-at-age and number-at-age. Catch-at-age was then calculated for each year and subtracted from the population. The numbers of pups that starved because their mothers were killed were also calculated and subtracted.

The estimated rate of annual pup production per mature individual,  $R_0$ , was modified by an age-specific relative pupping rate,  $R_a^{pup}$  that simulated reproduction senescence. The equilibrium number of mature animals was the estimated parameter  $K$ .

The model was fitted to pup estimates from the Auckland Islands population using maximum likelihood and Bayesian techniques. From the mode of the joint posterior distribution, Markov chain - Monte Carlo (MCMC) simulations were made and samples were taken from the chain. From each of these, a set of projections could be made with a specific bycatch control rule and randomly varying survival and pupping rate. Population and cost indicators were summarised from their posterior distributions and different bycatch control rules were compared by comparing the posterior summaries.

In descriptions below,  $a$  indexes age,  $ca$  indexes age in tagged adult data sets,  $y$  indexes year,  $k$  indexes sub-population,  $j$  indexes pup estimate,  $c$  indexes year of female pup tagging, and  $b$  indexes prior probability distributions. The description is for the 2009 version of the model.

The parameters estimated by the model are shown below; other quantities used in model calculations follow.

### 3.2 Estimated parameters

$K$	carrying capacity of mature animals
$N1$	number of 1-yr-olds used to initialise the population
$R0$	average annual pupping rate of a mature animal
$R^{decline}$	determined decline in relative pupping rate with age
$z$	parameter for the shape of density-dependent pup survival vs. mature numbers
$S0$	survival of pups until mid-January
$S1$	survival of pups from mid-January until the end of February
$S2$	survival of pups from the end of February until 31 December
$Surv$	a vector of survival of ages 1, 4, 8, 13, 19 and 26
$S1_y^{dev}$	annual deviation of pup survival from mid-January to end February in year $y$ , estimated for 1998 through 2009
$S_y^{dev}$	annual deviation of juvenile and adult survival in year $y$ , estimated for 1990 through 2008
$m_{50}$	age at 50% mature
$m_{95-50}$	difference between ages at 50% and 95% mature
$v_{50}$	age at 50% vulnerability to bycatch
$v_{95-50}$	difference between ages at 50% and 95% vulnerability to bycatch
$Q_k$	proportion of the population in the $k$ th sub-population (rookery)
$\sigma_k$	standard deviation of the pup estimate at rookery $k$
$P_{breeding}^{resight}$	probability that a breeding female tagged as a pup would be re-sighted
$P_{nonbreeding}^{resight}$	probability that a non-breeding female tagged as a pup would be re-sighted
$P_{nonbreeding}^{B,resight}$	probability that a female branded in 2000 would be sighted if not breeding
$P^{pupresight}$	probability that a pup from a female tagged as a pup would be identified
$P^{BF,resight}$	probability that a pup from a branded female would be identified
$\theta$	whole parameter vector (59 elements in this study)

### 3.3 Other variables used in estimation

$N_{a,y}$	number of individuals of age $a$ in year $y$
$S_a$	annual survival at age $a$ before stochastic deviations are applied
$S'_{a,y}$	annual survival at age $a$ after stochastic deviations are applied
$f^{His}$	a penalty on high survival-at-age values
$nSurvage$	the number of directly estimated adult survivals-at-age (6 in this study)
$Survage_t$	the ages for which survival-at-age was estimated (in this study 1, 4, 8, 13, 19, 26)
$p_a^{mat}$	proportion mature at age $a$
$N_y^{mat}$	number of mature individuals in year $y$
$R_a^{pup}$	relative pupping rate of a mature animal at age $a$
$y0$	the first year of model initialisation
$y1$	the first year of simulation (1965)
$y2$	the first year for which fishing effort data were available (1988)
$y3$	the last year for which data were available (varied with dataset)
$y4$	the last year of projections (2110 in this study)
$S_T$	intermediate variable used in calculating $N0$



$N_0$	the number of mature animals at which density-dependent pup survival would be zero
$R_{max}$	the population's maximum annual rate of increase
$V_a$	vulnerability to bycatch at age $a$ for ages 0–12
$N_y^{vuln}$	number of individuals vulnerable to capture in year $y$
$U_y$	the proportion of the vulnerable population taken as bycatch in year $y$ (exploitation rate)
$C_{a,y}$	numbers of age $a$ taken as bycatch in year $y$
$N_{0,y}^{starved}$	the number of pups that starved in year $y$ because their mothers were killed as bycatch
$P_{c,y}^{T, breeding}$	the probability of seeing in year $y$ a female tagged as a pup in year $c$ if she was breeding
$P_{c,y}^{T, non}$	the probability of seeing in year $y$ a female tagged as a pup in year $c$ if she was not breeding
$T_{c,c}$	the number of females tagged as pups in year $c$
$P_{ca,y}^{A,1999}$	the probability of seeing, in year $y$ , a female tagged in 1999 as a breeding adult of age $ca$ (similarly for 2001)
$P_{ca,y}^B$	the probability of seeing, in year $y$ , a female branded in 2000 as a breeding adult of age $ca$
$\tilde{N}_{a,y}^{popn, known}$	relative numbers-at-age for the predicted breeding female proportion-at-age calculation (similarly for estimated ages)
$n_y^{known}$	numbers of known-age animals in the breeding female age data set (similarly for estimated ages)
<b>A</b>	ageing error transition matrix
$\tilde{N}_y^{popn, known}$	the vector of relative numbers-at-age in year $y$ , after the ageing error was applied, for the estimated-age part of the breeding female proportion-at-age calculation
$\sigma_{y,k}^{pupcounts}$	calculated standard deviation for the pup production estimates in year $y$ area $k$
$\sigma_{c,y}^{Tpup}$	calculated standard deviation for pups from females tagged as pups
$\sigma_{ca,y}^{A,1999}$	calculated standard deviation for females tagged as adults at age $ca$ in 1999 re-sighted in year $y$ (similarly for 2001)
$\sigma_{c,y}^{Apup}$	calculated standard deviation for pup births from tagged adults
$\sigma_{ca,y}^B$	calculated standard deviation for females branded in 2000 at age $ca$ re-sighted in year $y$
$\sigma_{ca,y}^{Bpup}$	calculated standard deviation for pup births from branded females
$\sigma_{0,k}^{Jan}$	calculated standard deviation for pup survival through to mid-January in area $k$
$\sigma_0^{Feb}$	calculated standard deviation for pup survival through end-February in Sandy Bay
$n_y^{Auto}$	effective sample size in year $y$ for autopsy catch-at-age observations
$n_y^{popn}$	effective sample size in year $y$ for breeding female proportion-at-age observations
$\times_b$	a parameter value for comparing with a non-uniform prior
$-\ln(L)$	negative log-likelihood function value

### 3.4 Model predictions

$\hat{N}_{0,y,k}$	predicted pup births in sub-area $k$ in year $y$
$\hat{T}_{c,y}$	predicted number of females tagged as pups in year $c$ $T_{c,c}$ resighted in year $y$
$\hat{N}_{0,c,y}^T$	predicted pup births from females tagged as pups in year $c$ sighted in year $y$
$\hat{A}_{ca,y}^{1999}$	predicted number of adults tagged in 1999 at age $ca$ resighted in year $y$ (similarly for 2001)
$\hat{B}_{ca,y}$	predicted number of females branded at age $ca$ resighted in year $y$
$\hat{P}_{a,y}^{Auto}$	predicted proportion-at-age in year $y$ for the bycatch autopsy data set
$\hat{P}_{a,y}^{Popn}$	predicted proportion-at-age in year $y$ for the breeding female data set
$\hat{S}_{0,y}^{Jan}$	predicted pup mortality through to mid-January in year $y$
$\hat{S}_{0,y}^{Feb}$	predicted pup mortality at end-February

### 3.5 Assumed quantities

Values used in the base case operating model are shown in parentheses. Data set weighting was done by iteratively re-weighting to strive for standard deviations of normalised residuals close to 1.

$S^{limit}$	a survival value at the upper limit of credibility (0.95) (Chilvers, pers. comm.)
$r_{y,k}$	reliability code for the pup count in year $y$ for sub-population $k$ (see Table 1)
$CV^{Tpup}$	CV for pups from tagged females tagged as pups (0.5)
$\sigma_{0,k}^{tJan}$	standard deviation of pup mortality through to mid-January in area $k$ (for the four rookeries: 21, 148, 9 and 6)
$\sigma_0^{tFeb}$	standard deviation of pup mortality through end-February in Sandy Bay (48)
$w^{pupcounts}$	data weight for pup production estimates (1.01)
$w^T$	weight for the females tagged as pups (0.2)
$w^{Tpup}$	weight for pups from females tagged as pups (1.088)
$w^{A1999}$	weight for the adults tagged in 1999 (0.69)
$w^{A2001}$	weight for the adults tagged in 2001 (0.856)
$w^{BF}$	weight for the females branded in 2000 (0.2)
$w^{Auto}$	data weight for autopsy catch-at-age data (0.717)
$w_y^{Autoweight}$	relative weight for year $y$ of the autopsy data (for years 1996, 1997 and 2000–2005 they were 11 8 14, 24, 15, 7, 19 and 7 respectively)
$w^{Popn}$	data weight for breeding female proportion-at-age data (1.276)
$w^{Popweight}$	relative weight for year $y$ of the breeding female age data (for 1998–2001 they were 43, 286, 285 and 294)
$w^{Jan}$	data weight for mid-January pup survival data (0.942)
$w^{Feb}$	data weight for end-February pup survival data (2.919)
$\mu_b$	mean of the $b$ th prior
$\sigma_b$	standard deviation of the $b$ th prior

### 3.6 Data used in fitting the model and for projections

$C_y^{obs}$	observed bycatch in year $y$
$N_{0,y,k}^T$	observed pup numbers in sub-area $k$ in year $y$
$T_{c,y}$	observed number of tagged pups from cohort $c$ resighted in year $y$
$T_{c,c}$	number of female pups originally tagged in year $c$
$N_{0,c,y}^T$	observed pup births from tagged pups from cohort $c$ resighted in year $y$
$A_{ca,y}^{1999}$	observed number of adults tagged at age $ca$ in 1999 resighted in year $y$ (similarly for 2001)
$A_{ca,1999}^{1999}$	number of adults originally tagged at age $ca$ in 1999 (similarly for 2001)
$N_{0,c,y}^A$	observed pup births from tagged adults from cohort $c$ resighted in year $y$
$B_{ca,y}$	observed number of females in year $y$ branded in 2000 at age $ca$
$B_{ca,2000}$	number of females branded in year 2000 at age $ca$
$N_{0,c,y}^B$	observed pup births from branded females from cohort $c$ resighted in year $y$
$p_{a,y}^{Auto}$	observed catch-at-age in year $y$ for the autopsy sample
$p_{a,y}^{popn}$	observed proportion-at-age in year $y$ for the breeding female sample
$S_{0,y,k}^{Jan}$	predicted pup survival to mid-January in year $y$
$S_{0,y,1}^{Feb}$	predicted pup survival to end-Feb in year $y$
$f_y^{obs}$	observed fishing effort in year $y$
$f_y^{attempted}$	attempted fishing effort in year $y$

### 3.7 Initial conditions

The population was initialised by simulating the model dynamics over a 30-year period, assuming no bycatch. In the first year of initialisation,  $y_0$ , the number of individuals of age 1 was made equal to the estimated parameter  $N1$  :

$$\text{Eq. 4} \quad N_{1,y_0} = N1$$

In year  $y_0$ , for ages 2 and older the number-at-age was calculated from survival and the numbers in the previous age class:

$$\text{Eq. 5} \quad N_{a,y_0} = N_{a-1,y_0} S_{a-1}$$

Survival of pups was the product of three parameters:

$$\text{Eq. 6} \quad S_0 = S0S1S2$$

Survival of pups was calculated from  $S2$  and survival of older animals was calculated from the estimated vector of specified ages  $Survage$ , with interpolated values for ages between the ages estimated by the  $Survage$  vector:

**Eq. 7**  $S_a = S_2$  for  $1 \leq a \leq \text{Survage}_1 - 1$

**Eq. 8**  $S_a = \text{Surv}_i$  for  $a = \text{Survage}_i$  and  $1 \leq i \leq n\text{Survage}$

**Eq. 9**  $S_a = \text{Surv}_i + \frac{(a - \text{Survage}_i)(\text{Surv}_{i+1} - \text{Surv}_i)}{\text{Survage}_{i+1} - \text{Survage}_i}$  for  $\text{Survage}_i < a < \text{Survage}_{i+1}$ ,

Maturity-at-age was determined from the two estimated parameters:

**Eq. 10**  $P_a^{\text{mat}} = 1 - \left( 1 + \exp\left( -\frac{\ln(19)(a - m_{50})}{m_{95-50}} \right) \right)^{-1}$  for  $a > 4$

Because no animal of age 4 had been seen breeding in the tag-resightings data, maturity was set to 0.001 for ages less than 4.

The number of mature animals in year  $y_0$  was:

**Eq. 11**  $N_{y_0}^{\text{mat}} = \sum_{a=1}^{a=26} N_{a,y_0} P_a^{\text{mat}}$

and the number of pups was:

**Eq. 12**  $N_{0,y_0} = R_0 \sum_{a=1}^{a=26} N_{a,y_0} P_a^{\text{mat}} R_a^{\text{pup}}$

where  $R_a^{\text{pup}}$  modified the pupping rate to account for reproductive senescence:

**Eq. 13**  $R_a^{\text{pup}} = 1$  for  $a < 12$

**Eq. 14**  $R_a^{\text{pup}} = 1 - (a - 12)R^{\text{decline}}$  for  $a \geq 12$

The onset of reproductive senescence was set at age 13 after comparing exploratory fits; this seemed reasonable given the study of Beuplet et al. (2006) of reproduction in the sub-Antarctic fur seal (*Arctocephalus tropicalus*).

Each year after  $y_0$ , the numbers of 1-yr-olds and older animals were updated from numbers in the previous age in the previous year times survival. Survival of pups was assumed to be density-dependent:

**Eq. 15**  $N_{1,y_0+i} = N_{0,y_0+i-1} S_0 \left( 1 - \left( \frac{N_{y_0+i-1}^{\text{mat}}}{N_0} \right)^z \right)$  for  $a = 1$

$N_0$ , the theoretical population size at which pup survival becomes zero, was calculated as follows:

**Eq. 16**  $N_0 = K \left[ \frac{(S_T R_0 - 1)}{S_T R_0} \right]^{-1/z}$

$$\text{Eq. 17} \quad S_T = \sum_{a_1=1}^{a_1=26} \left( R_{a_1}^{pup} P_{a_1}^{mat} \left( \prod_{a=0}^{a=a_1-1} S_a \right) \right)$$

Numbers of older animals were simply the product of numbers-at-age in the previous year times survival-at-age:

$$\text{Eq. 18} \quad N_{a,y0+i} = N_{a,y0+i-1} S_a \quad \text{for } a > 1$$

Pups were determined from mature numbers-at-age and the pupping rate:

$$\text{Eq. 19} \quad N_{0,y0+i} = R0 \sum_{a=1}^{a=26} \left( N_{a,y0+i} P_a^{mat} R_a^{pup} \right)$$

The *posfun* function in AD Model Builder was used to constrain  $S_T R0$  to be greater than 1, to constrain  $R_a^{pup}$  to be greater than 0, and to constrain numbers-at-age to be greater than zero when  $N_y^{mat}$  becomes greater than  $NO$ . *Posfun* constrains a value to be a small positive number, provides a smooth differentiable function to the minimiser and adds a penalty to the total function value when the value would otherwise have been zero. This keeps the minimiser out of unrealistic parameter combinations but should have no effect on the final estimates.

For the first year of actual simulations,  $y1$ , the number of individuals at each age was equal to the number at age in the last year of the initialisation,  $y0 + 30$ :

$$\text{Eq. 20} \quad N_{y1,a} = N_{y0+30,a}$$

The annual rate of increase at minimum population size,  $Rmax$ , was calculated in a separate routine analogous to the initialising procedure described above. An arbitrarily small value (10) was used as the analogue of  $NI$ , the population was initialised and run for 35 years, and  $Rmax$  was calculated from:

$$\text{Eq. 21} \quad Rmax = \frac{N_{35}^{Rmax}}{N_{34}^{Rmax}} - 1$$

$Rmax$  was constrained to be greater than zero using *posfun*.

### 3.8 Dynamics: bycatch

In year  $y$ , after the initialisation, the number of individuals vulnerable to capture was the sum of the products of numbers-at-age and vulnerability-at-age,  $V_a$ :

$$\text{Eq. 22} \quad N_y^{vuln} = \sum_a N_{a,y} V_a$$

$$\text{Eq. 23} \quad V_a = \left( 1 + \exp \left( - \frac{\ln(19)(a - v_{50})}{v_{95-50}} \right) \right)^{-1} \quad \text{for } a < 13$$

Because no animal in the bycatch had been aged at greater than 12, vulnerability was set to zero for ages older than 12.

The exploitation rate was calculated from the catch data and vulnerable numbers:

$$\text{Eq. 24} \quad U_y = \max \left[ 0.95, \frac{(C_y^{obs} + 20)}{N_y^{vuln}} \right]$$

where 20 was the assumed non-SQU 6T bycatch, and 0.95 was an arbitrary maximum permitted exploitation rate (never approached). Model bycatch-at-age was the product of numbers-at-age, exploitation rate and vulnerability-at-age:

$$\text{Eq. 25} \quad C_{a,y} = N_{a,y} U_y V_a \quad \text{for } a < 13$$

### 3.9 Main dynamics

Each year after y1 (in y1 the numbers are those from the initialisation), numbers were updated from numbers in the previous age in the previous year, catch and survival-at-age. For 1-yr-olds this must include the pups who starve when their mothers are caught as bycatch, given by:

$$\text{Eq. 26} \quad N_{0,y}^{starved} = \left( \sum_{a=4}^{a=12} N_{a,y} U_y V_a R0 \right) (P_a^{mat} R_a^{pup})$$

The first term is the bycatch-at-age and the second is the age-specific probability that an animal will have had a pup. The numbers of 1-yr-olds is:

$$\text{Eq. 27} \quad N_{1,y} = (N_{0,y-1} - C_{0,y-1} - N_{0,y}^{starved}) S'_{0,y-1} \left( 1 - \left( \frac{N_{y0+i-1}^{mat}}{NO} \right)^z \right)$$

where  $S'_{a,y}$  is survival-at-age after consideration of annual deviations (equations 30 and 31). The numbers of animals older than 1 is given by:

$$\text{Eq. 28} \quad N_{a,y} = (N_{a-1,y-1} - C_{a-1,y-1}) S'_{a-1,y-1} \quad \text{for } 2 < a \leq 26$$

Annual survival deviations were estimated for pups and older animals separately. For pups, the annual deviations  $S1_y^{dev}$  were estimated from 1998 through 2009, and modified  $S1$ , the survival of pups from mid-January through the end of February:

$$\text{Eq. 29} \quad S'_{0,y} = S0 (S1 + S1_y^{dev} S1 (1 - S1)) S2$$

For older animals, a single annual deviation for all ages,  $S_y^{dev}$ , was estimated from 1990 through 2008:

$$\text{Eq. 30} \quad S'_{a,y} = S_a + S_y^{dev} S_a (1 - S_a)$$

Both sets of deviations were bounded to lie between -0.96 and 0.96. Because Louise Chilvers (DoC, pers. comm.) advised that a survival rate above 0.95 was not credible, estimated  $S_a$  had an upper bound of 0.95, and values of  $S'_{a,y}$  higher than 0.95 were penalised. The penalty was:

$$\text{Eq. 31} \quad f^{His} = 100 \sum_{a=0}^{a=26} \left[ (S^{limit} - S'_{a,y}) - abs(S^{limit} - S'_{a,y}) \right]^2$$

where  $S^{limit}$  was set at 0.95 and the multiplier of 100 was determined after exploratory runs. In each year, pups were calculated from mature numbers:

$$\text{Eq. 32} \quad N_{0,y} = R0 \sum_{a=1}^{a=26} N_{a,y} P_a^{mat} R_a^{pup}$$

Because numbers were determined partially by subtraction (e.g. Eq. 27), *posfun* was used to constrain them to be greater than zero (but after minimisation, numbers were never near zero)

### 3.10 Predictions

#### 3.10.1 Predicted pup numbers

The predicted pup numbers for each sub-area (rookery) were:

$$\text{Eq. 33} \quad \hat{N}_{0,y,k} = N_{0,y} Q_k$$

The sub-area proportions  $Q_k$  were estimated for  $k=1$  to 3;  $Q_4$  was determined by subtraction and a penalty was used to ensure that  $\sum_{k=1}^{k=4} Q_k$  equaled 1.

#### 3.10.2 Predicted tagged female pups re-sighting

The predicted number of tagged female pups from cohort  $c$  re-sighted in year  $y$  was the product of the number of females originally tagged in year  $c$  and the probability that an animal tagged in year  $c$  survived and was re-sighted in year  $y$ . For a breeding female, this probability was a function of the probability of being re-sighted if breeding, and for a non-breeding female was a function of the probability of being re-sighted if not breeding. The probability of re-sighting a tagged breeding female was:

$$\text{Eq. 34} \quad P_{c,y}^{T, breeding} = \left( \prod_{a=0, ye=c}^{a=y-c-1, ye=y-1} S'_{a, ye} / S0 \right) \left( 1 - \left( \frac{N_c^{mat}}{N0} \right)^z \right) P_{y-c}^{mat} R_{y-c}^{pup} P_{breeding}^{resight} 2R0$$

where the first term gave survival to year  $y$  conditional on having survived to mid-January, and  $P_{breeding}^{resight}$  was the probability of re-sighting and correctly identifying a female given that she was breeding. The 2 reflected the assumption that half the population is female; the  $P_{breeding}^{resight}$  term was included because the pup could not be scored unless the female was sighted and identified.

The probability of re-sighting a tagged non-breeding female was:

$$\text{Eq. 35} \quad P_{c,y}^{T, non} = \left( \prod_{a=0, ye=c}^{a=y-c-1, ye=y-1} S'_{a, ye} / S0 \right) \left( 1 - \left( \frac{N_c^{mat}}{N0} \right)^z \right) (1 - P_{y-c}^{mat} R_{y-c}^{pup} 2R0) P_{nonbreeding}^{resight}$$

where  $P_{nonbreeding}^{resight}$  was the probability of re-sighting and correctly identifying a female that is alive but not breeding. The prediction was:

$$\text{Eq. 36} \quad \hat{T}_{c,y} = T_{c,c} \left( P_{c,y}^{T, \text{breeding}} + P_{c,y}^{T, \text{non}} \right)$$

where  $T_{c,c}$  was the number originally tagged. Predictions were made for cohorts tagged in 1990–1993 and 1998–2004.

### 3.10.3 Predicted pup births from tagged female pups

The predicted number of pup births from tagged female pups from cohort  $c$  re-sighted in year  $y$  was the product of the number of observed females originally tagged as pups in cohort  $c$  and the probability that an animal had a resighted pup in year  $y$ . The latter was equal to the pupping rate times the probability for a pup being re-sighted (the same for all years). The prediction was made only if re-sighted tagged females,  $T_{c,y}$ , was greater than zero.

$$\text{Eq. 37} \quad \hat{N}_{0,c,y}^T = T_{c,c} \left( \prod_{a=0, ye=c}^{a=y-c-1, ye=y-1} S_{a,ye} / S_0 \right) \left( 1 - \left( \frac{N_c^{\text{mat}}}{NO} \right)^z \right) P_{y-c}^{\text{mat}} R_{y-c}^{\text{pup}} P^{\text{pupresight}} P_{\text{breeding}}^{\text{resight}} 2R0$$

### 3.10.4 Predicted tagged adults re-sighting

Breeding adult females of various ages (determined from tooth sections) were tagged in 1999 and 2001. The probability of sighting in year  $y$  an animal tagged in 1999 at age  $ca$  depended on expected survival, the probability of breeding given current age and the probabilities of sighting breeders and non-breeders:

$$\text{Eq. 38} \quad P_{ca,y}^{A,1999} = 2R0 \left( \prod_{a=ca, ye=1999}^{a=ca+y-1998, ye=y-1} S'_{a,ye} \right) \left[ P_{\text{breeding}}^{\text{resight}} R_{ca+y}^{\text{pup}} + P_{\text{non}}^{\text{resight}} (1 - R_{ca+y}^{\text{pup}}) \right]$$

Then the prediction was that probability times the number tagged in 1999 at age  $ca$ :

$$\text{Eq. 39} \quad \hat{A}_{ca,y}^{1999} = A_{ca,1999}^{1999} P_{ca,y}^{A,1999}$$

Predictions were analogous for adults tagged in 2001. There was no maturity-at-age term because all these adults were tagged while breeding.

### 3.10.5 Predicted branded female re-sighting

Breeding adult females were branded in 2000. We assumed that all branded females were re-sighted if they returned to the rookery, based on advice from Ian Wilkinson (formerly of DoC, personal communication). The probability of sighting in year  $y$  a female branded in 2000 at age  $ca$  was:

$$\text{Eq. 40} \quad P_{ca,y}^B = \left( \prod_{a=ca, ye=2000}^{a=ca+y-1999, ye=y-1} S'_{a,ye} \right) 2R0 \left( R_{ca+y}^{\text{pup}} + P_{\text{nonbreeding}}^{B, \text{resight}} (1 - R_{ca+y}^{\text{pup}}) \right)$$

and the prediction was:

$$\text{Eq. 41} \quad \hat{B}_{ca,y} = B_{ca,2000} P_{ca,y}^B$$



### 3.10.6 Predicted proportion of catch-at-age

The predicted proportion at age  $a$  and year  $y$  in the necropsy data was a simple proportion involving numbers- and vulnerability-at-age:

$$\text{Eq. 42} \quad \hat{P}_{a,y}^{Auto} = \frac{N_{a,y} V_a}{\sum_{a=0}^{a=12} N_{a,y} V_a}$$

This was done using ages only up to 12, because vulnerability was assumed to be zero after age 12. The ageing error transition matrix was not used because it was not clear that the ageing methods used for bycatch were the same as those used by Childerhouse et al. (2004).

### 3.10.7 Predicted breeding population age structure

This prediction proceeded in several steps for each year  $y$ . In each year, some of the ages were known without error (tagged animals), and others were estimated from tooth ageing. For each group, the vector of relative breeding numbers-at-age was calculated from model numbers and maturity, then weighted by the numbers of known or unknown ages:

$$\text{Eq. 43} \quad \tilde{N}_{a,y}^{popn,known} = n_y^{known} N_{a,y} P_a^{mat} R_a^{pup}$$

$$\text{Eq. 44} \quad \tilde{N}_{a,y}^{popn,est} = n_y^{est} N_{a,y} P_a^{mat} R_a^{pup}$$

The vector of estimated ages was then multiplied by the ageing error transition matrix:

$$\text{Eq. 45} \quad \tilde{N}_y^{popn,est} = \tilde{N}_y^{popn,est} \mathbf{A}$$

and normalised to proportions-at-age. Relative numbers-at-age were then summed from the two groups and normalised:

$$\text{Eq. 46} \quad \hat{P}_{a,y}^{Popn} = \frac{\tilde{N}_{a,y}^{Popn,known} + \tilde{N}_{a,y}^{Popn,est}}{\sum_{a=1}^{a=26} (\tilde{N}_{a,y}^{Popn,known} + \tilde{N}_{a,y}^{Popn,est})}$$

### 3.10.8 Predicted pup mortality through to mid-January

The predicted pup mortality in numbers through to mid-January in area  $k$  and in year  $y$  was calculated as:

$$\text{Eq. 47} \quad \hat{S}_{0,y,k}^{Jan} = N_{0,y} Q_k (1 - S_0)$$

### 3.10.9 Predicted pup mortality through end-February

The predicted pup mortality through the end of February in Sandy Bay in year  $y$  was calculated as:

$$\text{Eq. 48} \quad \hat{S}_{0,y,1}^{Feb} = N_{0,1} Q_1 (1 - S_0 (S_1^{dev} S_1 (1 - S_1)))$$

### 3.11 Likelihoods

#### 3.11.1 Pup count likelihood

The differences between observed and predicted pup numbers for each estimate were assumed to be normally distributed observation error with estimated standard deviations for each sub-area,  $\sigma_k$ , modified by the reliability code  $r_{y,k}$  and the weight applied to the pup production estimate data set,  $w^{pupcounts}$ :

$$\text{Eq. 49} \quad \sigma_{y,k}^{pupcounts} = \sigma_k r_{y,k} / w^{pupcounts}$$

The reliability code had values from 1 (the most reliable), to 4, so each step towards lower reliability increased the standard deviation (equation 52). Only data with codes 1 or 2 were used. The contribution to the negative log-likelihood function was:

$$\text{Eq. 50} \quad -\ln\left(L\left(\hat{N}_{0,y,k} \mid \theta\right)\right) = \frac{\left(N_{0,y,k}^{obs} - \hat{N}_{0,y,k}\right)^2}{2\left(\sigma_{y,k}^{pupcounts}\right)^2} + \ln\left(\sigma_{y,k}^{pupcounts}\right) + 0.5 \ln(2\pi)$$

#### 3.11.2 Tagged female pups re-sighting likelihood

The difference between observed and predicted tagged female pups for each estimate was assumed to be binomially distributed observation error. The standard deviation of this distribution is:

$$\text{Eq. 51} \quad \sigma_{c,y}^T = \sqrt{T_{c,c} \left(P_{c,y}^{T, breeding} + P_{c,y}^{T, non}\right) \left(1 - \left(P_{c,y}^{T, breeding} + P_{c,y}^{T, non}\right)\right)}$$

The contribution to the negative log-likelihood function (ignoring a constant term) was:

Eq. 52

$$-\ln\left(L\left(\hat{T}_{c,y} \mid \theta\right)\right) = -w^T \left(T_{c,y} \ln\left(\left(P_{c,y}^{T, breeding} + P_{c,y}^{T, non}\right)\right)\right) + \left(T_{c,c} - T_{c,y}\right) \ln\left(1 - \left(P_{c,y}^{T, breeding} + P_{c,y}^{T, non}\right)\right)$$

#### 3.11.3 Pup births from tagged female pups re-sighting likelihood

The difference between observed and predicted pup production from tagged female pups for each estimate was assumed to be normally distributed observation error. The standard deviation was determined from an assumed CV (0.5):

$$\text{Eq. 53} \quad \sigma_{c,y}^{Tpup} = 0.5 \hat{N}_{0,c,y} / w^{Tpup}$$

The contribution to the negative log-likelihood function was:

$$\text{Eq. 54} \quad -\ln\left(L\left(\hat{N}_{0,y,k}^T \mid \theta\right)\right) = \frac{\left(\hat{N}_{0,y,k}^T - N_{0,y,k}^T\right)^2}{2\left(\sigma_{c,y}^{Tpup}\right)^2} + \ln\left(\sigma_{c,y}^{Tpup}\right) + 0.5 \ln(2\pi)$$

### 3.11.4 tagged adults re-sighting likelihood

The difference between observed and predicted tagged adults for each estimate was assumed to be binomially distributed observation error. The standard deviation of this distribution (illustrated with the 1999 tagging) was:

$$\text{Eq. 55} \quad \sigma_{ca,y}^{A,1999} = \sqrt{A_{ca,1999}^{1999} P_{ca,y}^{A, re-sight} (1 - P_{ca,y}^{A, re-sight})}$$

The contribution to the negative log-likelihood function (illustrated with the 1999 tagging) was:

Eq. 56

$$-\ln\left(L\left(\hat{A}_{ca,y}^{1999} \mid \theta\right)\right) = -w^{A,1999} \left( A_{ca,y} \ln\left(P_{ca,y}^{A, re-sight}\right) + \left(A_{ca,1999}^{1999} - A_{ca,y}^{1999}\right) \ln\left(1 - P_{ca,y}^{A, re-sight}\right) \right)$$

### 3.11.5 Branded female re-sighting likelihood

The difference between observed and predicted branded female for each estimate is assumed to be binomially distributed observation error, with standard deviation:

$$\text{Eq. 57} \quad \sigma_{ca,y}^B = \sqrt{B_{ca,2000} P_{ca,y}^{B, resight} (1 - P_{ca,y}^{B, resight})}$$

The contribution to the negative log-likelihood function is:

$$\text{Eq. 58} \quad -\ln\left(L\left(\hat{B}_{ca,y} \mid \theta\right)\right) = -w^{BF} \left( B_{ca,y} \ln\left(P_{ca,y}^{B, resight}\right) + \left(B_{ca,2000} - B_{ca,y}\right) \ln\left(1 - P_{ca,y}^{B, resight}\right) \right)$$

### 3.11.6 Proportions-at-age in the autopsies likelihood

The predicted proportions-at-age were assumed to follow a multinomial distribution. The effective sample size of observations in year  $y$  was calculated as:

$$\text{Eq. 59} \quad n_y^{Auto} = 1 / \left( w^{Auto} w_y^{Autoweight} \right)$$

where  $w_y^{Autoweight}$  is the relative weight for the year  $y$  data within the dataset. The contribution from each age in a year's data to the negative log-likelihood function was:

$$\text{Eq. 60} \quad -\ln\left(L\left(\hat{p}_{a,y}^{Auto} \mid \theta\right)\right) = -n_y^{Auto} \left( p_{a,y}^{Auto} \ln\left(\hat{p}_{a,y}^{Auto}\right) + p_{a,y}^{Auto} \ln\left(p_{a,y}^{Auto}\right) \right)$$

### 3.11.7 Breeding female age structure likelihood

The predicted proportions-at-age of breeding females were assumed to follow a multinomial distribution. The effective sample size of observations in year  $y$  was calculated as follows:

$$\text{Eq. 61} \quad n_y^{popn} = 1 / \left( w^{Popn} w_y^{Popweight} \right)$$

The contribution for each estimate to the negative log-likelihood function was:

$$\text{Eq. 62} \quad -\ln\left(L\left(\hat{p}_{a,y}^{Popn}\right)\right|\theta) = -n_y^{Popn} \left( p_{a,y}^{Popn} \ln\left(\hat{p}_{a,y}^{Popn}\right) + p_{a,y}^{Popn} \ln\left(p_{a,y}^{Popn}\right) \right)$$

### 3.11.8 Mid-January pup mortality likelihood

The difference between observed and predicted pup survival was assumed to be normally distributed observation error with standard deviation calculated as:

$$\text{Eq. 63} \quad \sigma_{0,k}^{Jan} = \sigma_{0,k}^{tJan} / W^{Jan}$$

where  $\sigma_{0,k}^{tJan}$  was the assumed standard deviation of early pup mortality in area  $k$ . The contribution to the negative log-likelihood function was:

$$\text{Eq. 64} \quad -\ln\left(L\left(\hat{S}_{0,y,k}^{Jan}\right)\right|\theta) = \frac{\left(\hat{S}_{0,y,k}^{Jan} - S_{0,y,k}^{Jan}\right)^2}{2\left(\sigma_{0,k}^{Jan}\right)^2} + \ln\left(\sigma_{0,k}^{Jan}\right) + 0.5 \ln(2\pi)$$

### 3.11.9 End-February pup mortality likelihood

The difference between observed and predicted pup survival was assumed to be normally distributed observation error with standard deviation calculated as:

$$\text{Eq. 65} \quad \sigma_0^{Feb} = \sigma_0^{tFeb} / W^{Jan}$$

where  $\sigma_0^{tFeb}$  is the assumed standard deviation of early pup mortality in Sandy Bay. The contribution to the negative log-likelihood function was:

$$\text{Eq. 66} \quad -\ln\left(L\left(\hat{S}_{0,y,1}^{Feb}\right)\right|\theta) = \frac{\left(\hat{S}_{0,y,1}^{Feb} - S_{0,y,1}^{Feb}\right)^2}{2\left(\sigma_0^{Feb}\right)^2} + \ln\left(\sigma_0^{Feb}\right) + 0.5 \ln(2\pi)$$

## 3.12 Prior probability distributions

The likelihood of the data given the model was combined with the joint prior probability for the parameters to obtain a joint posterior probability distribution of the parameters given the data. For normal and log-normal (but not uniform) priors, a term was added to the total negative log-likelihood function. When the  $b$ th prior was normal with mean  $\mu_b$  and standard deviation  $\sigma_b$ , for a parameter value  $x_b$  the term added to the function value was:

$$\text{Eq. 67} \quad 0.5 \ln(2\pi) + \ln(\sigma_b) + \frac{(x_b - \mu_b)^2}{2\sigma_b^2}$$

When the  $b$ th prior was log-normal with mean  $\mu_b$  and CV  $\sigma_b$ , for a parameter value  $x_b$  the term added to the function value was:

Eq. 68 
$$0.5\ln(2\pi) + \ln(\sigma_b) + \frac{(\ln(\mu_b) - \ln(x_b) + 0.5(\sigma_b^2))^2}{2(\sigma_b^2)}$$

Assumed prior distributions for estimated parameters are shown in Table 10. Most were uninformative, implemented as uniform distributions with wide bounds. Survival deviations were given a normal distribution in log space. The pupping rate,  $RO$ , was given a normal prior distribution with a mean of 0.30, corresponding to a mature female rate of 0.60, based on preliminary work reported by Gilbert & Chilvers (2008).

A prior was also used for the derived parameter  $Rmax$ , the maximum rate of population increase, with mean 0.08 and CV 0.2. The mean was based on the value agreed by the 1996 Technical Working Group (Ministry of Fisheries, unpublished report) and the CV was determined in explorations in the 2003 modelling work.

The parameter for the shape of density-dependence,  $z$ , was arbitrarily fixed to 3 (see Figure 3).

### 3.13 Alternative operating models

Five alternative operating models were made. The Aquatic Environment Working Group requested to see exploration of sensitivity to a different prior for  $Rmax$ , including having no prior, to changes in the shape parameter  $z$  and to having a fixed  $RO$  that was 0.60, close to the level estimated by David Gilbert (unpublished data).

The table below shows the changes that produced the five alternative models. Changes were made one at a time; there was no attempt to combine them.

Model	Change	Assumed discount rate	$Rmax$ prior	$Rmax$ prior mean	Fixed $z$	$RO$
Base	base case model	0.20	lognormal	0.08	3	estimated
Sens1	$Rmax$ prior mean = 0.05	0.20	lognormal	0.05	3	estimated
Sens2	$Rmax$ prior uniform	0.20	uniform	n.a.	3	estimated
Sens3	fixed $z = 2$	0.20	lognormal	0.08	2	estimated
Sens4	fixed $z = 4$	0.20	lognormal	0.08	4	estimated
Sens5	fixed $RO$	0.20	lognormal	0.08	3	fixed = 0.315

All operating models were fitted to bycatch data that were estimated for 2002–09 using an assumed discount rate of 20%. Ideally, assumed bycatch estimates for 2002–09 should be consistent with the discount rate used in projections. That would require a new McMC for each discount rate/model combination, putting the projects beyond the timeframe specified by MFish. The error involved is only in the 2002–09 assumed bycatch, which affects the initial numbers when projections begin. The consequence of this was explored in a sensitivity trial reported to the AEWG and was small.

For the sens5 model,  $RO$  was fixed to 0.315. When this work was done, Gilbert (unpublished data) had estimated a peak pupping rate of 0.61, which translated to 0.305 in the combined sex model. However, minimisation did not result in a positive definite Hessian matrix (pdH, essential for running an McMC) with this value. The fixed  $RO$  value was increased in 0.0025 increments until pdH was obtained at 0.315.

Each of these alternative operating models was run with McMC for five million simulations, starting at the MPD value, and 5000 equally-spaced samples were saved as in the base case.

### 3.14 Projection model

The operating model used the set of 5000 joint parameter vectors produced by the base case MCMC simulations. Projections used the same dynamics as the minimisation phase of the model described above. Making projections involved additional steps.

For each one of the saved MCMC parameter vectors, projections involved initialising the population model and running it from 1965 through 2009 with the parameters from that vector. The model calculated catchability for each year from 1988 through 2001 as:

$$\text{Eq. 69} \quad \ln(q_y) = \ln\left(\frac{C_y}{f_y N_y^{vuln}}\right)$$

For 2002 onwards, the use of SLEDs complicates this, making bycatch estimates much less reliable and dependent on an assumed rate of survival from SLEDs. For 2002 onwards, catchability was estimated from the strike rate that was estimated from the BKS model:

$$\text{Eq. 70} \quad \ln(q_y) = \ln\left(\frac{\hat{S}R_y}{N_y^{vuln}}\right)$$

The model was then run forward for 100 years. For each of these projection years, the process involved:

- determining the fishing effort that would be attempted by the fishery in that year,
- determining what catchability would apply in that year,
- applying observation error to the number of pups born in that year and obtaining the average of pup births over the past two years,
- from the average pup births and the rule being evaluated, obtaining the FRML,
- from the FRML and assumed strike rate and discount rate, calculating the maximum permitted number of tows, mimicking the way MPI implements the FRML,
- from the attempted and maximum permitted fishing effort, applying implementation error and from catchability calculating the actual bycatch,
- tabulating a variety of population and fishery indicators,
- determining survival and pupping rate deviations for that year and
- running the model dynamics to obtain the population vector at the start of the following year.

These steps are elaborated below.

#### 3.14.1 Fishing effort, catchability and pup counts

Attempted fishing effort  $f_y^{proj}$  was obtained by randomly re-sampling the attempted fishing effort estimates from 1988–2009, using uniformly distributed random numbers. For all the stochastic projection elements, the strings of random numbers were generated from the same seeds, so that runs using different bycatch control rules could be compared directly.

Projected catchability  $q_y^{proj}$  was also obtained by randomly re-sampled the calculated values. The base case operating model resampled values from 1997 through 2009. This choice of years was made because there was an increasing trend in catchability (Figure 4), with 1997 being a convenient dividing point. In 2008 a sensitivity trial to this choice was made as described below.

Observation error was applied to pup counts after 2009 (for 2009 the observed pup counts were used). This was lognormally distributed with standard deviation  $\sigma_y^{obs}$ :

$$\text{Eq. 71} \quad N_{0,y}^{obs} = N_{0,y} \exp\left(\varepsilon_y^{obs} \sigma_y^{obs} - 0.5(\sigma_y^{obs})^2\right)$$

For input into rule 3 (described below), the mean of the two most recent pup counts was used. The FRML that would be applied to the fishery operating in 2010 would be determined from the mean of the observed 2008 and 2009 pup counts. In reality, when the fishery began in February 2010, the 2010 pup count would be known, but it could not be used in setting the FRML because of the requirement to consult on FRMLs and make a Ministerial decision. The 1-year lag is therefore inevitable.

### 3.14.2 Bycatch control rules, projected effort and bycatch

Four bycatch control rules were used. Rule 0 allowed no fishing in SQU 6T. Bycatch was limited to the “background bycatch” in fisheries other than SQU 6T. Lost fishing effort was equal to attempted effort.

Rule 1 had no limit on fishing. The lost fishing effort was zero. Projected bycatch was:

$$\text{Eq. 72} \quad C_y^{proj} = (1 - DR^{actual}) q_y^{proj} f_y^{proj} N_y^{vuln} + C^{background}$$

where  $DR^{actual}$  is the actual survival of animals encountering a SLED that would otherwise be drowned.

Members of the rule 2 family set a constant FRML ranging from 50 to 500. This was translated into a maximum permitted number of tows, mimicking the way MPI implements the FRML. MPI assumes a default strike rate, currently 5.65%, and a discount rate (the assumed survival rate of sea lions that encounter a SLED that would have drowned in a net without a SLED), which was 35% in the 2009 modelling (MFish 2009). If 100% of the nets have SLEDs, then the numbers of sea lions that would be drowned under these assumptions was:

$$\text{Eq. 73} \quad C_y = f_y SR^{assumed} (1 - DR^{assumed})$$

where  $SR^{assumed}$  and  $DR^{assumed}$  refer to the assumed strike rate and discount rate used to determine the permissible tows. Thus the number of permissible tows was:

$$\text{Eq. 74} \quad f_y^{permitted} = \frac{FRML_y^{Rule2}}{SR^{assumed} (1 - DR^{assumed})}$$

The actual number of tows made was the maximum of the attempted tows and the permitted tows with normally distributed implementation error added:

$$\text{Eq. 75} \quad f_y^{proj} = \min\left(f_y^{attempted}, f_y^{permitted} + \varepsilon_y^{tows} \sigma^{tows}\right)$$

Bycatch was determined as for rule 1, and lost fishing effort was:

$$\text{Eq. 76} \quad f_y^{lost} = \max\left(0, f_y^{attempted} - \left(f_y^{permitted} + \varepsilon_y^{tows} \sigma^{tows}\right)\right)$$

Members of the rule 3 family set an FRML based on observed pup counts:

$$\text{Eq. 77} \quad FRML_y^{Rule3} = M 0.02577 \frac{N_{0,y-1}^{obs} + N_{0,y-2}^{obs}}{2}$$

where  $M$  is a multiplier. When  $M = 1$ , the bycatch control rule is exactly the same as rule 310 of Breen & Kim (2006a), and approximately the same as the New Zealand Wade rule used before 2004 to set FRMLs.  $M$  values ranged from 0.5 through 5 (Rules 305 to 350). Bycatch and lost effort were calculated as for rule 2.

### 3.14.3 Management criteria and other indicators

The Ministry of Fisheries (now MPI) indicated that they wished rules to be compared on the basis of two criteria (also used by Breen & Kim 2006a; 2006b):

- *MFish1*: the probability, based on 100-year runs, that the mature numbers in a given year would be either 90%  $K$  or 90% of the mature numbers obtained in the absence of fishing (but including the background catch)
- *MFish2*: the average mature numbers from the second 50 years of 100-year runs as a fraction of  $K$ .

DoC indicated that they wished to see two criteria evaluated, both based on 20-year runs:

- *DOC1*: the number of years in which mature numbers were at least 90%  $K$ ,
- *DOC2*: the probability that the mature numbers in the 20th year would be greater than mature numbers in the last year before projections.

The agreed acceptable levels of rule performance were 90% for *MFish1*, 0.90 for *MFish2*, and 0.50 for *DOC2*. No level was agreed for *DOC1*.

For each projection year the model determined whether mature numbers were greater than 90% of unfished mature numbers: to facilitate this, the model was first run with no SQU 6T fishing (but with the background catch), and the mature numbers for each year for each sample were written to a file.

The mean mature numbers as a percentage of  $K$  (*meanNK*) was calculated for each sample by summing mature numbers from the 51st through 100th projection years and dividing by  $50K$ .

A series of other indicators was saved for each set of runs. The ones reported in this study were:

- *Nmat0*: mature numbers in the last pre-projection year;
- *Nmat20*: mature numbers in the 20th projection year;
- *Nmat20/K*;
- *Nmat100/K*;
- *nadir*: the lowest mature numbers seen in the 100-year run;
- *nadir/K*;
- *%mat*: the average of mature numbers divided by total numbers (including pups) during the 100-year run;
- *maxcatch*: maximum bycatch (excluding the background bycatch) during the 100-year run;
- *meancatch*;
- *Umax*: maximum exploitation rate including background bycatch) during the 100-year run;
- *Umean*;
- *meanFRML*;
- *minFRML*;
- *maxFRML*;
- *closure*: the number of years during the 100-year run in which the fishery was closed by the FRML;
- *effortlost*: the difference between expended and attempted effort caused by closure;
- *pupmin*: the minimum number of pup births during the 100-year run;
- *pupmax*;
- *puprange*.

For comparing rule performances, the indicators involving the *MFish* and *DOC* key criteria were summarised by the mean of the posterior distribution, and others by the median.



### 3.14.4 Stochastic population processes

Survival deviations were randomly re-sampled from the annual estimates of  $S_y^{dev}$  and  $S1_y^{dev}$ . As in the main dynamics, the same  $S_y^{dev}$  was used for all ages within a year. Pup births were modified using lognormal error:

$$\text{Eq. 78} \quad N_{0,y} = R0 \sum_{a=4}^{a=26} \left[ N_{a,y} p_a^{mat} R_a^{pup} \exp \left( \varepsilon_y^{pup} \sigma^{pup} - 0.5 (\sigma^{pup})^2 \right) \right]$$

Experiments with  $\sigma^{pup}$  were made to find a value that gave projected pup counts that were frequently below 1500, and a value  $\sigma^{pup} = 0.2$  was chosen for this study.

### 3.14.5 Projection dynamics

Projection dynamics, after the bycatch was calculated, were as described for the minimisation phase. The starting point for projections was 2009. The model was run forward to 2010 using the 2009 bycatch, the estimated pup survival deviation and a projected post-pup survival deviation. Because this catch is invariant, the 2010 population is unaffected by bycatch control rules, and the first year in which rules affect the population is 2011. Population indicators were therefore calculated from 2011–2030 (20 years) and 2011–2110 (100 years). However, fishery variables such as catch, effort lost, FRML, etc. are determined by the rules in 2010. Fishery indicators were therefore evaluated from 2010–2029 (20 years) and 2010–2109 (100 years).

## 4. MODEL FITTING

The base case model was fitted to all data sets except the pups from the three sets of females tagged as breeding adults (Table 11). These females were not a random sample of mature females, so fitting to their pups would probably over-estimate the pupping rate parameter. Gilbert & Chilvers (2008) show that the probability of pupping is higher for animals that pupped in the previous year. The switches and data weights that define the base case model, and resulting standard deviations of Pearson residuals (sdnrs), are shown in Table 11. Weights were established by starting with those from the 2008 study; the sdnrs were similar to those obtained in the 2008 study, and most were near 1 except for the tagged pup dataset. It was not possible to decrease the sdnr for this dataset.

The base case operating model also assumed a prior on  $Rmax$  with a mean of 0.08 (Table 10), as in previous sea lion modelling projects.

The model was fitted to the data in several steps:

- 1) an exploratory sets of runs was made, in which fits were examined informally; data set weights were adjusted to balance the residuals and any problems were identified and addressed;
- 2) a base case was established in which no aspects of the fit were unacceptable;
- 3) a long McMC chain was obtained;
- 4) the marginal posterior distributions of estimated and derived parameters were summarised and
- 5) a set of sensitivity trials was run to test the effects of major modelling decisions and the effects of individual data sets.

This process is analogous to that used in major stock assessments such as that for rock lobsters (Breen et al. 2009) or paua (Breen et al. 2003b). This process adjusted dataset weights iteratively to obtain sets of normalised (Pearson) residuals with a standard deviation near 1. This is not entirely a straightforward process because the weights interact and may not have predictable effects on these diagnostics. Although

the data set weights are sometimes easy to balance, in other situations the modeller must accept over- or under-weighted data sets to achieve an acceptable base case fit to the data.

A standard set of plots from each run was made from the main model output file, and these were used to compare the predicted and observed data points, show residuals and analyses of residuals as diagnostics, show population trajectories and maturity and survival schedules, etc.

The fit obtained by the minimisation is the mode of the joint posterior distribution (MPD) of parameters. The MCMC chain was evaluated by inspecting the “traces”, which are plots of each parameter estimate in sequence during the run, and by making plots of the running moments of the distribution and moving means.

MPD parameter estimates are shown in the last column of Table 10. The fits to pup counts are shown in Figure 5 and their normalised residuals in Figure 6. These were reasonably good, but the assumption of a constant population proportion in the rookeries was obviously flawed. SE Point declined faster than other rookeries, so the predictions exceeded observed numbers in the last four years. The observed and predicted numbers summed for all four rookeries (Figure 7) were reasonably good, but the model prediction was higher than the observed 2009 pup count data.

The fits to resightings of females tagged as pups cannot be shown because of restrictions on DoC’s data, but the residuals are shown in Figure 8. The fits were reasonably good. Residuals from the fits to pups from the females tagged as pups are shown in Figure 9. Residuals from the fits to resightings of tagged and branded breeding females are shown in Figure 10, Figure 11 and Figure 12.

The fits to each year of the breeding female age data are shown in Figure 13 and their residuals in Figure 14. In each year, although most of the proportions-at-age were fitted well, the highest observed proportion (age 8, 9 or 10 depending on year) was always higher than predicted.

The fit to observed pup mortality at each rookery is shown in Figure 15 and residuals are shown in Figure 16. Pup mortality was well estimated for Dundas, but tended to be under-estimated at Figure of Eight in the early years and over-estimated for SE Point.

The fit to end of February pup mortality at Sandy Bay was fitted well (Figure 17).

Figure 18 shows some important estimated population dynamics parameter relations against age. Survival declined with age to just over half the maximum by age 26. Figure 19 shows some MPD trajectories.

An MCMC was run for 5 million iterations starting from the MPD, saving 5000 samples of the joint posterior distribution. Some traces are shown in Figure 20; the traces were well mixed and appeared converged, except for the *S2* survival parameter: this was estimated on its upper bound, which causes AD Model Builder to estimate a low associated variance, and the resulting MCMC chain is not well mixed. For this report, simple diagnostics involving running medians and a moving mean were made for some key or representative parameters (Figure 21). These support the conclusion that the chains were converged, apart from that for *S2*.

The likelihood and parameter posteriors are summarised in Table 12; uncertainty around most estimates is not great. *Rmax* varied from 0.039 to 0.055, well below the prior mean of 0.08.

The posteriors for survival deviations for pups and adults are summarised in Figure 22 and Figure 23 respectively. Note the low pup survival in 1998 and 2002. Adult survival was higher than average from 1992–97, and in four of the last five years was less than average. Base survival-at-age (Figure 24) was well determined by the data and the model, with little variability except for the very old ages, and with lower ages close to the upper bounds of survival.

The posterior trajectory of mature numbers is shown in Figure 25.

## 5. OPERATING MODEL PROJECTIONS

### 5.1 Base case results

Runs made under rule 0, (no fishing except for the background bycatch), showed considerable individual fluctuation in trajectories of mature numbers (Figure 26). The entire posterior distribution of the mature numbers trajectory is summarised in Figure 27. Even with no fishing, the median of mature numbers after 100 years was 94.4% of  $K$ . The difference from 100%  $K$  is not caused by the background catch, which made only a trifling difference. This result is an artefact of the parameterisation of the survival deviations, and means that assessing rule performance against  $K$  with this model was more conservative than it should be. The current population had a median of 72%  $K$ .

Under rule 1, with no limit on fishing (but with fishing constrained to have the same intensity as estimated in the vector of attempted effort from 1988–2007), the population stabilised at a median of 88.0% of  $K$ . This suggests a relatively small effect of fishing under the base case model assumptions.

At MPI request, runs with fishing under the rule 3 family were made with seven assumed discount rates (survival in nets with SLEDs): 0%, 20%, 35%, 50%, 65%, 75% and 85%. Runs with fishing under the rule 2 family were made only with the first four values for discount rate. There was agreement within the AEWG that none of these rates would be called the “base case”, so there are seven sets of results from the base case operating model.

The rule 2 family is compared in Table 13 for the base case operating model and an assumed discount rate of 0%. The *MFish1* key criterion – 90% of years with either numbers above 90% of the no-fishing level or above 90% of  $K$  – failed at a constant FRML of just above 100. The *MFish2* key criterion – to have *meanNK* greater than 0.90 – failed just below 100. The *DOC1* key criterion – for 90% of years to have numbers above 90% of the no-fishing level in the first 20 years (i.e. a mean above 18) – failed just above 100. The second *DOC* criterion — having a 20-year population increase in at least half the runs — was easily met by all rules. Although the table shows only rules up to a constant FRML of 300, a constant FRML of 375 in rule 2 gave indicators identical to those from rule 1.

Results from rule 2 with higher assumed discount rates are shown in Table 15 (20%), Table 17 (35%) and Table 19 (50%). As the discount rate increased, the point at which the key criteria failed also increased.

Results from rule 3 are shown in Table 14 (0% discount rate), Table 16 (20%), Table 18 (35%), Table 20 (50%), Table 21 (65%), Table 22 (75%) and Table 23 (85%). The *MFish1* criterion failed at just below a multiplier of 2 for 0% discount rate, just below 2.25 for 20% discount rate, just below 2.75 for 35% and was met by unrestrained fishing at a 50% discount rate. These effects for the four key criteria are shown in Figure 28.

The effect of discount rate on rule 320 under the base case is shown in Table 24. Some effects of the assumed discount rate are shown in Figure 29. Mean bycatch had an asymptote, as rules become less restrictive, near 150 for 0% discount rate and near 80 for 50%. Maximum bycatch had an asymptote near 500 for 0% and near 275 for 50%. The percentage of years closed early through action of a rule was highest for 0% discount rate, and declined steeply for all discount rates between rules 310 and 330. The number of tows lost had a similar form, and was low for all discount rates by rule 330.

Other indicators can be examined in the tables.

A sensitivity trial was made to explore the effect of assuming a 20% discount rate when estimating the 2002–09 bycatch, but assuming a different rate when making projections. A data file was prepared based on assuming a 35% discount rate and modifying the 2002–09 bycatch estimates accordingly. An MCMC was run in the same way as for the base case operating model. Table 25 compares the indicators from rule 320 from the base case and this trial. The differences between the base case and this trial are small enough to vindicate the approach taken.

## 5.2 Alternative operating model results

The key parameter posterior distributions from the alternative operating McMCs are summarised in Table 26. There was not much change in these except for  $R_{max}$ , which went to a very low value in the sens2 trial (with a uniform prior on  $R_{max}$ ), and for a much higher  $K$  from sens5 (with fixed  $R_0$ ).  $R_{max}$  was also reduced in the sens1 and sens5 trials. Reducing the mean of the prior on  $R_{max}$  from 0.08 to 0.05 (sens1) reduced the mean  $R_{max}$  only from 0.047 to 0.040. The lowest  $R_0$  (apart from the fixed trial, sens5) was from sens2, showing the effect of a uniform prior on  $R_{max}$ .

Figure 30 shows the survival-at-age curves from each trial: there was little difference among the trials. Some indicators from rule 0 (no fishing) are compared in Table 27. Sens2, with a uniform  $R_{max}$  prior, differs strongly from the others in that the population decreases throughout the run (median numbers at 100 years are smaller than numbers at 20 years). Note the higher numbers for sens5 (fixed  $R_0$ ). The minimum pup count is less than 1500 for all models, and is much lower for sens2.

To compare results from these trials with different rules, we inspected the output for each of the four key criteria and found the highest rule that met each criterion, doing this for each operating model and each assumed discount rate. Such rules usually fell between two rules that had been run, and we used linear interpolation to estimate the exact rule that just met each criterion. The rule that just meets a criterion has in the past been called a “cusp rule” with respect to that criterion.

These results are shown in Table 28 for the rule 2 family and in Table 29 for the rule 3 family. The *DOC2* criterion was met under all rules except in the sens2 trial, where it was met by no rule. In the sens2 trial, no rule met the *MFish2* criteria and only very conservative rules met the *MFish1* criterion, and only at high discount rates. The sens2 model did not change results much for the *DOC1* criterion, perhaps because this model had the lowest  $K$  estimate.

Among the other trials, cusp rules varied widely among the alternative models. As shown above, the cusp rule increased as the assumed discount rate increased. When the discount rate was assumed to be 50%, in many trials the criteria were met under rule 1, unrestricted fishing. When 65% discount rate was assumed, rule 1 (no FRML) met all four criteria in all models except for sens2, which had a uniform prior on  $R_{max}$ . Under that model, the *MFish2* and *DOC2* criteria are failed even with no fishing, and the *MFish1* criterion was met only with low multipliers.

Reducing the prior mean for  $R_{max}$  (sens1) gave less generous results than the base case. Less generous means that a specific rule has a larger effect on the population. Reducing  $z$  (sens3) also gave less optimistic results, and increasing  $z$  (sens4) gave more optimistic results. Fixing  $R_0$  at 0.315 (sens5) gave results only slightly less optimistic than the base case.

## 5.3 Sensitivity trials from the 2008 study

In 2008, sensitivity was explored with various trials, including but not limited to those requested by the AEWG. These were all McMC trials. The results of the 2009 study differed from the 2008 results, with cusp rules that were less conservative than in the 2008 results. However, the 2008 sensitivity trials were valuable explorations of the effects of some modelling choices.

With the base case numbered as 1, the 2008 sensitivity trials were:

1. 2008 base case;
2. assuming discount rate = 0% (in the base case this was 35%) (requested by AEWG);
3. assuming discount rate = 50% (requested by AEWG);
4. using an attempted effort vector based on a 16-week season instead of 13 weeks (requested by AEWG);

5. using an alternative bycatch vector in the data file – all bycatch estimates from 1988–2007 were multiplied by 1.5 (requested by AEWG);
6. using an operating model that had no density-dependence (requested by AEWG);
7. using alternative seeds for the stochastic projections (to explore whether 5000 simulations were sufficient: this trial gave essentially the same results and will not be described further);
8. fixing the probability of resighting a breeding female to 0.9 (in the base case this was estimated);
9. fixing  $R0$  to 0.31 (in the base case this was estimated);
10. using a mean of 0.06 in the prior for  $Rmax$  (in the base case it was 0.08);
11. using a mean of 0.04 in the prior for  $Rmax$ ;
12. fixing the density-dependence shape parameter ( $z$ ) to 2 (in the base case it was fixed to 3);
13. fixing  $z$  to 4.1;
14. increasing the penalty on high survival rates by lowering its threshold from 0.95 to 0.93;
15. decreasing the penalty on high survival rates by raising its threshold from 0.95 to 0.97;
16. using an alternative ageing error transition matrix, and re-calculating the breeding female age distributions by assuming that first age reading is the most accurate (requested by AEWG): age frequency distributions were re-worked using the first age reading only (Childerhouse, unpublished data);
17. (withdrawn)
18. re-sampling  $q$  from 1988 onwards (in the base case 1997 was used).

In 2008 an alternative base case trial was requested by MFish with the assumed discount rate set to 20%.

Most of these trials (all but 4, 7 and 18) required alternative MCMC simulations. Trials 2, 3, 6, 7, and 18, and the alternative base case, required altered model code. For trial 6, the model was altered by removing all instances of the density-dependent pup mortality. All trials except 7 and 18 required an altered input data file. The alternative MCMCs were run for 10 million simulations with 5000 samples saved, the same as for the 2008 base case.

In comparisons with no fishing, results (not shown here) were broadly similar across the sensitivity trials. Trial 6, with no density-dependence, was starkly different; without any information the  $K$  distribution was equal to the prior (a uniform distribution between the upper and lower bounds). The posterior biomass trajectory from rule 0 (no fishing) is summarised in Figure 31: some runs increased strongly while others declined towards a nadir of 1000 or less. Sixty-five percent of runs declined, with a median decline of 20% over 100 years. Even when the background bycatch (10 animals in 2088) was removed, 60% of runs declined, with median decline of 13%. Fishing had a much larger effect than in the base case (Figure 32): unlike in the base case, the lack of density-dependence ensured an increasing divergence between the fished and unfished runs.

Population indicators under rule 1 were better than those from the base case in trials 3 (high assumed discount rate), 13 ( $z = 4$ ), 15 (weaker penalty on high survival rates), 16 (alternative ageing error transition matrix) and 18 (resampling  $q$  from a longer period). Each of these trials, except 18, allowed the operating population model to be more productive; in trial 18 the mean  $q$  was much lower than in the base case.

The remaining trials showed poorer population indicators under rule 1. In these trials, either the fishing model had a more substantial effect on the population (trials 2, 4, and 5, and the alternative base case) or the population model had a weaker density-dependent response (6, 8 through 12 and 14). Cusp rules from these trials are compared in Table 30.

In trials with various assumed discount rates (alternative base case and trials 2 and 3), higher assumed discount rates result in higher cusp rules. Higher  $z$  values also result in higher cusp rules and vice versa (trials 12 and 13). Results from the no density-dependence trial (trial 6) cannot be evaluated against the MFish criteria, but this trial was far more pessimistic than the base case against the DOC criteria.

Of the remaining trials, trial 8 (fixed probability of resighting a tagged female) gave lower cusp rules than the base case; fixing  $R0$  (trial 9) gave higher cusp rules; reducing the mean of the  $Rmax$  prior (trials 10 and 11) gave lower cusp rules; increasing or decreasing the penalty on high survival rates (trials 14 and 15) gave lower or higher cusp rules respectively; the alternative ageing error transition matrix (trial 16) and resampling  $q$  from a longer period (trial 18) both gave higher cusp rules.

## 6. 2013 modelling

In 2013, MPI organised a week-long review of the work described above, involving three overseas reviewers. There were two days of presentations, open to the public, followed by two days free to the reviewers, and then a partial day of presentation of the reviewers' draft results. A final report (Bradshaw et al. 2013) followed some time later.

### 6.1 Unbounded survival

Early on, the reviewers focussed on the restricted upper range for survival as an issue that needed exploration. Accordingly, the upper bound on estimated survival was raised from 0.95 to 0.998 and the penalty on high survival after application of the deviations was removed. MPD results from this run ("noSbound") are compared with the 2011 base case in Table 31. The overall fit was better by 22 likelihood units, with better fits to the tagged female pup resightings and their pups. Estimated survival rates were higher, in some cases much higher, and  $Rmax$  was estimated as 0.068 instead of 0.048. The fit to pup counts (Figure 33) was similar to that in the 2011 base case (Figure 5) and the main difference was in the survival trajectory (Figure 34, compared with Figure 18).

Two variants of this were run, both with the high upper bound on survival and no penalty for high survival: noSbound0.4 with the mean of the prior on  $Rmax$  reduced to 0.04, and noSboundUniform with a uniform prior on  $Rmax$ . Estimated  $Rmax$  was close to 0.05 in the noSbound0.4 run and similar to the noSbound run when a uniform prior was used.

These three trials were all run as McMCs as for the base case, and a set of projections was made with rule 3 variants to determine the cusp rules for each of the four main criteria over a range of assumed discount rates. The results are compared with 2011 base case results in Table 32. When the discount rate was zero, the cusp rule was more conservative for all trials (except for the  $DoC1$  criterion, which all runs met in all trials). At higher discount rates, the trials usually produced more liberal cusp rules. At a discount rate of 35% or higher, rule 1 (no bycatch limit) would meet all four criteria in these trials.

### 6.2 Review-requested trials

The reviewers focussed on several issues. They requested additional trials, all based on the NoSbounds trial, with:

- no density-dependence ("noDD")
- $z = 1$  ("Z1")
- $z = 2$  ("Z2")
- vulnerability extended to all ages (the base dropped to zero after age 12 ("vuln26"))
- the proportion of animals in the fourth rookery estimated, not determined by subtraction ("propQ")
- all pup count reliability codes = 1 ("rely1")

The base case for all these additional runs was the noSbounds run. For the noDD run, it was agreed to make  $N0$  in equation 16 very large, simply by fixing  $K$  to a large value: the MPD in noSbound was 8218, so  $K$  was fixed at 100 000 in this trial. The Z1 trial was not pdH when  $z = 1.00$ ; the smallest value of  $z$  that was pdH and would start an McMC was 1.011. For the vuln26 trial, vulnerability for ages greater than 12 was based on the vulnerability parameters. It was necessary to fix these to the

noSbound values to obtain pdH. For the propQ trial, the model estimated proportions of pups at all rookeries instead of obtaining the last one by subtraction, and it normalised the estimates to produce the proportions. The MPD estimates were not pdH although they were nearly the same as the noSbound trial, so this trial was not taken further. For the rely1 trial, all pup count reliability codes were set to 1.

All runs except “propQ” were run as MCMCs in the same way as in the 2009 model, and a limited set of rule evaluations was performed. The reviewers requested to see the fit to pup counts and a plot of projected mature numbers (*Nmat*) for 10 randomly chosen runs (using random numbers): the same runs were plotted for all trials. Fits to pup counts are shown here only for the noDD trial (the rest were similar to the noSbound trial), and MPD results from these trials are compared in Table 31. The worst fit was seen in the noDD run. In this run the early pup counts were not fitted well, suggesting that a longer initialisation was required (Figure 35). Estimated Rmax was only 0.018 in noDD, was near 0.05 in Z1, and in the vuln26 and rely1 trials was close to the noSbound estimate. These last two trials differed little from the noSbound trial.

In the noDD trial most runs increased with no fishing, some a lot (Figure 36), but 45 runs decreased, and the worst run decreased to 37% of the pre-projection value. The average annual increase (mean of the posterior) over the 100 years was 1.4%, calculated for each sample of the posterior from:

$$AAI = \exp \left( \ln \left( \frac{Nmat_{2110}}{Nmat_{2010}} \right) / 100 \right)$$

In the noSbound trial, 89% of runs increased, but only by an average 0.22% annually (because the increase was limited by density-dependence). In the noDD trial fishing steadily reduced the size of the mature population compared with the unfished population (Figure 37).

Typical trajectories are shown for the z1 and vuln26 trials in Figure 38 and Figure 39 respectively.

Based on the MCMCs, rule evaluations were made for these trials with rules 0, 320 and 1 (i.e., no fishing, twice the Wade rule and unconstrained fishing), all with discount rates of 0%, 20% and 50% as specified by the panel. Results for the trials are compared for discount rates of zero and 50% in Table 33 to Table 37. As noted above, the Z2, vuln26 and rely1 trial results were all similar to those from noSbound. The noDD trial gave pessimistic results and the Z1 trial was intermediate.

## 7. DISCUSSION

The 2011 model fit the data reasonably well, with MCMC traces and some limited diagnostics looking acceptable.

With no fishing (rule 0) the population stabilised at a median of 94% of *K*. The difference from 100% *K* is a modelling artefact and was not caused by the background catch. Ideally an untouched population should stabilise at *K*, and any future work should parameterise survival in a way that ensures this. This phenomenon made assessment of rule performance against *K* more conservative, using this operating model, than it should have been.

Performance of any chosen bycatch control rule, evaluated against the key *MFish* criteria, decreased as the model evolved, at least until the 2013 version. In the 2003 work, all rules of the rule 300 family met the two key *MFish* criteria whereas in 2011 rules above 319 failed the *MFish1* criterion. The assumed background bycatch increased as the model evolved but should have had only a small effect. Major differences between the 2003 and 2011 models were the stochastic minimisation model, allowing population size at the start of projections to be lower, altered density-dependence dynamics and increased stochastic noise in projections. Experimentation would be required to discover which was the dominant cause of decreased rule performance.

The 2013 trials showed that limiting the estimated base survival rate to 0.95, and penalising higher stochastic survival rates, had strong effects. When these constraints were relaxed, the model fitted the data better, estimated survival rates increased, estimated  $R_{max}$  increased, and performance under any chosen rule was better, such that cusp rules were more liberal than those estimated from the 2011 model. Constraints on survival were used at the suggestion of Dr. Louise Chilvers of DoC, who advised that rates above 0.95 were implausible. However, Chilvers & McKenzie (2010) estimated much higher survival rates, especially for males.

Evaluations of rule performance were sensitive to the assumed discount rate, with higher discount rates giving more liberal results (i.e. cusp rules were higher numbered rules as discount rate increased). The current MPI assumption is for an 80% discount rate, but there is controversy about this. Survival of sea lions that escape from the net through the SLED has not been estimated directly (and would be nearly impossible to measure). From the 2011 model, all rules met all key criteria at a discount rate of 50% or more; the 2013 model version obtained this result at discount rates above 20%.

For all trials the same discount rate was used in projection dynamics and in the MPI procedure for implementing the FRML. In reality, these could easily be different. If MPI's assumed discount rate were larger than the survival rate in reality, then a bycatch control rule would perform less well than the simulations indicated, and vice-versa.

Results were not very sensitive to  $R_0$ . The model with a fixed (low)  $R_0$  had a much higher  $K$  to produce the observed pups during the minimisation; hence this trial (sens5) had higher numbers at the start of projections, proportionally reducing the effect of fishing and compensating for the reduced pup productivity. The fixed value was 0.315, which was substantially lower than the model's median estimate of 0.374.

Independent estimates of pupping rate (Gilbert & Chilvers 2008) suggest lower values than estimates from this model. These authors found a maximum population mean pupping at age 11 of just under 0.5 per female, which corresponds to 0.25 in the present model. However, their estimation assumptions are different. The present model assumes, through its prior on  $R_{max}$ , a substantial maximum growth rate, whereas other methods may make no assumption about this, and other methods are free to estimate pupping rates that cannot replace the current population.

A larger problem is the sensitivity of results to the model's treatment of density-dependence. There was sensitivity in both 2011 and 2013 trials to the choice of prior mean for  $R_{max}$  and also to the assumed value of  $z$ . Nothing is known about  $z$  except that it seems unlikely to be 1. For  $R_{max}$ , the 1996 Technical Working Group (MFish, unpublished report) agreed that  $R_{max}$  was more likely to be 0.08 for Hooker's sea lions than the NMFS default value of 0.12 (see the quotation above). Lalas & Bradshaw (2003), studying the tiny Otago population, estimated a rate of increase of 0.07 to 0.13. It was encouraging that the estimated  $R_{max}$  was similar to the noSbound result when the prior was made uniform. Brandon et al. (2007) discuss the importance of prior choice in marine mammal conservation problems.

There are many other potential uncertainties. These include where density-dependence takes place in the real population: is it in pup survival, pup production or both? In a study with two different models of California sea lions (*Zalophus californicus*), Underwood et al. (2008) found that survival rates affect  $R_{max}$  more than reproductive rates do, and the pup survival was more important than adult survival. (Values for  $R_{max}$  used by these authors varied from -0.02 to 0.05), much lower than either the default suggested by Wade (1998) or the 0.08 agreed by the 1996 Technical Working Group for *Phocarctos hookeri*.)

A problem identified by Dan Goodman, the reviewer of the 2003 modelling, involved spatial complexity:

*"The lack of mechanistic metapopulation dynamics among the four subpopulations considered ignores the possibility that the bycatch might affect the subpopulations differentially. If, for example, one of the subpopulations were to decline substantially while the other three maintained their numbers, this would seriously compromise your conservation goal of*



*increasing the number of breeding colonies. But the model does not allow for such dynamics. Of course, predictive representation of such dynamics will require more data about movements between subpopulations, and a means to assign origin of sea lions killed in the bycatch. The latter, in particular, will require extensive tagging or marking, or perhaps genetic fingerprinting if the four subpopulations have distinguishable signatures. Genetics analysis would be worthwhile, in any case, for the light it might shed on the population histories.”*

The two smaller rookeries declined far faster in the past decade than the two larger rookeries. The Southeast Point rookery had no pups for four years (Blue Planet Marine 2016), so the assumption of a constant proportion of the population breeding at each rookery was flawed. The time series of pup counts is now much longer than it was when this modelling began, and it would make sense to model the Auckland Islands as a single population. However, areas used for foraging differ among females from the three largest rookeries (Chilvers 2009b) and thus the bycatch may affect the rookeries in different proportion from their abundance. The current data do not allow sub-population modelling except for pup count predictions.

Although it is the basis for MPI's bycatch management, this work is now badly dated. If further work were to be conducted with a version of this model, much work would be required (in addition to incorporating the most recent data and the good estimates of bycatch now available, e.g. Thompson et al. 2013). This would include:

- revising the parameterisation for stochastic survival to remove the artefact
- including tag loss estimation in the predictions for tagged female re-sightings (Chilvers & MacKenzie 2010)
- trying to obtain pre-1988 bycatch estimates, which might have been high when the squid fishery first began (Richard Wells, pers. comm.)
- considering a female-only model, although this should not make much material difference
- running sensitivity trials on the effects of assumed  $z$ , and basing the assumption of  $z$  on a literature review
- combining the rookery pup counts after 1993 and fitting a single Auckland Islands population
- relaxing the prior on  $R_{max}$  and conducting sensitivity trials to the effect of this prior
- given the increase in tow length in the fishery, re-considering the estimation and projection of catchability

With respect to  $z$ , the reviewers were divided in their opinion (Bradshaw et al. 2013):

*a. Bradshaw recommends defaulting to  $z = 1$  in the absence of information regarding the ‘true’ shape parameter and the phenomenological evidence for some moderate compensatory feedback, especially considering multispecies assessments of feedback strength are generally lower for large-bodied (slow life history) species*

*b. Haddon recommends that rather than only fixing a  $z$  value, searching for some plausible prior to use in future analyses is an option that could at least provide an improved notion of uncertainty. Alternatively, when doing sensitivity analyses, the outcome of including  $z$  values from 3 to 1 should at least be included in the range of uncertainty*

*c. Lonergan recommends using parametric bootstrapping to investigate the stability of  $z$  parameter estimates based on fitting to these data and, on the basis of the results, adopting either a single value or a prior distribution for  $z$*

Although the model described here is dated, the integrated modelling approach is arguably the best approach (Maunder & Punt 2013). The reviewers

*found that the modelling framework used was robust and capable of performing the tasks required from it. ... The methods used are all well-known and in common use in other situations. The model structure itself and its implementation appears to be fully robust and well structured and the review panel could find no issues.*

The advantages of the integrated approach over the sequential approach, where estimates (e.g. survival) are made outside the model and then used as input, are:

- total uncertainty is estimated properly, whereas in the sequential approach some uncertainty is lost
- the assumptions of estimation are consistent, whereas in the sequential approach assumptions used in parameter estimation may differ from those used in the simulation model
- the covariance among parameters is estimated and used in projections
- estimates must be consistent with the total data set, whereas in the sequential approach they need not be (survival estimates might be incompatible with the population trajectory)

The role of the fishery bycatch in Hooker's sea lion population trends is controversial. For instance, the present work suggests that, given the data, the assumptions of the model and MPI's assumptions, the current bycatch management and that of Maunder et al. (2000), Breen et al. (2003a), Breen & Kim (2006b) and Hamilton & Baker (2015) suggest that fishery bycatch, while undesirable, is not a major population problem. Conversely, Chilvers (2012) and Meyer et al. (2015) claim that fishery bycatch is the likely cause of population decline. These latter studies used only part of the whole data set, focussing especially on the tagged pup re-sightings, and used highly simplistic models that contrast with the model described here. More complex models with more realism are not automatically better (Adkison 2009), but the models of Chilvers (2012) and Meyer et al. (2015) were too simple to be credible (Breen et al. 2012; Middleton & Breen 2016).

Recently, a model has estimated the relative effects of alternative stressors on the Auckland Islands population of Hooker's sea lions (Roberts & Doonan 2016). This was an integrated model fit to most of the data sets described above, but was an individual-based model with very slow MCMC capability.

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**Table 1: Pup birth estimates and their reliability codes from the four rookeries (Ian Wilkinson and Louise Chilvers, DoC, unpublished data and Chilvers 2009a).**

January year	Sandy Bay		Dundas		Figure of Eight		SE Point	
	Estimate	Code	Estimate	Code	Estimate	Code	Estimate	Code
1943	350	4						
1966	465	2						
1973	525	2	1 000	4	29	3		
1975	420	2						
1976	481	2						
1977	428	2						
1978	434	2	2 077	2				
1980	193	4						
1981	471	2	2 468	3	51	3		
1982	523	2					21	3
1983	142	4						
1984	458	2						
1985	500	2	253	4	47	4		
1986	452	2	1 344	2				
1987	473	2	1 386	4	105	1		
1990	434	2			120	1		
1991	429	2	1 132	4				
1992	489	2	1 934	2				
1993	424	1	1 870	2	69	1	26	3
1995	467	1	1 837	1	143	1	71	1
1996	455	1	2 017	1	144	1	69	1
1997	509	1	2 260	1	143	1	63	1
1998	477	1	2 373	1	120	1	51	1
1999	513	1	2 186	1	109	1	59	1
2000	506	1	2 163	1	137	1	50	1
2001	562	1	2 148	1	94	1	55	1
2002	403	1	1 756	1	96	1	27	1
2003	489	1	1 891	1	95	1	43	1
2004	507	1	1 869	1	87	1	52	1
2005	441	1	1 587	1	83	1	37	1
2006	422	1	1 581	1	62	1	24	1
2007	437	1	1 693	1	70	1	24	1
2008	448	1	1 635	1	74	1	18	1
2009	301	1	1 132	1	54	1	14	1

**Table 2: Pup mortalities observed at the four rookeries by year through to mid-January and at Sandy Bay for the end of February (Louise Chilvers, DoC, unpublished data and Chilvers 2009).**

Year	Sandy Bay	Dundas	Figure of Eight	SE Point	end Feb
1995	46	234	20	12	
1996	38	207	31	20	
1997	36	177	9	24	
1998	9	625	23	14	200
1999	40	229	9	17	46
2000	24	124	6	13	56
2001	35	346	2	8	56
2002	83	361	6	6	133
2003	80	336	5	17	103
2004	34	120	1	13	76
2005	30	74	4	6	53
2006	39	232	7	4	68
2007	23	106	3	5	70
2008	23	123	2	5	63
2009	12	67	6	6	36

**Table 3: Numbers of known age and estimated age females in the breeding female age data set by year (Simon Childerhouse, personal communication).**

Year	Known age	Estimated age	Total
1998	7	36	43
1999	57	229	286
2000	57	228	285
2001	63	231	294
total	184	724	908

**Table 4: Age estimates from autopsied females (see text for sources).**

Year	Age												Total	
	0	1	2	3	4	5	6	7	8	9	10	11		12
1996	1	1	1	3	0	0	0	3	0	0	1	1	0	11
1997	0	0	0	3	1	1	1	1	1	0	0	0	0	8
2000	0	0	0	0	1	1	3	3	3	1	1	1	0	14
2001	0	0	0	4	2	9	6	0	2	0	1	0	0	24
2002	0	0	1	1	2	1	2	1	2	1	3	0	1	15
2003	0	0	0	0	0	1	1	1	1	0	1	1	1	7
2004	0	0	2	1	4	5	4	1	0	1	0	0	1	19
2005	0	0	0	2	0	0	0	2	0	1	1	1	0	7
<b>Sum</b>	1	1	4	14	10	18	17	12	9	4	8	4	3	105

**Table 5: Parameter estimates from fitting the estimated ages vs. true ages (Childerhouse et al. 2004) using two approaches as described in the text; “-LL” is the log-likelihood function.**

	Base case	Alternative
a	1.59	2.67
b	0.829	0.669
sigma	0.852	1.869
-LL	93.1	151.3

**Table 6: Uncorrected age estimates from randomly selected breeding females by year (Simon Childerhouse, personal communication; see Childerhouse et al. 2004).**

Year	1998	1999	2000	2001	Total
4	0	2	1	0	3
5	1	11	7	10	29
6	4	28	12	11	55
7	9	35	29	17	90
8	5	40	43	37	125
9	3	30	41	44	118
10	8	32	26	41	107
11	2	21	23	27	73
12	4	21	18	19	62
13	3	17	13	14	47
14	1	14	14	14	43
15	2	10	13	14	39
16	1	7	14	11	33
17	0	4	8	10	22
18	0	6	6	9	21
19	0	3	5	5	13
20	0	1	6	5	12
21	0	1	2	4	7
22	0	3	2	1	6
23	0	0	2	1	3
<b>Total</b>	43	286	285	294	908

**Table 7: Annual tows in SQU 6T: the left column shows extracts made by MPI; “estimated” was obtained from strike rate and bycatch estimates published by MPI (for 1988 and 1989 used to make estimates and for the remaining years as a veracity check); the next three columns show estimates from the authors indicated; “DG” indicates estimates from the Deepwater Group, its predecessor and Paul Starr (personal communication); “max” shows the maximum of the various estimates; the last two columns show the date of closure, if any, through the action of bycatch management, and the last column shows estimated effort that would have been made in the absence of closure.**

Year	MPI	estimated	Abraham (2008)	Smith/ Baird (2005a)	Smith/ Baird (2005b)	DG	max	closure	attempted tows
1988	687	1 833					1 833		1 833
1989	lost	3 811					3 811		3 811
1990	5 297	5 318					5 318		5 297
1991	3 331	3 500					3 500		3 331
1992	2 166	2 158		2 154	2 153		2 166		2 166
1993	674	654		707	656	644	707		674
1994	4 727			4 677	2 677	4 397	4 727		4 727
1995	4 040			4 005	4 000	3 623	4 040		4 040
1996	4 471			4 460	4 460	4 412	4 471	4-May	4 471
1997	3 743			3 710	3 708	3 534	3 743	28-Mar	6 082
1998	1 449			1 463	1 442	1 394	1 463	27-Mar	2 355
1999	405			402	399	392	405		405
2000	1 215		1 206	1 207	1 206	1 191	1 215	8-Mar	3 159
2001	583		582	307	588	562	588	7-Mar	1 516
2002	1 647		1 646	1 523	1 635	1 651	1 651	13-Apr	2 141
2003	1 468		1 466			1 383	1 468		1 468
2004	2 604		2 595	2 597		2 555	2 604		2 604
2005	2 697			2 693		2 646	2 697	20-Apr	3 187
2006	2 464					2 450	2 464		2 464
2007	1 318					1 318	1 318		1 318
2008	1 247					1 257	1 257		1 247
2009	1 846						1 846		1 846

**Table 8: SQU 6T bycatch estimates discussed in the text. The BKS estimates are from the Breen et al. (2005) model with data through to 2008 (Breen unpublished data). Mean values were rounded to the nearest sea lion for use as model input. The final column shows the BKS strike rate estimates.**

	IPP MFish 2006	Smith Baird 2005b	Smith Baird 2007a,b	Abraham 2008	BKS	default & discount	mean	BKS strike rate
1988	33						33	
1989	141						141	
1990	117						117	
1991	21						21	
1992	82	79					81	
1993	17	18					18	
1994	32	43					38	
1995	109	112					111	
1996	101	104					103	
1997	123	147					135	
1998	62	65					64	
1999	14	13					14	
2000	71	69		53			64	
2001	67	34		51			51	
2002	84	76		56	63	79	72	0.043
2003	39			36	45	62	45	0.038
2004	118		147	223	153	107	149	0.076
2005	115		101	109	110	113	109	0.052
2006	110			110	166	104	122	0.085
2007	-			56	63	56	58	0.072
2008	-				45	57	51	0.045
2009	-					83	83	

**Table 9: Observed sea lion bycatch for other fisheries. Species codes from left are jack mackerel, hoki, orange roughy, southern blue whiting, scampi and squid.**

	JMA/ JMM	HOK	ORH	SBW	SCI	SQU
1992					3	
1996	1	1			3	
1997			1		1	
1998			1			
2000	2	1				
2001					4	3
2002		1		1		
2003					2	
2004				1		
2005				2		3
2006				2		
2007				6	1	

**Table 10: Estimated parameters and their assigned estimation phase, bounds and prior information: 0 denotes a uniform prior probability distribution, 1 a normal and 2 a log-normal; a negative phase indicates a fixed parameter. The final column gives the base case MPD estimate, in which grey indicates fixed values.**

Parameter	Phase	Lower bound	Upper bound	Prior type	Prior mean	Prior CV	est. value
$K$	1	1	200000	0	0	0	6987
$NI$	1	1	100000	0	0	0	412.7
$R0$	3	0.1	0.5	1	0.3	0.025	0.377
$R^{decline}$	3	0	1	1	0.03	0.02	0.017
$z$	-1	0.25	8	0	0	0	3
$S0$	2	0.00005	0.95	0	0	0	0.908
$S1$	2	0.00005	0.95	0	0	0	0.894
$S2$	2	0.00005	0.95	0	0	0	0.950
$Surv(age\ 1)$	2	0.05	0.95	0	0	0	0.937
$Surv(age\ 4)$	2	0.05	0.95	0	0	0	0.934
$Surv(age\ 8)$	2	0.05	0.95	0	0	0	0.928
$Surv(age\ v13)$	2	0.05	0.95	0	0	0	0.833
$Surv(age\ 19)$	2	0.05	0.95	0	0	0	0.811
$Surv(age\ 26)$	2	0.05	0.95	0	0	0	0.549
$S1dev$	3	-0.96	0.96	1	0	1	
$Sdev$	3	-0.96	0.96	1	0	1	
$m_{50}$	2	0	15	0	0	0	5.445
$m_{95-50}$	2	0.1	25	0	0	0	2.067
$v_{50}$	2	0.01	25	0	0	0	2.217
$v_{95-50}$	2	0.01	25	0	0	0	1.556
$Q(1)$	1	0	1	0	0	0	0.184
$Q(2)$	1	0	1	0	0	0	0.755
$Q(3)$	1	0	1	0	0	0	0.041
$\sigma_1$	3	5	6000	0	0	0	35.1
$\sigma_2$	3	5	6000	0	0	0	111.0
$\sigma_3$	3	5	6000	0	0	0	18.9
$\sigma_4$	3	5	6000	0	0	0	13.7
$P_{breeding}^{resight}$	1	0.001	1	0	0	0	0.528
$P_{nonbreeding}^{resight}$	1	0.001	1	0	0	0	0.544
$P_{nonbreeding}^{B,resight}$	1	0.001	1	0	0	0	1.000
$P_{pupresight}$	2	0.001	1	0	0	0	0.841
$P_{BF,resight}$	-2	0.001	1	0	0	0	1
$Rmax$	-3	0	1	2	0.08	0.2	0.048

**Table 11: Base case: likelihood components from datasets, priors and penalties, dataset weights and the resulting standard deviations of normalised residuals (sdnr) for each dataset.**

<b>Dataset</b>	<b>-LL</b>	<b>switch</b>	<b>weight</b>	<b>sdnr</b>
pupcounts	422.0	1	1.01	1.00
tagged female pup resightings	1009.5	1	0.2	1.41
pups from tagged females	178.1	1	1.088	1.00
1999 tagged adult resightings	295.4	1	0.69	1.02
2001 tagged adult resightings	177.7	1	0.856	1.00
branded female resightings	101.5	1	0.2	1.22
proportions-at-age in autopsies	47.2	1	0.717	1.00
proportions-at-age breeding females	49.4	1	1.276	1.00
pup mortality through mid-January	271.6	1	0.942	1.00
pup mortality through end February	51.1	1	2.919	1.01
<i>Rmax</i> prior likelihood contribution	2.7			
<i>S1dev</i> prior likelihood contribution	13.2			
<i>Sdev</i> prior likelihood contribution	20.2			
<i>RO</i> prior likelihood contribution	2.0			
<i>R<sup>decline</sup></i> prior likelihood contribution	-2.8			
penalty on population proportions	0.0			
penalty on negative numbers <i>N</i> :	0.0			
<i>STRO</i> penalty:	0.0			
penalty on negative <i>Rmax</i> :	0.0			
penalty on high survival rate:	6.5			
Total function value	2645.6			

**Table 12: Summaries of the base case McMC posterior distributions of dataset likelihoods, some estimated parameters and the derived parameter  $R_{max}$ .**

	<b>0.05</b>	<b>median</b>	<b>mean</b>	<b>0.95</b>
total function value	2666.2	2673.8	2674.1	2683.3
tagged female pup resightings	426.2	431.2	431.6	438.1
pups from tagged females	1008.6	1012.1	1012.2	1016.4
1999 tagged adult resightings	176.4	180.2	180.2	184.2
1999 tagged adult resightings	294.6	296.1	296.2	298.1
2001 tagged adult resightings	176.3	178.8	178.9	182.1
branded female resightings	100.5	102.2	102.4	104.9
proportions-at-age in autopsies	46.3	47.9	48.2	50.8
proportions-at-age breeding females	48.0	50.9	51.1	54.8
pup mortality through mid-January	268.8	271.3	271.4	274.2
pup mortality through end February	53.3	57.0	57.2	61.9
$R_{max}$ prior likelihood contribution	1.2	3.1	3.3	6.2
$S1_{dev}$ prior likelihood contribution	12.4	13.0	13.0	13.7
$S_{dev}$ prior likelihood contribution	19.4	20.0	20.0	20.7
$R_0$ prior likelihood contribution	-1.0	1.6	1.9	5.7
$R^{decline}$ prior likelihood contribution	-3.0	-2.9	-2.8	-2.2
$K$	6532	7135	7152	7818
$N1$	353	962	981	1662
$R_0$	0.347	0.374	0.375	0.403
$R^{decline}$	0.004	0.021	0.022	0.040
$uS_0$	-2.456	-2.264	-2.270	-2.106
$uS_1$	-2.449	-2.192	-2.201	-1.976
$uS_2$	-2.941	-2.910	-2.888	-2.783
$uSurv(1)$	-2.915	-2.669	-2.645	-2.295
$uSurv(2)$	-2.902	-2.660	-2.649	-2.351
$uSurv(3)$	-2.874	-2.593	-2.595	-2.315
$uSurv(4)$	-1.867	-1.637	-1.642	-1.431
$uSurv(5)$	-1.959	-1.530	-1.549	-1.192
$uSurv(6)$	-1.165	-0.166	-0.169	0.762
$m_{50}$	5.230	5.457	5.459	5.698
$m_{95-50}$	1.760	2.118	2.132	2.557
$v_{50}$	1.619	2.284	2.292	3.001
$v_{95-50}$	1.036	1.802	1.898	3.057
$Q(1)$	0.178	0.184	0.184	0.191
$Q(2)$	0.747	0.755	0.755	0.763
$Q(3)$	0.038	0.041	0.041	0.044
$\sigma_1$	29.9	38.5	39.2	50.9
$\sigma_2$	104.7	139.8	142.8	194.3
$\sigma_3$	15.5	20.6	21.2	28.5
$\sigma_4$	11.2	15.5	16.3	23.6
$P_{breeding}^{resight}$	0.466	0.530	0.532	0.600
$P_{nonbreeding}^{resight}$	0.408	0.522	0.526	0.654
$P_{nonbreeding}^{B,resight}$	0.578	0.880	0.843	0.990
$P_{pupresight}$	0.734	0.855	0.855	0.972
$R_{max}$	0.039	0.047	0.047	0.056



**Table 13: Summary of posterior distributions of evaluation results from rule 2, using the base case operating model and assuming a discount rate of zero.**

Rule	0	2	2	2	2	2	2	1
multiplier		50	100	150	200	250	300	
<i>MFish1</i>		99.89	90.84	73.67	63.07	57.25	54.61	53.63
<i>MFish2</i>	0.949	0.921	0.893	0.871	0.856	0.846	0.841	0.839
<i>DOC1</i>		20.00	18.06	12.67	10.05	8.89	8.46	8.30
<i>DOC2</i>	0.941	0.925	0.892	0.856	0.827	0.803	0.789	0.784
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6639	6404	6239	6119	6054	6018	6005
<i>N20/K</i>	0.961	0.928	0.896	0.872	0.855	0.845	0.840	0.838
<i>nadir</i>	4820	4756	4660	4566	4499	4444	4417	4405
<i>nadir/K</i>	0.677	0.667	0.655	0.642	0.632	0.626	0.622	0.620
<i>%mat</i>	0.469	0.463	0.457	0.453	0.450	0.449	0.448	0.448
<i>maxcatch</i>	0.0	105.3	193.8	276.5	354.9	425.5	479.1	513.4
<i>meancatch</i>	0.0	49.6	91.1	118.3	135.2	145.0	149.6	151.5
<i>Umax</i>	0.0034	0.0155	0.0262	0.0369	0.0472	0.0569	0.0647	0.0698
<i>Umean</i>	0.0026	0.0090	0.0146	0.0184	0.0208	0.0223	0.0230	0.0233
<i>meanFRML</i>	0	50	100	150	200	250	300	0
<i>minFRML</i>	0	50	100	150	200	250	300	0
<i>maxFRML</i>	0	50	100	150	200	250	300	0
<i>closure</i>	100	91	71	42	27	17	7	0
<i>effortlost</i>	2737	1883	1147	647	325	130	35	0
<i>pupmin</i>	1257	1235	1207	1182	1163	1151	1145	1142
<i>pupmax</i>	4319	4172	4042	3942	3881	3840	3820	3812
<i>puprange</i>	3075	2949	2834	2758	2711	2685	2670	2664

**Table 14: Summary of posterior distributions of results from rule 3, using the base case operating model and assuming a discount rate of zero. See the caption for Table 13.**

Rule	0	3	3	3	3	3	3	1
multiplier		0.5	1.0	1.5	2.0	3.0	5.0	
<i>MFish1</i>		100.00	99.99	98.17	89.80	71.41	56.80	53.63
<i>MFish2</i>	0.949	0.933	0.917	0.901	0.888	0.867	0.846	0.839
<i>DOC1</i>		20.00	20.00	19.83	17.57	12.15	8.93	8.30
<i>DOC2</i>	0.941	0.934	0.925	0.908	0.889	0.854	0.806	0.784
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6734	6593	6467	6357	6208	6041	6005
<i>N20/K</i>	0.961	0.941	0.921	0.903	0.888	0.866	0.844	0.838
<i>nadir</i>	4820	4806	4765	4717	4666	4579	4458	4405
<i>nadir/K</i>	0.677	0.674	0.669	0.662	0.656	0.643	0.627	0.620
<i>%mat</i>	0.469	0.465	0.461	0.458	0.455	0.452	0.449	0.448
<i>maxcatch</i>	0.0	81.6	149.0	210.0	263.3	356.9	472.1	513.4
<i>meancatch</i>	0.0	31.5	59.3	82.9	101.3	125.5	146.4	151.5
<i>Umax</i>	0.0034	0.0122	0.0203	0.0277	0.0343	0.0463	0.0626	0.0698
<i>Umean</i>	0.0026	0.0066	0.0102	0.0133	0.0158	0.0192	0.0224	0.0233
<i>meanFRML</i>	0	30.5441	60.0827	88.6816	116.6	171.332	279.165	0
<i>minFRML</i>	0	18.5221	36.7942	54.7024	72.2567	106.528	173.466	0
<i>maxFRML</i>	0	47.6797	93.3827	137.438	180.412	264.419	431.647	0
<i>closure</i>	100	96	89	76	62	38	12	0
<i>effortlost</i>	2737	2202	1724	1310	980	524	107	0
<i>pupmin</i>	1257	1248	1237	1222	1208	1182	1153	1142
<i>pupmax</i>	4319	4228	4141	4065	3999	3913	3832	3812
<i>puprange</i>	3075	2988	2911	2843	2796	2730	2677	2664

**Table 15: Summary of posterior distributions of results from rule 2, using the base case operating model and assuming a discount rate of 20%. See the caption for Table 13.**

<b>Rule</b>	<b>0</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>1</b>
<b>multiplier</b>		<b>50</b>	<b>100</b>	<b>150</b>	<b>200</b>	<b>250</b>	<b>300</b>	
<i>MFish1</i>		99.91	93.18	80.87	73.54	70.61	69.93	69.93
<i>MFish2</i>	0.949	0.922	0.897	0.881	0.871	0.867	0.866	0.866
<i>DOC1</i>		20.00	18.69	14.89	12.82	12.08	11.93	11.93
<i>DOC2</i>	0.941	0.926	0.898	0.875	0.859	0.851	0.848	0.848
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6643	6437	6306	6236	6205	6199	6199
<i>N20/K</i>	0.961	0.928	0.900	0.882	0.871	0.867	0.866	0.866
<i>nadir</i>	4820	4756	4673	4607	4561	4540	4537	4537
<i>nadir/K</i>	0.677	0.668	0.657	0.648	0.642	0.639	0.638	0.638
<i>%mat</i>	0.469	0.463	0.457	0.455	0.453	0.452	0.452	0.452
<i>maxcatch</i>	0.0	102.9	191.1	273.1	345.7	397.1	418.1	418.1
<i>meancatch</i>	0.0	49.1	85.9	106.9	117.9	122.3	123.4	123.4
<i>Umax</i>	0.0034	0.0151	0.0258	0.0363	0.0460	0.0534	0.0564	0.0564
<i>Umean</i>	0.0026	0.0089	0.0139	0.0168	0.0183	0.0189	0.0191	0.0191
<i>meanFRML</i>	0	50	100	150	200	250	300	0
<i>minFRML</i>	0	50	100	150	200	250	300	0
<i>maxFRML</i>	0	50	100	150	200	250	300	0
<i>closure</i>	100	91	57	30	17	4	0	0
<i>effortlost</i>	2737	1681	865	389	130	24	0	0
<i>pupmin</i>	1257	1236	1211	1193	1182	1177	1176	1176
<i>pupmax</i>	4319	4173	4060	3986	3946	3928	3924	3924
<i>puprange</i>	3075	2950	2849	2795	2763	2752	2751	2751

**Table 16: Summary of posterior distributions of results from rule 3, using the base case operating model and assuming a discount rate of 20%. See the caption for Table 13.**

<b>Rule</b>	<b>0</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>
<b>multiplier</b>		<b>0.5</b>	<b>1.0</b>	<b>1.5</b>	<b>2.0</b>	<b>3.0</b>	<b>5.0</b>	
<i>MFish1</i>		100.00	99.99	98.63	92.91	79.84	70.76	69.93
<i>MFish2</i>	0.949	0.933	0.917	0.904	0.893	0.878	0.868	0.866
<i>DOC1</i>		20.00	20.00	19.90	18.54	14.63	12.14	11.93
<i>DOC2</i>	0.941	0.934	0.924	0.910	0.897	0.874	0.853	0.848
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6739	6600	6487	6399	6288	6209	6199
<i>N20/K</i>	0.961	0.942	0.922	0.906	0.894	0.879	0.868	0.866
<i>nadir</i>	4820	4807	4764	4722	4679	4613	4546	4537
<i>nadir/K</i>	0.677	0.674	0.669	0.663	0.658	0.648	0.640	0.638
<i>%mat</i>	0.469	0.465	0.461	0.458	0.456	0.454	0.452	0.452
<i>maxcatch</i>	0.0	79.6	145.9	204.4	256.6	339.0	411.0	418.1
<i>meancatch</i>	0.0	31.2	58.1	79.0	93.8	111.6	122.4	123.4
<i>Umax</i>	0.0034	0.0120	0.0199	0.0269	0.0336	0.0442	0.0548	0.0564
<i>Umean</i>	0.0026	0.0066	0.0101	0.0128	0.0148	0.0173	0.0189	0.0191
<i>meanFRML</i>	0	30.5495	60.1132	88.9021	117.21	173.248	285.6	0
<i>minFRML</i>	0	18.5219	36.8196	54.7496	72.4503	107.289	176.781	0
<i>maxFRML</i>	0	47.6977	93.4542	137.989	181.682	268.322	442.889	0
<i>closure</i>	100	94	83	64	48	25	4	0
<i>effortlost</i>	2737	2076	1497	1039	702	289	22	0
<i>pupmin</i>	1257	1248	1237	1223	1211	1192	1178	1176
<i>pupmax</i>	4319	4229	4146	4078	4025	3967	3928	3924
<i>puprange</i>	3075	2989	2915	2856	2820	2774	2752	2751

**Table 17: Summary of posterior distributions of results from rule 2, using the base case operating model and assuming a discount rate of 35%. See the caption for Table 13.**

<b>Rule</b>	<b>0</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>1</b>
<b>multiplier</b>		<b>50</b>	<b>100</b>	<b>150</b>	<b>200</b>	<b>250</b>	<b>300</b>	
<i>MFish1</i>		99.92	95.66	88.07	84.34	83.64	83.64	83.64
<i>MFish2</i>	0.949	0.922	0.902	0.890	0.886	0.885	0.885	0.885
<i>DOC1</i>		20.00	19.34	17.13	16.02	15.83	15.83	15.83
<i>DOC2</i>	0.941	0.926	0.903	0.888	0.880	0.879	0.879	0.879
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6648	6474	6385	6348	6344	6344	6344
<i>N20/K</i>	0.961	0.929	0.905	0.893	0.887	0.886	0.886	0.886
<i>nadir</i>	4820	4758	4689	4641	4622	4616	4616	4616
<i>nadir/K</i>	0.677	0.668	0.659	0.653	0.650	0.650	0.650	0.650
<i>%mat</i>	0.469	0.463	0.458	0.456	0.456	0.455	0.455	0.455
<i>maxcatch</i>	0.0	100.7	187.5	266.0	323.9	343.4	343.4	343.4
<i>meancatch</i>	0.0	48.3	79.2	94.5	100.4	101.4	101.4	101.4
<i>Umax</i>	0.0034	0.0148	0.0254	0.0356	0.0435	0.0463	0.0463	0.0463
<i>Umean</i>	0.0026	0.0089	0.0130	0.0151	0.0159	0.0160	0.0160	0.0160
<i>meanFRML</i>	0	50	100	150	200	250	300	0
<i>minFRML</i>	0	50	100	150	200	250	300	0
<i>maxFRML</i>	0	50	100	150	200	250	300	0
<i>closure</i>	100	83	41	20	5	0	0	0
<i>effortlost</i>	2737	1456	618	193	28	0	0	0
<i>pupmin</i>	1257	1236	1216	1202	1199	1198	1198	1198
<i>pupmax</i>	4319	4175	4080	4031	4009	4004	4004	4004
<i>puprange</i>	3075	2953	2866	2831	2816	2813	2813	2813

**Table 18: Summary of posterior distributions of results from rule 3, using the base case operating model and assuming a discount rate of 35%. See the caption for Table 13.**

<b>Rule</b>	<b>0</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>
<b>multiplier</b>		<b>0.5</b>	<b>1.0</b>	<b>1.5</b>	<b>2.0</b>	<b>3.0</b>	<b>5.0</b>	
<i>MFish1</i>		100.00	99.99	99.08	95.74	87.95	83.77	83.64
<i>MFish2</i>	0.949	0.933	0.918	0.907	0.898	0.889	0.885	0.885
<i>DOC1</i>		20.00	20.00	19.95	19.31	17.10	15.88	15.83
<i>DOC2</i>	0.941	0.934	0.925	0.914	0.903	0.890	0.879	0.879
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6739	6611	6515	6447	6378	6344	6344
<i>N20/K</i>	0.961	0.942	0.923	0.910	0.901	0.891	0.886	0.886
<i>nadir</i>	4820	4807	4765	4726	4694	4648	4617	4616
<i>nadir/K</i>	0.677	0.674	0.669	0.664	0.660	0.653	0.650	0.650
<i>%mat</i>	0.469	0.465	0.462	0.459	0.457	0.456	0.455	0.455
<i>maxcatch</i>	0.0	78.3	143.0	199.2	246.3	310.8	342.7	343.4
<i>meancatch</i>	0.0	30.8	56.3	73.8	85.3	97.0	101.3	101.4
<i>Umax</i>	0.0034	0.0118	0.0195	0.0264	0.0323	0.0410	0.0460	0.0463
<i>Umean</i>	0.0026	0.0065	0.0098	0.0121	0.0137	0.0153	0.0160	0.0160
<i>meanFRML</i>	0	30.5566	60.1835	89.2107	117.938	175.168	290.788	0
<i>minFRML</i>	0	18.5221	36.8292	54.8048	72.6342	107.988	179.259	0
<i>maxFRML</i>	0	47.7197	93.6265	138.601	183.046	271.974	451.803	0
<i>closure</i>	100	92	74	52	35	14	0	0
<i>effortlost</i>	2737	1932	1260	781	463	128	0	0
<i>pupmin</i>	1257	1248	1237	1225	1215	1203	1198	1198
<i>pupmax</i>	4319	4230	4151	4096	4058	4017	4005	4004
<i>puprange</i>	3075	2990	2921	2874	2847	2820	2813	2813

**Table 19: Summary of posterior distributions of results from rule 2, using the base case operating model and assuming a discount rate of 50%. See the caption for Table 13.**

Rule	0	2	2	2	2	2	2	1
multiplier		50	100	150	200	250	300	
<i>MFish1</i>		99.95	98.04	95.53	95.09	95.09	95.09	95.09
<i>MFish2</i>	0.949	0.923	0.908	0.902	0.902	0.902	0.902	0.902
<i>DOC1</i>		20.00	19.80	19.23	19.11	19.11	19.11	19.11
<i>DOC2</i>	0.941	0.926	0.912	0.904	0.903	0.903	0.903	0.903
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6661	6530	6484	6479	6479	6479	6479
<i>N20/K</i>	0.961	0.930	0.912	0.906	0.905	0.905	0.905	0.905
<i>nadir</i>	4820	4763	4710	4692	4689	4689	4689	4689
<i>nadir/K</i>	0.677	0.669	0.662	0.660	0.659	0.659	0.659	0.659
<i>%mat</i>	0.469	0.463	0.460	0.459	0.459	0.459	0.459	0.459
<i>maxcatch</i>	0.0	98.6	183.0	248.9	266.6	266.6	266.6	266.6
<i>meancatch</i>	0.0	46.2	69.6	77.7	78.7	78.7	78.7	78.7
<i>Umax</i>	0.0034	0.0145	0.0249	0.0336	0.0362	0.0362	0.0362	0.0362
<i>Umean</i>	0.0026	0.0086	0.0117	0.0127	0.0129	0.0129	0.0129	0.0129
<i>meanFRML</i>	0	50	100	150	200	250	300	0
<i>minFRML</i>	0	50	100	150	200	250	300	0
<i>maxFRML</i>	0	50	100	150	200	250	300	0
<i>closure</i>	100	71	27	7	0	0	0	0
<i>effortlost</i>	2737	1147	325	35	0	0	0	0
<i>pupmin</i>	1257	1237	1222	1215	1214	1214	1214	1214
<i>pupmax</i>	4319	4182	4114	4085	4083	4083	4083	4083
<i>puprange</i>	3075	2958	2898	2877	2875	2875	2875	2875

**Table 20: Summary of posterior distributions of results from rule 3, using the base case operating model and assuming a discount rate of 50%. See the caption for Table 13.**

Rule	0	3	3	3	3	3	3	1
multiplier		0.5	1.0	1.5	2.0	3.0	5.0	
<i>MFish1</i>		100.00	100.00	99.57	98.28	95.77	95.09	95.09
<i>MFish2</i>	0.949	0.933	0.920	0.912	0.907	0.902	0.902	0.902
<i>DOC1</i>		20.00	20.00	19.99	19.84	19.29	19.11	19.11
<i>DOC2</i>	0.941	0.934	0.926	0.919	0.912	0.904	0.903	0.903
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6741	6632	6560	6518	6484	6479	6479
<i>N20/K</i>	0.961	0.942	0.926	0.916	0.910	0.906	0.905	0.905
<i>nadir</i>	4820	4807	4768	4738	4715	4694	4689	4689
<i>nadir/K</i>	0.677	0.674	0.670	0.666	0.663	0.660	0.659	0.659
<i>%mat</i>	0.469	0.465	0.462	0.460	0.459	0.459	0.459	0.459
<i>maxcatch</i>	0.0	76.4	138.3	189.2	227.2	261.3	266.6	266.6
<i>meancatch</i>	0.0	30.3	52.6	65.6	72.9	78.0	78.7	78.7
<i>Umax</i>	0.0034	0.0116	0.0190	0.0253	0.0302	0.0351	0.0362	0.0362
<i>Umean</i>	0.0026	0.0065	0.0093	0.0111	0.0121	0.0128	0.0129	0.0129
<i>meanFRML</i>	0	30.5626	60.3113	89.6774	118.921	177.597	295.82	0
<i>minFRML</i>	0	18.5243	36.855	54.9333	72.9731	108.95	181.457	0
<i>maxFRML</i>	0	47.7394	93.918	139.5	184.976	276.264	460.315	0
<i>closure</i>	100	89	60	36	20	4	0	0
<i>effortlost</i>	2737	1708	940	475	213	24	0	0
<i>pupmin</i>	1257	1248	1237	1229	1222	1216	1214	1214
<i>pupmax</i>	4319	4231	4161	4124	4100	4084	4083	4083
<i>puprange</i>	3075	2992	2932	2901	2882	2875	2875	2875

**Table 21: Summary of posterior distributions of results from rule 3, using the base case operating model and assuming a discount rate of 65%. See the caption for Table 13.**

<b>DRate</b>	<b>0.65</b>	<b>0.65</b>	<b>0.65</b>	<b>0.65</b>	<b>0.65</b>	<b>0.65</b>	<b>0.65</b>	<b>0.65</b>
<b>rule</b>	<b>0</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>
<b>mult</b>	<b>0.50</b>	<b>1.25</b>	<b>1.50</b>	<b>2.00</b>	<b>3.00</b>	<b>5.00</b>		
<i>MFish1</i>		100.00	99.98	99.93	99.76	99.60	99.58	99.58
<i>MFish2</i>	0.949	0.934	0.921	0.920	0.918	0.917	0.917	0.917
<i>DOC1</i>		20.00	20.00	20.00	19.99	19.98	19.98	19.98
<i>DOC2</i>	0.941	0.934	0.926	0.925	0.923	0.922	0.921	0.921
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6746	6646	6630	6616	6611	6611	6611
<i>N20/K</i>	0.961	0.943	0.928	0.926	0.924	0.923	0.923	0.923
<i>nadir</i>	4820	4807	4766	4756	4746	4743	4743	4743
<i>nadir/K</i>	0.677	0.674	0.669	0.668	0.667	0.666	0.666	0.666
<i>%mat</i>	0.469	0.465	0.463	0.462	0.462	0.462	0.462	0.462
<i>maxcatch</i>	0	73.8	151.5	167.1	183.3	188.3	188.3	188.3
<i>meancatch</i>	0	29.1	49.8	52.5	54.9	55.6	55.6	55.6
<i>Umax</i>	0.0034	0.0113	0.0208	0.0228	0.0252	0.0261	0.0261	0.0261
<i>Umean</i>	0.0026	0.0063	0.0090	0.0094	0.0097	0.0098	0.0098	0.0098
<i>meanFRML</i>	0	30.58	75.48	90.40	120.31	180.40	300.67	0.00
<i>minFRML</i>	0	18.53	46.03	55.14	73.42	110.04	183.40	0.00
<i>maxFRML</i>	0	47.79	117.68	140.96	187.65	281.37	468.95	0.00
<i>closure</i>	100	77	25	16	5	0	0	0
<i>effortlost</i>	2737	1328	295	156	32	0	0	0
<i>pupmin</i>	1257	1248	1236	1234	1232	1231	1231	1231
<i>pupmax</i>	4319	4236	4173	4164	4158	4155	4155	4155
<i>puprange</i>	3075	2997	2943	2939	2935	2935	2935	2935

**Table 22: Summary of posterior distributions of results from rule 3, using the base case operating model and assuming a discount rate of 75%. See the caption for Table 13.**

<b>DRate</b>	<b>0.75</b>	<b>0.75</b>	<b>0.75</b>	<b>0.75</b>	<b>0.75</b>	<b>0.75</b>	<b>0.75</b>	<b>0.75</b>
<b>rule</b>	<b>0</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>
<b>mult</b>	<b>0.50</b>	<b>1.00</b>	<b>1.50</b>	<b>2.00</b>	<b>3.00</b>	<b>5.00</b>		
<i>MFish1</i>		100.00	100.00	99.99	99.98	99.98	99.98	99.98
<i>MFish2</i>	0.949	0.935	0.929	0.927	0.927	0.927	0.927	0.927
<i>DOC1</i>		20.00	20.00	20.00	20.00	20.00	20.00	20.00
<i>DOC2</i>	0.941	0.934	0.929	0.928	0.928	0.928	0.928	0.928
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6760	6703	6694	6693	6693	6693	6693
<i>N20/K</i>	0.961	0.945	0.937	0.935	0.935	0.935	0.935	0.935
<i>nadir</i>	4820	4806	4785	4774	4772	4772	4772	4772
<i>nadir/K</i>	0.677	0.674	0.672	0.671	0.670	0.670	0.670	0.670
<i>%mat</i>	0.469	0.466	0.464	0.464	0.464	0.464	0.464	0.464
<i>maxcatch</i>	0.0	70.6	116.4	132.9	135.3	135.3	135.3	135.3
<i>meancatch</i>	0.0	26.7	37.1	39.6	39.8	39.9	39.9	39.9
<i>Umax</i>	0.0034	0.0109	0.0166	0.0189	0.0194	0.0194	0.0194	0.0194
<i>Umean</i>	0.0026	0.0060	0.0074	0.0077	0.0077	0.0077	0.0077	0.0077
<i>meanFRML</i>	0.00	30.62	60.85	91.13	121.48	182.21	303.68	0.00
<i>minFRML</i>	0.00	18.54	36.94	55.34	73.77	110.65	184.42	0.00
<i>maxFRML</i>	0.00	47.87	95.03	142.33	189.77	284.66	474.43	0.00
<i>closure</i>	100	59	19	3	0	0	0	0
<i>effortlost</i>	2737	921	197	20	0	0	0	0
<i>pupmin</i>	1257	1248	1243	1240	1240	1240	1240	1240
<i>pupmax</i>	4319	4243	4210	4203	4203	4203	4203	4203
<i>puprange</i>	3075	3004	2974	2972	2973	2973	2973	2973

**Table 23: Summary of posterior distributions of results from rule 3, using the base case operating model and assuming a discount rate of 85%. See the caption for Table 13.**

<b>DRate</b>	<b>0.85</b>	<b>0.85</b>	<b>0.85</b>	<b>0.85</b>	<b>0.85</b>	<b>0.85</b>	<b>0.85</b>	<b>0.85</b>
<b>rule</b>	<b>0</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>1</b>
<b>mult</b>	<b>0.50</b>	<b>1.00</b>	<b>1.50</b>	<b>2.00</b>	<b>3.00</b>	<b>5.00</b>		
<i>MFish1</i>	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
<i>MFish2</i>	0.949	0.938	0.936	0.936	0.936	0.936	0.936	0.936
<i>DOC1</i>	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
<i>DOC2</i>	0.941	0.937	0.937	0.937	0.937	0.937	0.937	0.937
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6864	6782	6768	6767	6767	6767	6767	6767
<i>N20/K</i>	0.961	0.949	0.946	0.946	0.946	0.946	0.946	0.946
<i>nadir</i>	4820	4809	4801	4800	4800	4800	4800	4800
<i>nadir/K</i>	0.677	0.675	0.674	0.674	0.674	0.674	0.674	0.674
<i>%mat</i>	0.469	0.466	0.466	0.466	0.466	0.466	0.466	0.466
<i>maxcatch</i>	0.0	63.4	81.2	81.6	81.6	81.6	81.6	81.6
<i>meancatch</i>	0.0	21.1	23.9	24.0	24.0	24.0	24.0	24.0
<i>Umax</i>	0.0034	0.0101	0.0126	0.0127	0.0127	0.0127	0.0127	0.0127
<i>Umean</i>	0.0026	0.0053	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057
<i>meanFRML</i>	0.00	30.71	61.30	91.95	122.60	183.90	306.50	0.00
<i>minFRML</i>	0.00	18.55	37.03	55.54	74.05	111.08	185.13	0.00
<i>maxFRML</i>	0.00	48.06	95.96	143.93	191.90	287.85	479.76	0.00
<i>closure</i>	100	28	1	0	0	0	0	0
<i>effortlost</i>	2737	344	7	0	0	0	0	0
<i>pupmin</i>	1257	1250	1247	1247	1247	1247	1247	1247
<i>pupmax</i>	4319	4261	4252	4252	4252	4252	4252	4252
<i>puprange</i>	3075	3018	3010	3010	3010	3010	3010	3010

**Table 24: Performance of rule 320 with the base case model under each of the assumed discount rates.**

<b>DRate</b>	<b>0.00</b>	<b>0.20</b>	<b>0.35</b>	<b>0.50</b>	<b>0.65</b>	<b>0.75</b>	<b>0.85</b>
<b>rule</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>	<b>3</b>
<b>mult</b>	<b>2.00</b>	<b>2.00</b>	<b>2.00</b>	<b>2.00</b>	<b>2.00</b>	<b>2.00</b>	<b>2.00</b>
<i>MFish1</i>	89.80	92.91	95.74	98.28	99.76	99.98	100.00
<i>MFish2</i>	0.888	0.893	0.898	0.907	0.918	0.927	0.936
<i>DOC1</i>	17.57	18.54	19.31	19.84	19.99	20.00	20.00
<i>DOC2</i>	0.889	0.897	0.903	0.912	0.923	0.928	0.937
<i>Nmat0</i>	5251	5251	5251	5251	5251	5251	5251
<i>Nmat20</i>	6357	6399	6447	6518	6616	6693	6767
<i>N20/K</i>	0.888	0.894	0.901	0.910	0.924	0.935	0.946
<i>nadir</i>	4666	4679	4694	4715	4746	4772	4800
<i>nadir/K</i>	0.656	0.658	0.660	0.663	0.667	0.670	0.674
<i>%mat</i>	0.455	0.456	0.457	0.459	0.462	0.464	0.466
<i>maxcatch</i>	263.3	256.6	246.3	227.2	183.3	135.3	81.6
<i>meancatch</i>	101.3	93.8	85.3	72.9	54.9	39.8	24.0
<i>Umax</i>	0.0343	0.0336	0.0323	0.0302	0.0252	0.0194	0.0127
<i>Umean</i>	0.0158	0.0148	0.0137	0.0121	0.0097	0.0077	0.0057
<i>meanFRML</i>	116.60	117.21	117.94	118.92	120.31	121.48	122.60
<i>minFRML</i>	72.26	72.45	72.63	72.97	73.42	73.77	74.05
<i>maxFRML</i>	180.41	181.68	183.05	184.98	187.65	189.77	191.90
<i>closure</i>	62	48	35	20	5	0	0
<i>effortlost</i>	980	702	463	213	32	0	0
<i>pupmin</i>	1208	1211	1215	1222	1232	1240	1247
<i>pupmax</i>	3999	4025	4058	4100	4158	4203	4252
<i>puprange</i>	2796	2820	2847	2882	2935	2973	3010

**Table 25: Comparing performance of rule 320 evaluated with the base case operating model and data set, assuming a discount rate of 35%, with a trial that used bycatch estimates for 2002–09 calculated with a 35% discount rate (the base case data set used 20%).**

	<b>Base</b>	<b>Trial</b>
discount rate	0.35	0.35
rule	320	320
<i>K</i>	7135	7123
<i>Nmat0</i>	5251	5286
<i>Nmat20</i>	6447	6440
<i>N20/K</i>	0.901	0.902
<i>DOC1</i>	19.3	20.0
<i>DOC2</i>	0.903	0.888
<i>N100/K</i>	0.893	0.894
<i>MFish1</i>	95.7	100.0
<i>MFish2</i>	0.898	0.898
<i>nadir</i>	4694	4698
<i>nadir/K</i>	0.660	0.661
<i>%mat</i>	0.457	0.458
<i>maxcatch</i>	246.3	246.0
<i>meancatch</i>	85.3	85.1
<i>Umax</i>	0.032	0.032
<i>Umean</i>	0.014	0.014
<i>meanFRML</i>	117.9	117.9
<i>minFRML</i>	72.6	72.6
<i>maxFRML</i>	183.0	182.7
<i>closure</i>	35	35
<i>effortlost</i>	463	464
<i>pupmin</i>	1215	1216
<i>pupmax</i>	4058	4050
<i>puprange</i>	2847	2835

**Table 26: Comparing medians of the distributions of some estimated and derived parameters from the base case and alternative operating models.  $S(n)$  indicates survival at age  $n$ .**

	base	sens1	sens2	sens3	sens4	sens5	sens6
total function value	2673.8	2668.8	2669.0	2682.4	2667.5	2680.3	2673.6
$R_{max}$ prior contribution	3.130	0.109	0.000	3.912	3.780	6.032	3.162
$K$	7135.4	7333.7	6243.5	7230.7	7295.8	8574.1	7123.2
$NI$	962.3	1161.0	3212.0	1254.7	983.3	1199.7	992.5
$RO$	0.374	0.364	0.341	0.373	0.367	0.315	0.374
$R^{decline}$	0.021	0.025	0.039	0.031	0.018	0.029	0.021
$m_{50}$	5.46	5.50	5.66	5.47	5.47	5.28	5.46
$m_{95-50}$	2.12	2.11	2.09	2.06	2.17	1.88	2.11
$v_{50}$	2.28	2.32	2.71	2.37	2.26	2.25	2.29
$v_{95-50}$	1.80	1.84	2.13	1.88	1.75	1.82	1.80
$Q(1)$	0.184	0.184	0.184	0.185	0.184	0.185	0.184
$Q(2)$	0.755	0.755	0.755	0.755	0.755	0.755	0.755
$Q(3)$	0.041	0.041	0.041	0.041	0.041	0.041	0.041
$\sigma_1$	38.5	38.2	34.2	35.3	39.8	37.6	38.7
$\sigma_2$	139.8	136.7	134.1	140.4	143.9	143.5	138.9
$\sigma_3$	20.6	20.8	22.7	21.6	20.4	21.1	20.7
$\sigma_4$	15.5	15.6	16.5	16.0	15.4	15.8	15.5
$P_{breeding}^{resight}$	0.530	0.544	0.616	0.553	0.519	0.533	0.530
$P_{nonbreeding}^{resight}$	0.522	0.482	0.336	0.481	0.524	0.445	0.523
$P_{nonbreeding}^{B.resight}$	0.880	0.921	0.969	0.903	0.867	0.900	0.905
$P_{pupresight}$	0.855	0.844	0.766	0.840	0.865	0.884	0.853
$R_{max}$	0.047	0.040	0.002	0.044	0.045	0.039	0.047
$S(0)$	0.772	0.773	0.763	0.774	0.772	0.778	0.771
$S(1)$	0.935	0.931	0.915	0.933	0.936	0.941	0.936
$S(2)$	0.934	0.929	0.895	0.931	0.935	0.940	0.935
$S(5)$	0.933	0.928	0.876	0.930	0.934	0.940	0.934
$S(10)$	0.893	0.893	0.899	0.897	0.891	0.902	0.892
$S(15)$	0.832	0.835	0.852	0.837	0.832	0.842	0.832
$S(20)$	0.781	0.786	0.813	0.790	0.781	0.791	0.781
$S(25)$	0.581	0.585	0.619	0.605	0.570	0.594	0.580

**Table 27: Medians of posterior distributions of some indicators obtained under rule 0 (no fishing) from the base case and alternative operating models.**

	$N20/K$	$N100/K$	$N100$	$meanNK$	$pupmin$
base	96.1%	94.4%	6733	94.9%	1257
sens1	95.2%	94.0%	6895	94.6%	1246
sens2	94.5%	71.7%	4474	84.0%	791
sens3	94.5%	94.9%	6862	95.4%	1269
sens4	94.6%	93.9%	6848	93.8%	1222
sens5	96.4%	94.8%	8130	95.7%	1297



**Table 28: From the rule 2 family, the rule (constant FRML) that just met each of the key criteria for each operating model and for each assumed discount rate. Double plus signs indicate that the criterion was met under unrestrained fishing, while 0 indicates that the criterion was not met under no fishing.**

model	DRate			
	0%	20%	35%	50%
<i>MFish1</i>				
base	102	113	136	++
sens1	82	87	98	145
sens2	0	0	0	0
sens3	71	75	80	99
sens4	118	136	195	++
sens5	99	108	128	++
<i>MFish2</i>				
base	87	93	106	++
sens1	66	68	71	84
sens2	0	0	0	0
sens3	57	59	61	68
sens4	97	105	124	++
sens5	88	94	108	++
<i>DOC1</i>				
base	100	109	130	++
sens1	91	101	117	++
sens2	79	83	90	120
sens3	87	94	108	++
sens4	107	120	149	++
sens5	108	120	150	++
<i>DOC2</i>				
base	++	++	++	++
sens1	++	++	++	++
sens2	0	0	0	0
sens3	++	++	++	++
sens4	++	++	++	++
sens5	++	++	++	++

**Table 29: From the rule 3 family, the point (rule multipliers) at which the four main criteria fail under each assumed discount rate and each model. ++ indicates that rule 1 (no FRML) would meet the criterion; 0 indicates that the criterion would not be met even under no fishing.**

model	DRate						
	0%	20%	35%	50%	65%	75%	85%
<i><b>MFish1</b></i>							
base	1.99	2.20	2.68	++	++	++	++
sens1	1.65	1.75	1.96	3.06	++	++	++
sens2	0	0	0	0	0.40	0.42	0.55
sens3	1.42	1.49	1.60	1.99	++	++	++
sens4	2.30	2.64	4.01	++	++	++	++
sens5	1.91	2.10	2.52	++	++	++	++
<i><b>MFish2</b></i>							
base	1.54	1.66	1.90	++	++	++	++
sens1	1.16	1.20	1.27	1.50	++	++	++
sens2	0	0	0	0	0	0	0
sens3	1.00	1.02	1.06	1.19	++	++	++
sens4	1.74	1.92	2.30	++	++	++	++
sens5	1.55	1.66	1.92	++	++	++	++
<i><b>DOC1</b></i>							
base	1.93	2.12	2.54	++	++	++	++
sens1	1.86	2.02	2.36	++	++	++	++
sens2	1.72	1.82	2.01	2.81	++	++	++
sens3	1.75	1.87	1.75	++	++	++	++
sens4	2.06	2.31	2.92	++	++	++	++
sens5	2.09	2.34	2.96	++	++	++	++
<i><b>DOC2</b></i>							
base	++	++	++	++	++	++	++
sens1	++	++	++	++	++	++	++
sens2	0	0	0	0	0	0	0
sens3	++	++	++	++	++	++	++
sens4	++	++	++	++	++	++	++
sens5	++	++	++	++	++	++	++

**Table 30: Results from the 2008 sensitivity trials with 2009 base case results included for comparison. Values show the rules that just meet each of the four criteria tested. For rules in the rule 2 family, the value is the constant FRML; for rule 3 the value is the multiplier. Double plus signs indicate that the criterion was met under unrestrained fishing, while double minus signs indicate that the criterion was not met under no fishing; “n.a.” means that the criterion is not applicable.**

	trial	Constant FRML in rule 2				Multipliers in rule 3			
		<i>MFish1</i>	<i>MFish2</i>	<i>DOC1</i>	<i>DOC2</i>	<i>MFish1</i>	<i>MFish2</i>	<i>DOC1</i>	<i>DOC2</i>
2008 base case	1	++	++	209	++	++	++	3.7	++
alternative base case with assumed discount rate = 20%	–	150	169	139	++	2.7	2.8	2.5	++
2009 with discount rate = 35%		136	106	130	++	2.7	1.9	2.5	++
sensitivity trials									
assumed discount rate = 0	2	131	140	123	++	2.3	2.3	2.1	++
assumed discount rate = 50%	3	++	++	++	++	++	++	++	++
attempted effort from 16 weeks	4	182	250	164	++	3.2	4.4	2.8	++
bycatch x 1.5	5	129	147	119	++	2.3	2.5	2.1	++
no density-dependence	6	n/a	n/a	102	--	n/a	n/a	1.9	--
fixed RprobBreeding = 0.9	8	148	146	200	++	2.5	2.4	3.3	++
fixed $R0 = 0.31$	9	189	++	++	++	3.5	++	++	++
alternative $Rmax$ prior mean = 0.06	10	159	167	174	++	2.9	2.9	3.2	++
alternative $Rmax$ prior mean = 0.04	11	101	91	147	++	1.8	1.5	2.6	++
alternative fixed $z = 2$	12	101	96	137	++	1.8	1.6	2.4	++
alternative fixed $z = 4.1$	13	++	++	++	++	++	++	++	++
lower HiS penalty floor = 0.93	14	137	150	158	++	2.4	2.6	2.7	++
higher HiS penalty floor = 0.97	15	++	++	++	++	++	++	++	++
alternative AETM	16	++	++	239	++	++	++	3.9	++
resampling $q$ from 1988	18	++	++	++	++	++	++	++	++

**Table 31: MPD values for the noSbound base case and the six trials requested by the reviewers compared with the 2011 base case.**

	2011 base	noSbound	noDD	Z1	Z2	vuln26	propQ	rely1
dataset	<b>sdnrs</b>							
pupcounts	1.00	0.999	0.992	0.999	0.999	0.999	0.999	0.999
tagFpup	1.41	1.101	1.634	1.730	1.192	1.103	1.101	1.124
puptagFpup	1.00	0.920	1.028	1.023	0.946	0.919	0.920	0.908
tagA99	1.02	1.000	1.102	1.055	1.008	1.002	1.000	0.998
tagA01	1.00	0.999	1.052	1.018	0.999	1.002	0.999	1.005
BF	1.22	1.252	1.195	1.221	1.268	1.254	1.252	1.274
Auto	1.00	1.065	1.019	0.991	1.035	1.067	1.065	1.078
Pop	1.00	0.982	0.910	0.978	1.021	0.979	0.982	0.969
pupmortJan	1.00	0.998	1.020	1.004	1.000	0.998	0.998	0.994
pupmortFeb	1.01	0.943	0.904	0.967	0.913	0.947	0.943	0.884
	<b>-LLs</b>							
pupcounts	422.01	425.3	458.9	421.9	424.9	425.4	425.3	425.4
tagFpup	1009.50	1004.6	1013.6	1015.4	1005.9	1004.6	1004.6	1004.9
puptagFpup	178.14	170.8	181.2	180.8	172.9	170.7	170.8	169.8
tagA99	295.44	294.6	295.9	296.0	295.3	294.6	294.6	294.5
tagA01	177.74	177.7	176.6	177.0	177.8	177.8	177.7	178.0
BF	101.55	102.0	101.7	101.6	102.2	102.0	102.0	102.4
Auto	47.24	50.6	47.1	46.9	49.6	50.7	50.6	51.4
Pop	49.36	46.1	42.7	47.5	49.7	45.8	46.1	44.7
pupmortJan	271.63	271.3	273.9	272.2	271.4	271.3	271.3	270.8
pupmortFeb	51.14	50.7	50.9	51.1	50.3	50.8	50.7	50.0
	<b>priors</b>							
RmaxPriorlike:	2.7	-0.3	27.6	2.6	-0.6	-0.3	-0.3	0.0
S1devPriorlike:	13.2	13.1	13.2	13.0	13.1	13.1	13.1	13.1
SdevPriorlike:	20.2	21.9	23.2	22.2	22.7	21.9	21.9	21.8
R0Priorlike	2.0	-2.1	-1.2	-1.1	-1.5	-2.1	-2.1	-2.2
RdeclinePriorlike	-2.8	-2.9	-2.8	-2.8	-3.0	-2.9	-2.9	-3.0
<b>TotalLL</b>	<b>2645.6</b>	<b>2623.3</b>	<b>2702.6</b>	<b>2644.5</b>	<b>2630.8</b>	<b>2623.5</b>	<b>2623.3</b>	<b>2621.6</b>
	<b>pars</b>							
<i>K</i>	6987.1	8200.3	<b>100000.0</b>	7889.8	7915.3	8169.7	8200.3	8307.4
<i>NI</i>	412.7	205.5	570.6	1610.1	202.3	204.3	205.5	227.9
<i>R0</i>	0.377	0.3284	0.3443	0.3457	0.3404	0.3284	0.3284	0.3262
<i>Rdecline</i>	0.0170	0.0213	0.0411	0.0428	0.0269	0.0204	0.0213	0.0248
<i>z</i>	3	3	3	<b>1.011</b>	<b>2</b>	3	3	3
<i>S0</i>	0.908	0.907	0.914	0.910	0.908	0.907	0.907	0.906
<i>S1</i>	0.894	0.888	0.887	0.889	0.890	0.888	0.888	0.887
<i>S2</i>	0.95	0.998	0.998	0.998	0.998	0.998	0.998	0.998
<i>Surv(age 1)</i>	0.937	0.998	0.998	0.998	0.987	0.998	0.998	0.973
<i>Surv(age 4)</i>	0.934	0.988	0.792	0.886	0.984	0.989	0.988	0.998
<i>Surv(age 8)</i>	0.928	0.925	0.969	0.965	0.944	0.922	0.925	0.923
<i>Surv(age 13)</i>	0.833	0.814	0.868	0.832	0.813	0.817	0.814	0.816
<i>Surv(age 19)</i>	0.811	0.820	0.901	0.853	0.827	0.829	0.820	0.822
<i>Surv(age 26)</i>	0.549	0.577	0.594	0.590	0.584	0.574	0.577	0.573
<i>Mat50</i>	5.444	5.481	5.579	5.367	5.360	5.472	5.481	5.441
<i>Mat95-50</i>	2.067	2.263	1.884	1.867	2.127	2.264	2.263	2.225
<i>v50</i>	2.217	2.026	3.116	2.399	2.027	<b>2.026</b>	2.026	2.044
<i>v95</i>	1.556	1.457	2.174	1.751	1.463	<b>1.457</b>	1.457	1.455
<i>propQ(1)</i>	0.184	0.184	0.187	0.185	0.184	0.184	0.184	0.183
<i>propQ(2)</i>	0.755	0.756	0.753	0.755	0.756	0.756	0.756	0.756
<i>propQ(3)</i>	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
<i>propQ(4)</i>	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019
<i>pcountStdDev(1)</i>	35.1	37.6	63.2	34.2	38.3	37.5	37.6	48.4
<i>pcountStdDev(2)</i>	111.0	129.0	190.1	101.3	119.8	130.1	129.0	195.1
<i>pcountStdDev(3)</i>	18.9	17.6	25.5	20.5	17.9	17.7	17.6	16.2
<i>pcountStdDev(4)</i>	13.7	13.3	16.6	14.5	13.4	13.3	13.3	12.5
<i>RProbBreed</i>	0.528	0.478	0.595	0.549	0.461	0.474	0.478	0.478

	<b>2011 base</b>	<b>noSbound</b>	<b>noDD</b>	<b>Z1</b>	<b>Z2</b>	<b>vuln26</b>	<b>propQ</b>	<b>rely1</b>
<i>RProbNonBreed</i>	0.544	0.509	0.288	0.429	0.567	0.512	0.509	0.506
<i>RProbBFNon</i>	1.000	0.983	1.000	0.989	0.960	0.982	0.983	0.981
<i>pupRProb</i>	0.841	0.925	0.690	0.811	0.948	0.928	0.925	0.922
<i>pupBFRProb</i>	1	1	1	1	1	1	1	1
<i>Rmax</i>	<b>0.048</b>	<b>0.068</b>	<b>0.018</b>	<b>0.049</b>	<b>0.075</b>	<b>0.068</b>	<b>0.068</b>	<b>0.065</b>
<i>S1dev(1998)</i>	-0.961	-0.961	-0.961	-0.961	-0.961	-0.961	-0.961	-0.961
<i>S1dev(1999)</i>	0.915	0.820	0.864	0.897	0.899	0.819	0.820	0.846
<i>S1dev(2000)</i>	0.701	0.744	0.601	0.641	0.732	0.744	0.744	0.781
<i>S1dev(2001)</i>	0.716	0.714	0.596	0.677	0.723	0.709	0.714	0.699
<i>S1dev(2002)</i>	-0.960	-0.961	-0.961	-0.961	-0.961	-0.961	-0.961	-0.961
<i>S1dev(2003)</i>	-0.556	-0.440	-0.596	-0.448	-0.445	-0.441	-0.440	-0.403
<i>S1dev(2004)</i>	-0.055	-0.016	-0.168	-0.046	-0.039	-0.018	-0.016	-0.025
<i>S1dev(2005)</i>	0.275	0.248	0.244	0.262	0.244	0.249	0.248	0.262
<i>S1dev(2006)</i>	-0.140	-0.186	-0.207	-0.147	-0.187	-0.185	-0.186	-0.210
<i>S1dev(2007)</i>	-0.147	-0.153	-0.074	-0.101	-0.163	-0.151	-0.153	-0.195
<i>S1dev(2008)</i>	-0.139	-0.175	-0.068	-0.151	-0.195	-0.174	-0.175	-0.206
<i>S1dev(2009)</i>	0.351	0.365	0.732	0.337	0.352	0.369	0.365	0.373
<i>Sdev(1990)</i>	-0.374	-0.936	0.960	0.668	-0.896	-0.926	-0.936	-0.862
<i>Sdev(1991)</i>	-0.526	-0.598	0.960	-0.102	-0.677	-0.579	-0.598	-0.404
<i>Sdev(1992)</i>	0.287	-0.036	-0.803	-0.888	-0.168	-0.002	-0.036	0.046
<i>Sdev(1993)</i>	0.549	0.960	-0.048	-0.089	0.960	0.960	0.960	0.960
<i>Sdev(1994)</i>	0.609	0.836	-0.318	0.960	0.960	0.848	0.836	0.960
<i>Sdev(1995)</i>	0.572	0.228	0.960	0.960	0.553	0.209	0.228	0.284
<i>Sdev(1996)</i>	0.610	0.898	0.960	0.960	0.960	0.891	0.898	0.734
<i>Sdev(1997)</i>	0.570	0.556	0.960	0.960	0.832	0.539	0.556	0.525
<i>Sdev(1998)</i>	-0.682	-0.914	-0.960	-0.458	-0.960	-0.918	-0.914	-0.960
<i>Sdev(1999)</i>	0.330	0.615	0.441	0.455	0.582	0.608	0.615	0.720
<i>Sdev(2000)</i>	0.050	-0.003	-0.820	-0.335	-0.045	-0.003	-0.003	-0.016
<i>Sdev(2001)</i>	-0.822	-0.728	-0.960	-0.960	-0.944	-0.715	-0.728	-0.636
<i>Sdev(2002)</i>	0.448	0.960	-0.334	0.499	0.960	0.960	0.960	0.939
<i>Sdev(2003)</i>	0.314	0.275	-0.353	-0.044	0.191	0.269	0.275	0.144
<i>Sdev(2004)</i>	-0.528	-0.596	-0.728	-0.868	-0.671	-0.594	-0.596	-0.558
<i>Sdev(2005)</i>	-0.147	-0.217	-0.740	-0.351	-0.258	-0.221	-0.217	-0.357
<i>Sdev(2006)</i>	0.313	0.450	0.697	0.520	0.452	0.450	0.450	0.319
<i>Sdev(2007)</i>	-0.615	-0.792	-0.833	-0.925	-0.870	-0.819	-0.792	-0.877
<i>Sdev(2008)</i>	-0.960	-0.960	0.960	-0.960	-0.960	-0.960	-0.960	-0.960
<i>NO</i>		10464.5	177315.0	20223.0	11035.0	10409.5	10464.5	10718.6

**Table 32: 2013 trials compared with the 2011 base case: from the rule 3 family, the point (rule multipliers) at which the four main criteria fail under each assumed discount rate and each model. ++ indicates that rule 1 (no FRML) would meet the criterion; 0 indicates that the criterion would not be met even under no fishing.**

model	DRate						
	0%	20%	35%	50%	65%	75%	85%
<b>MFish1</b>							
2011 base	1.99	2.20	2.68	++	++	++	++
noSbound	4.25	++	++	++	++	++	++
noSbound0.4	2.75	4.00	++	++	++	++	++
noSboundUniform	3.75	++	++	++	++	++	++
<b>MFish2</b>							
2011 base	1.54	1.66	1.90	++	++	++	++
noSbound	4.50	++	++	++	++	++	++
noSbound0.4	2.25	3.00	++	++	++	++	++
noSboundUniform	3.25	++	++	++	++	++	++
<b>DoC1</b>							
2011 base	1.93	2.12	2.54	++	++	++	++
noSbound	3.00	5.00	++	++	++	++	++
noSbound0.4	2.50	3.25	++	++	++	++	++
noSboundUniform	3.00	3.75	++	++	++	++	++
<b>DoC2</b>							
2011 base	++	++	++	++	++	++	++
noSbound	++	++	++	++	++	++	++
noSbound0.4	++	++	++	++	++	++	++
noSboundUniform	++	++	++	++	++	++	++

**Table 33: Comparing 2013 trials: Rule 0 (same result for all discount rates). FRML, catch and closure indicators are omitted.**

<b>Trial</b>	<b>noSbound</b>	<b>noDD</b>	<b>Z1</b>	<b>Z2</b>	<b>vuln26</b>	<b>rely1</b>
DRate	0%	0%	0%	0%	0%	0%
Rule	0	0	0	0	0	0
<i>MFish1</i>	0.00	0.00	0.00	0.00	0.00	0.00
<i>MFish2</i>	0.947	0.295	0.945	0.962	0.948	0.949
<i>DoC1</i>	0.0	0.0	0.0	0.0	0.0	0.0
<i>DoC2</i>	0.808	0.853	0.836	0.914	0.813	0.811
<i>N20/K</i>	0.909	0.108	0.903	0.953	0.913	0.907
<i>nadir/K</i>	0.623	0.074	0.673	0.692	0.626	0.627
<i>pupmin</i>	1203	1501	1241	1289	1202	1206
<i>pupmax</i>	4469	15169	4190	4409	4449	4464
<i>puprange</i>	3285	13673	2950	3138	3263	3272

**Table 34: Comparing 2013 trials: 0% discount rate, rule 320.**

<b>Trial</b>	<b>noSbound</b>	<b>noDD</b>	<b>Z1</b>	<b>Z2</b>	<b>vuln26</b>	<b>rely1</b>
DRate	0%	0%	0%	0%	0%	0%
Rule	320	320	320	320	320	320
<i>MFish1</i>	99.41	13.21	38.54	99.07	99.82	99.41
<i>MFish2</i>	0.918	0.146	0.808	0.913	0.923	0.919
<i>DoC1</i>	19.9	13.2	15.6	19.5	20.0	19.9
<i>DoC2</i>	0.850	0.686	0.625	0.902	0.853	0.872
<i>N20/K</i>	0.903	0.092	0.801	0.909	0.909	0.905
<i>nadir/K</i>	0.661	0.067	0.597	0.685	0.661	0.666
<i>maxcatch</i>	291.1	669.6	214.3	274.1	278.0	297.7
<i>meancatch</i>	111.1	176.2	82.5	107.0	105.5	113.0
<i>meanFRML</i>	122.6	178.0	106.1	121.1	123.2	123.0
<i>minFRML</i>	74.0	87.9	66.0	75.5	73.9	74.2
<i>maxFRML</i>	190.9	317.7	163.8	186.4	191.9	190.6
<i>closure</i>	59	38	67	59	58	58
<i>effortlost</i>	917.5	533.1	1095.4	930.7	912.8	915.5
<i>pupmin</i>	1245	1501	1097	1268	1241	1250
<i>pupmax</i>	4236	7061	3635	4142	4257	4232
<i>puprange</i>	3006	5625	2528	2882	3028	2994

**Table 35: Comparing 2013 trials: 0% discount rate, rule 1.**

<b>Trial</b>	<b>base</b>	<b>noDD</b>	<b>Z1</b>	<b>Z2</b>	<b>vuln26</b>	<b>rely1</b>
DRate	0%	0%	0%	0%	0%	0%
Rule	1	1	1	1	1	1
<i>MFish1</i>	86.28	8.98	17.48	75.38	92.86	86.51
<i>MFish2</i>	0.895	0.124	0.707	0.882	0.905	0.897
<i>DoC1</i>	14.6	9.0	7.8	11.6	17.1	14.5
<i>DoC2</i>	0.848	0.585	0.435	0.861	0.855	0.870
<i>N20/K</i>	0.892	0.086	0.734	0.879	0.902	0.892
<i>nadir/K</i>	0.657	0.062	0.524	0.665	0.660	0.662
<i>maxcatch</i>	566.3	693.5	421.5	536.1	528.4	578.1
<i>meancatch</i>	165.6	184.7	124.5	159.2	156.0	168.1
<i>effortlost</i>	0.0	0.0	0.0	0.0	0.0	0.0
<i>pupmin</i>	1234	1410	974	1229	1231	1238
<i>pupmax</i>	4125	5862	3297	4004	4165	4123
<i>puprange</i>	2900	4520	2315	2780	2940	2898

**Table 36: Comparing 2013 trials: 50% discount rate, rule 320.**

<b>Trial</b>	<b>base</b>	<b>noDD</b>	<b>Z1</b>	<b>Z2</b>	<b>vuln26</b>	<b>rely1</b>
DRate	50%	50%	50%	50%	50%	50%
Rule	320	320	320	320	320	320
<i>MFish1</i>	99.85	19.31	64.42	99.97	99.94	99.86
<i>MFish2</i>	0.927	0.194	0.842	0.928	0.931	0.928
<i>DoC1</i>	20.0	18.3	19.6	20.0	20.0	20.0
<i>DoC2</i>	0.842	0.742	0.690	0.911	0.842	0.861
<i>N20/K</i>	0.908	0.097	0.826	0.925	0.913	0.910
<i>nadir/K</i>	0.652	0.070	0.616	0.688	0.652	0.657
<i>maxcatch</i>	248.1	525.8	194.2	235.0	233.3	253.3
<i>meancatch</i>	77.5	126.3	63.1	75.8	73.8	78.9
<i>meanFRML</i>	123.9	213.0	109.7	123.0	124.2	124.1
<i>minFRML</i>	73.4	91.1	68.1	75.8	73.1	73.5
<i>maxFRML</i>	194.3	419.3	170.2	190.3	194.8	194.2
<i>closure</i>	18	5	25	18	18	18
<i>effortlost</i>	185.2	41.3	276.6	185.4	183.6	182.9
<i>pupmin</i>	1236	1501	1133	1277	1229	1240
<i>pupmax</i>	4313	9289	3783	4228	4318	4308
<i>puprange</i>	3085	7856	2638	2960	3101	3082

**Table 37: Comparing 2013 trials: 50% discount rate, rule 1.**

<b>Trial</b>	<b>base</b>	<b>noDD</b>	<b>Z1</b>	<b>Z2</b>	<b>vuln26</b>	<b>rely1</b>
DRate	50%	50%	50%	50%	50%	50%
Rule	1	1	1	1	1	1
<i>MFish1</i>	99.61	18.29	54.30	99.67	99.86	99.62
<i>MFish2</i>	0.925	0.193	0.829	0.925	0.929	0.926
<i>DoC1</i>	20.0	17.6	18.1	19.9	20.0	20.0
<i>DoC2</i>	0.845	0.733	0.663	0.909	0.845	0.864
<i>N20/K</i>	0.909	0.096	0.816	0.923	0.914	0.911
<i>nadir/K</i>	0.652	0.070	0.606	0.687	0.651	0.657
<i>maxcatch</i>	287.6	521.5	232.5	274.7	268.3	293.7
<i>meancatch</i>	83.2	126.5	69.2	81.2	78.9	84.4
<i>effortlost</i>	0.0	0.0	0.0	0.0	0.0	0.0
<i>pupmin</i>	1236	1501	1117	1273	1227	1237
<i>pupmax</i>	4302	9192	3735	4214	4311	4300
<i>puprange</i>	3077	7759	2608	2949	3093	3076



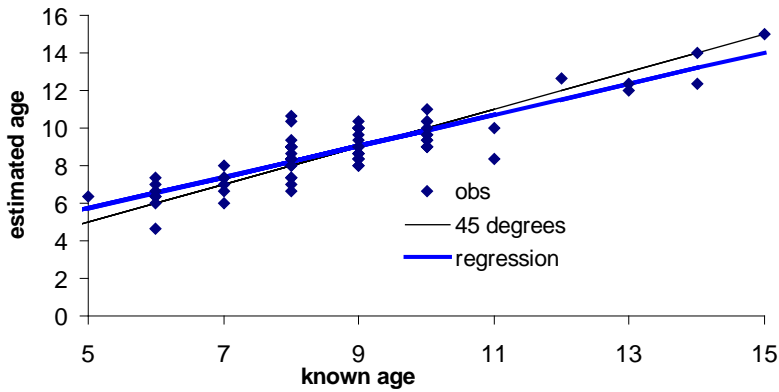


Figure 1: Estimated ages from tooth sections (“obs”) plotted against known ages for 74 sea lions, the predicted estimated age from the regression described in the text (heavy line) and the 45 degree line. Data from Simon Childerhouse, personal communication, and Childerhouse et al. (2004).

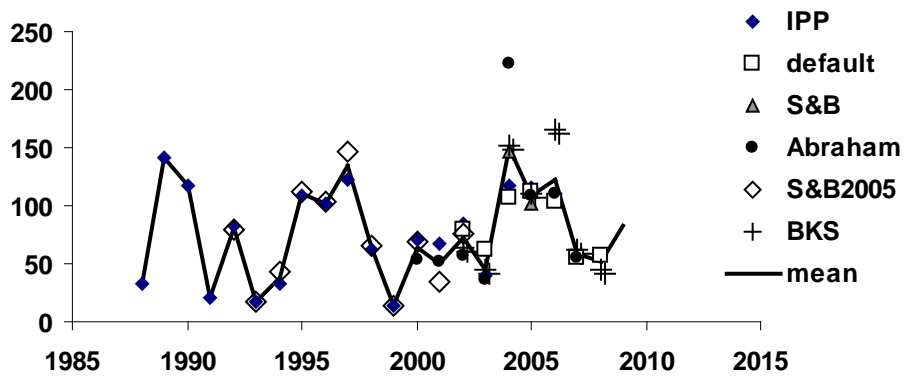


Figure 2: Bycatch estimates discussed in the text.

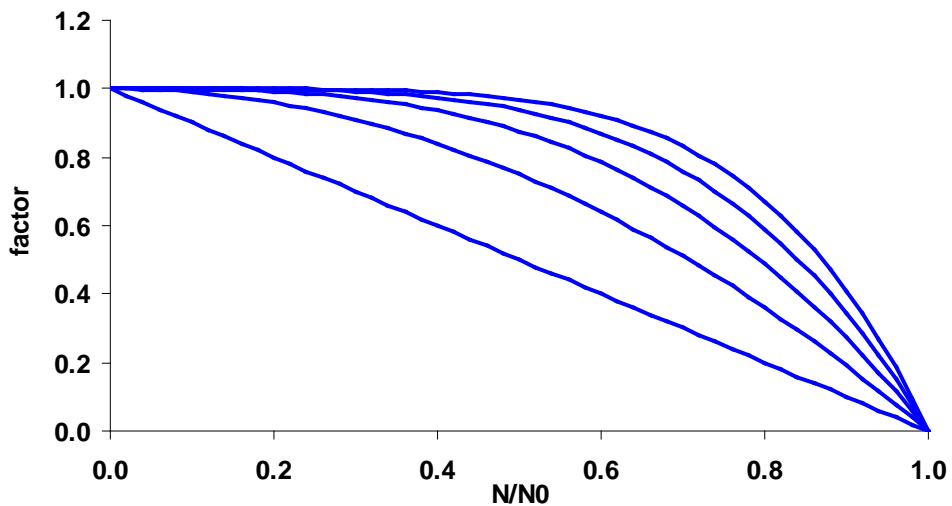


Figure 3: Shape of the density-dependent factor acting on pup survival, as a function of  $N/N_0$  and the shape parameter,  $z$ . The straight line was made with  $z = 1$ , the line above it with  $z = 2$  and so on to  $z = 5$ .

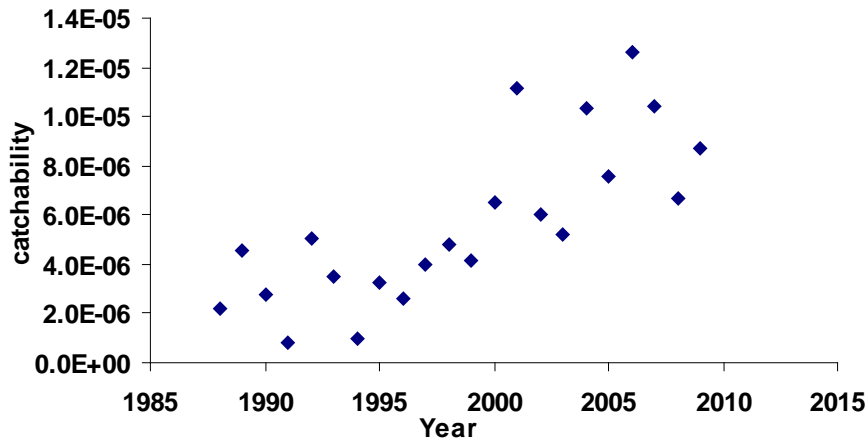


Figure 4: MPD estimates of catchability from the base case operating model.

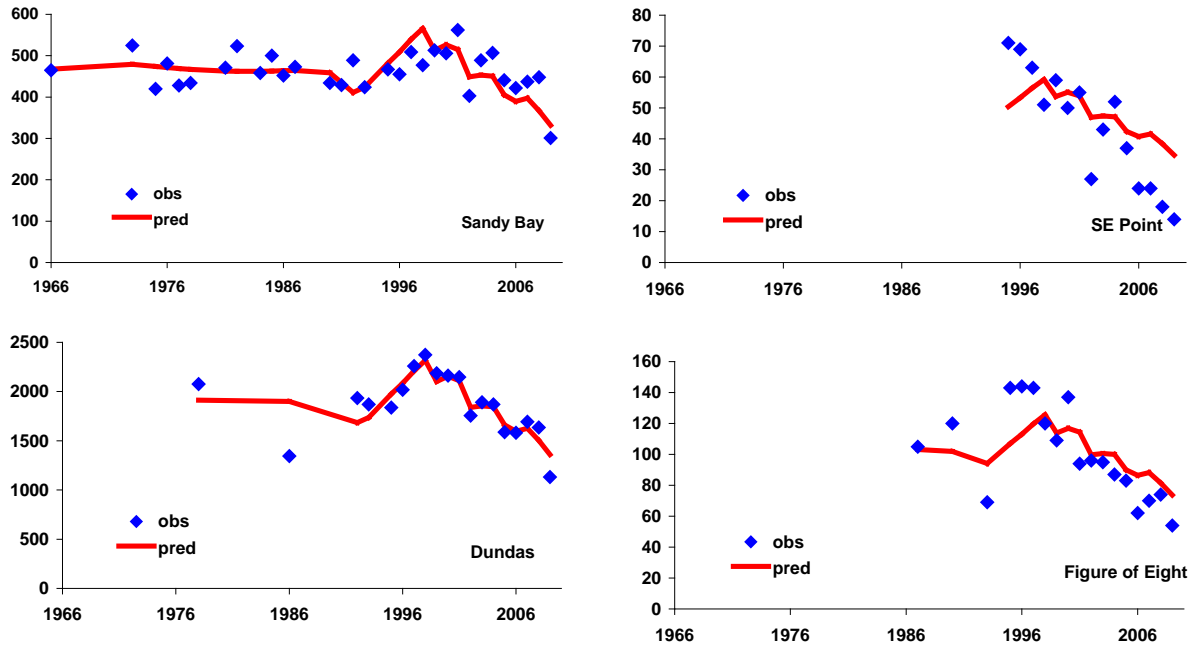


Figure 5: The fits to pup counts from each of the four rookeries in the base case MPD. Diamonds are observed data and the line connects model predictions.

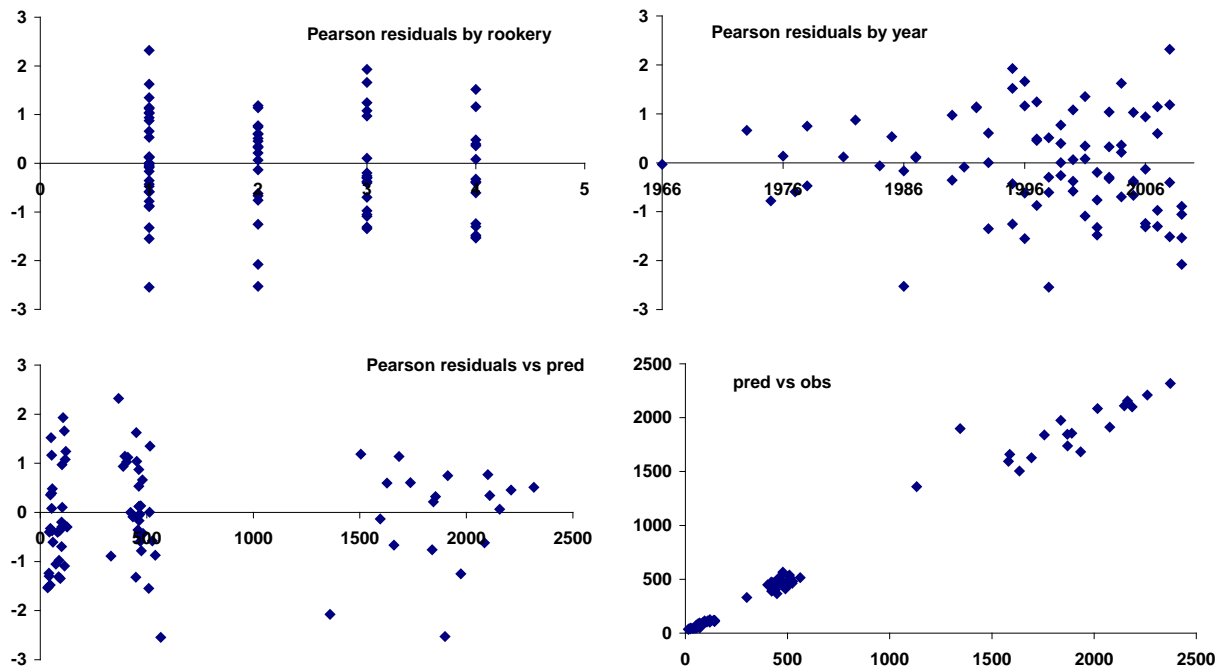


Figure 6: Residuals from the fits shown in Figure 5, plotted in various ways, and the predicted values plotted against the observed.

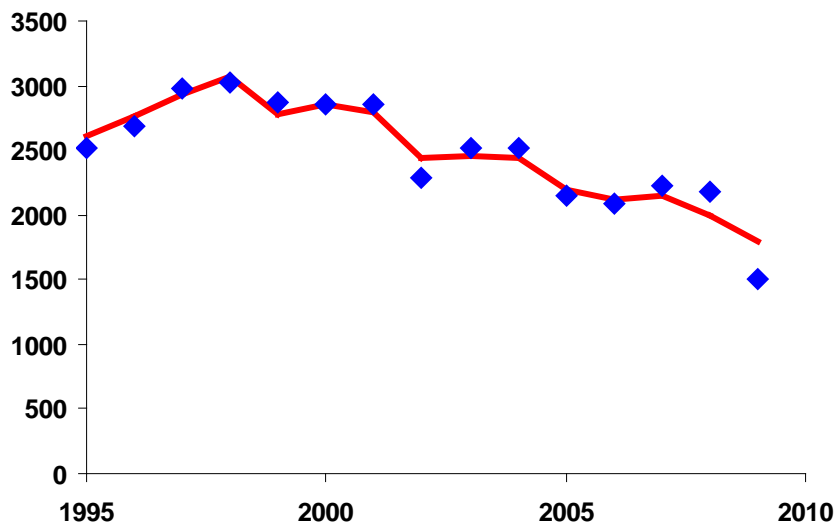


Figure 7: The fit to pup counts from all four rookeries combined in the base case MPD. Diamonds are observed data and the line connects model predictions.

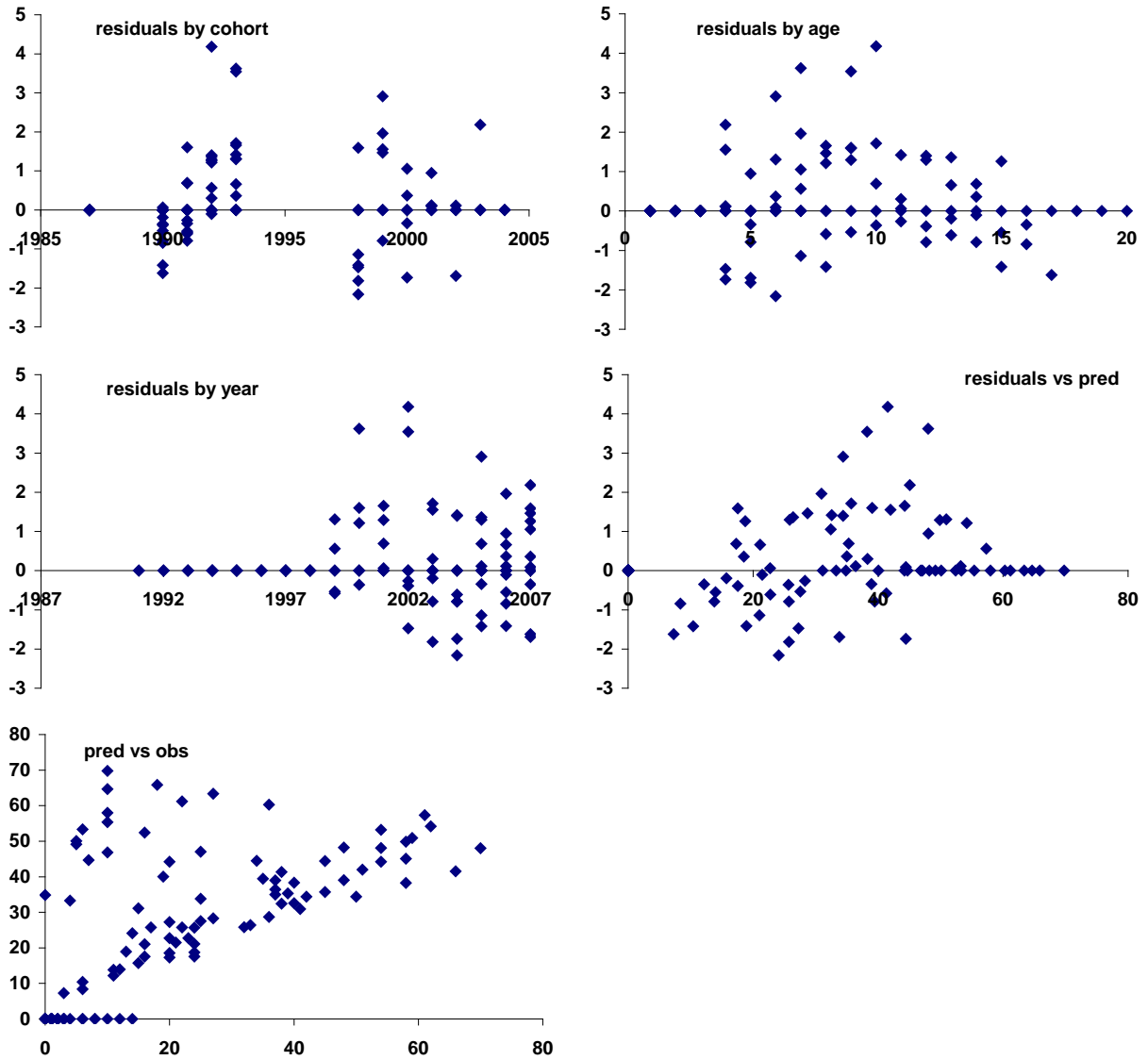


Figure 8: Residuals from the fits to resightings of females tagged as pups, plotted in various ways, and predicted versus observed (bottom).

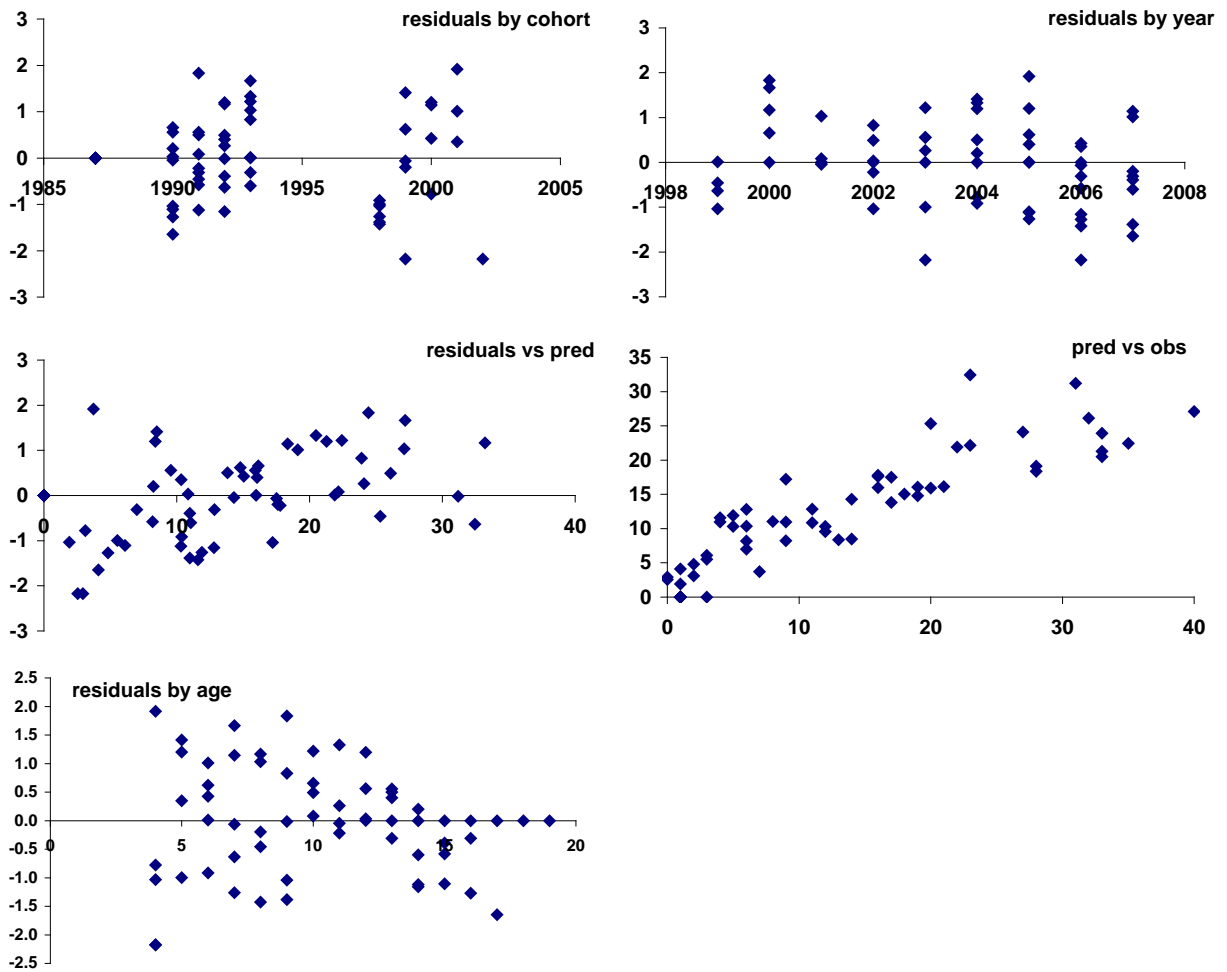


Figure 9: Residuals from the fits to pups from females tagged as pups plotted in various ways.

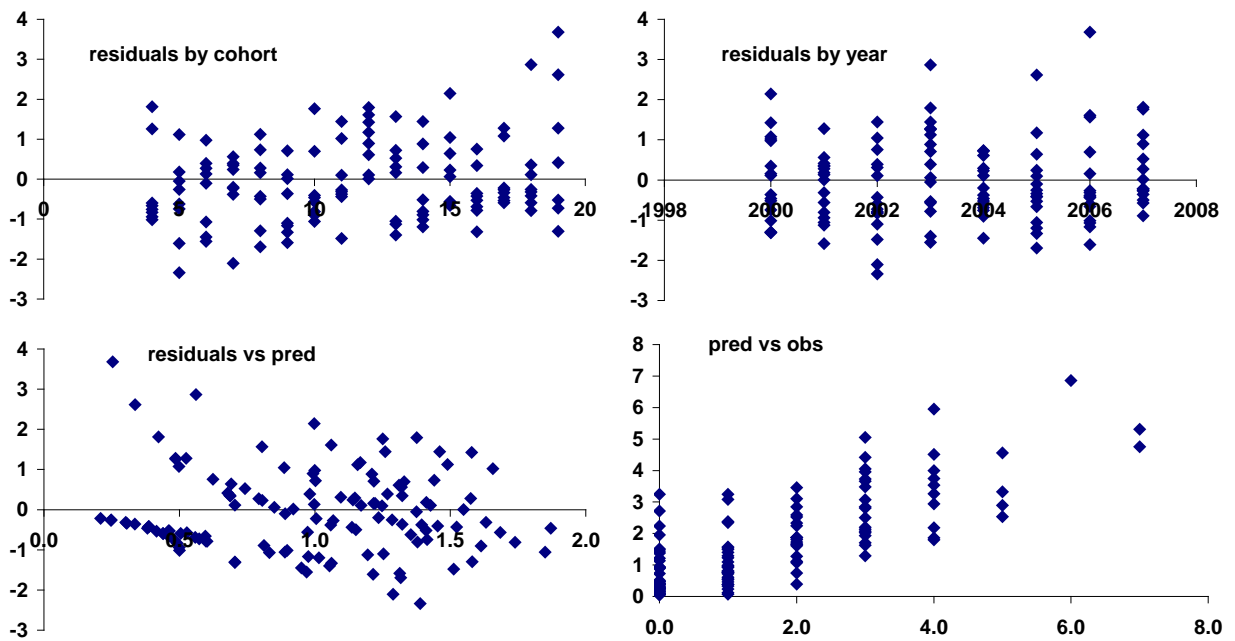


Figure 10: Residuals from the fit to resightings of females tagged as breeding adults in 1999.

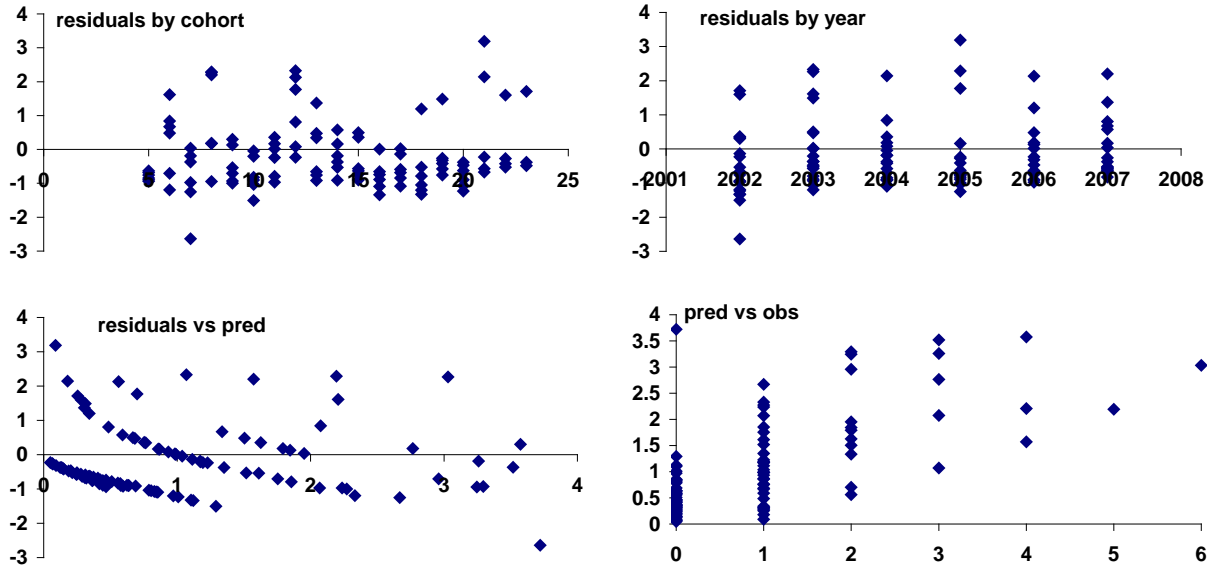


Figure 11: Residuals from the fit to resightings of females tagged as breeding adults in 2001.

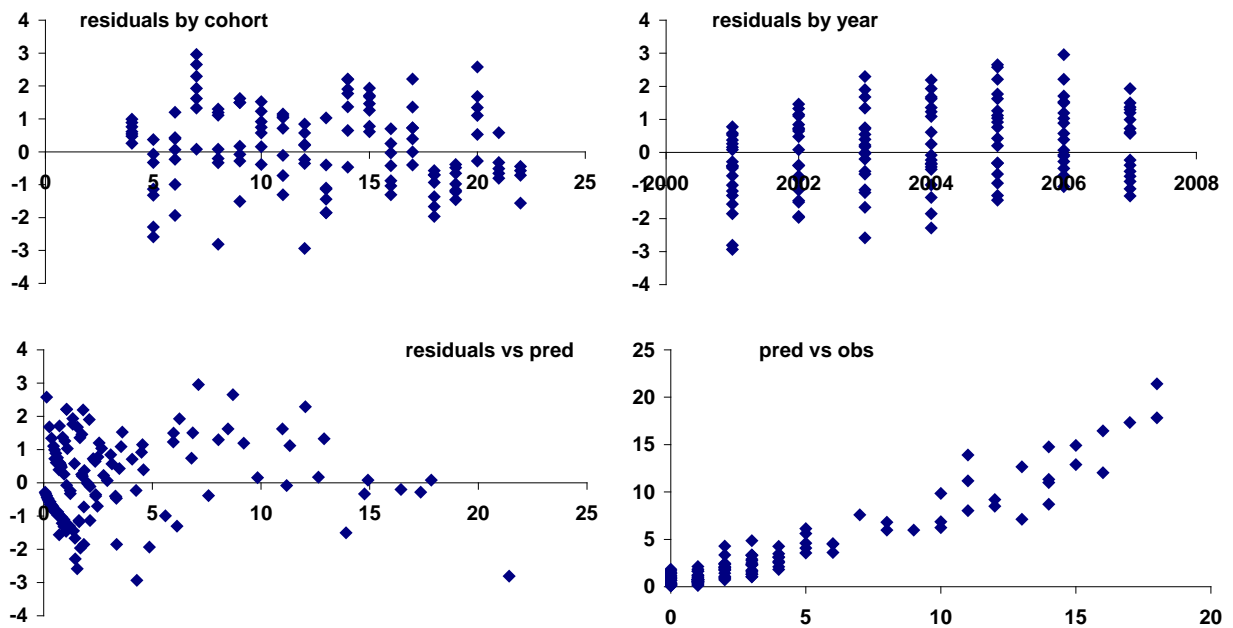


Figure 12: Residuals from the fit to resightings of breeding females branded in 2000.

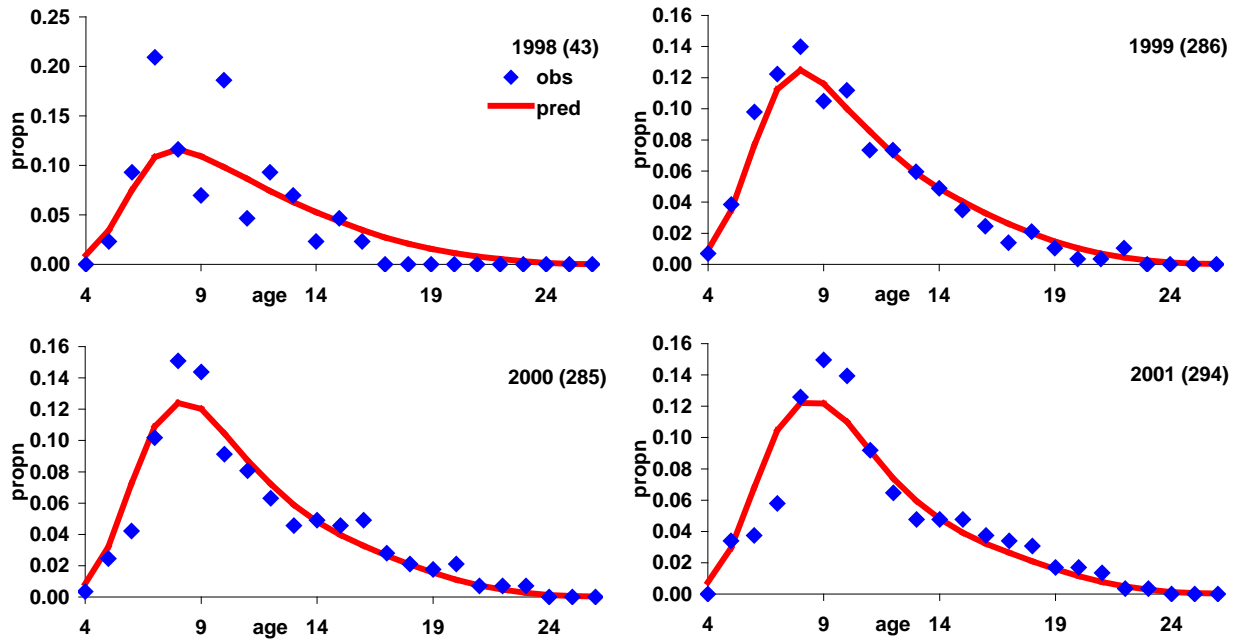


Figure 13: The fits to each of the four years of breeding female ageing data. Diamonds are observed data and the line connects model predictions.

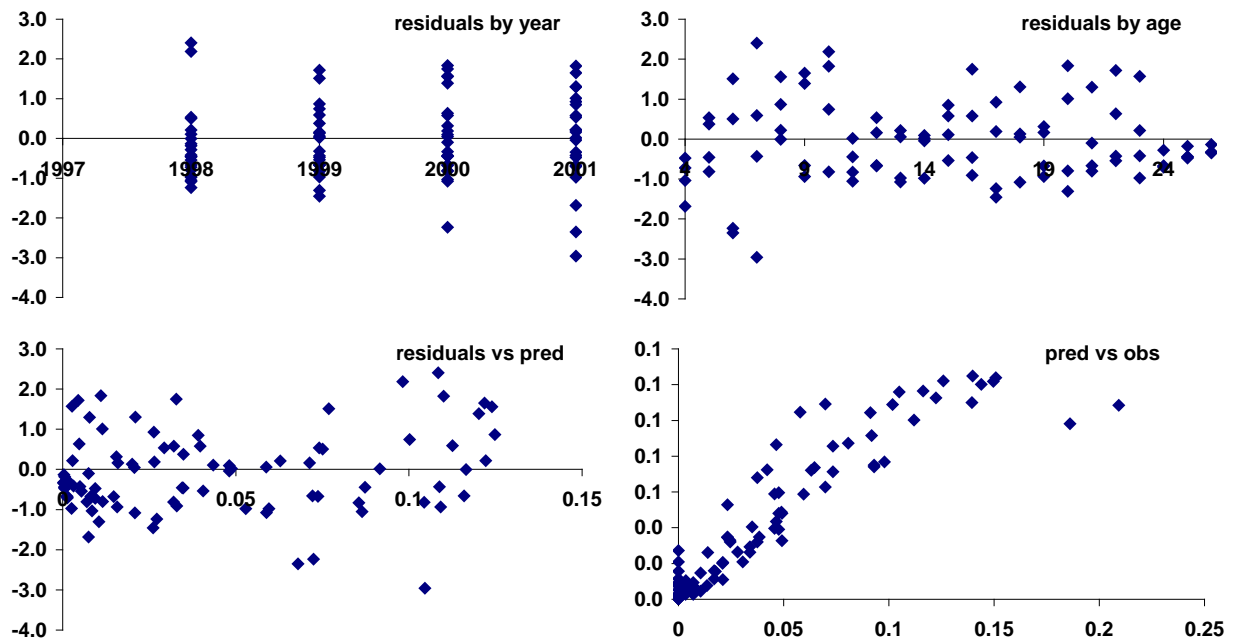


Figure 14: Residuals from the fits shown in Figure 13, plotted in various ways, and the predicted values plotted against the observed.

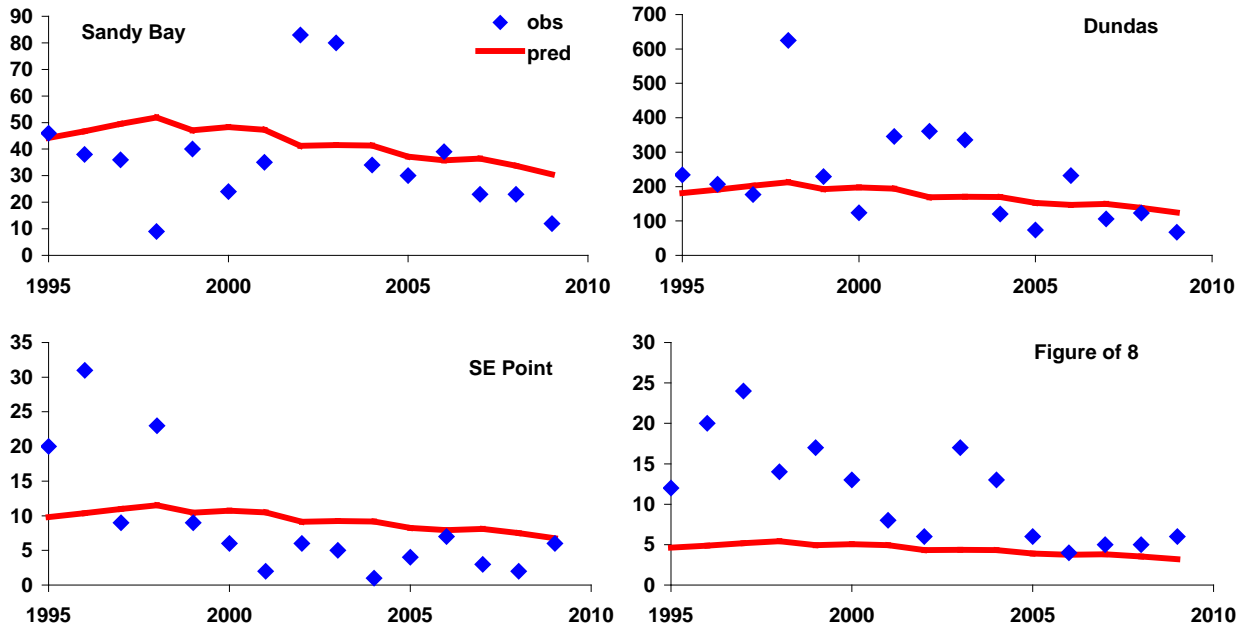


Figure 15: The fits to mid-January pup mortalities from each of the four rookeries in the base case MPD. Diamonds are observed data and the line connects model predictions.

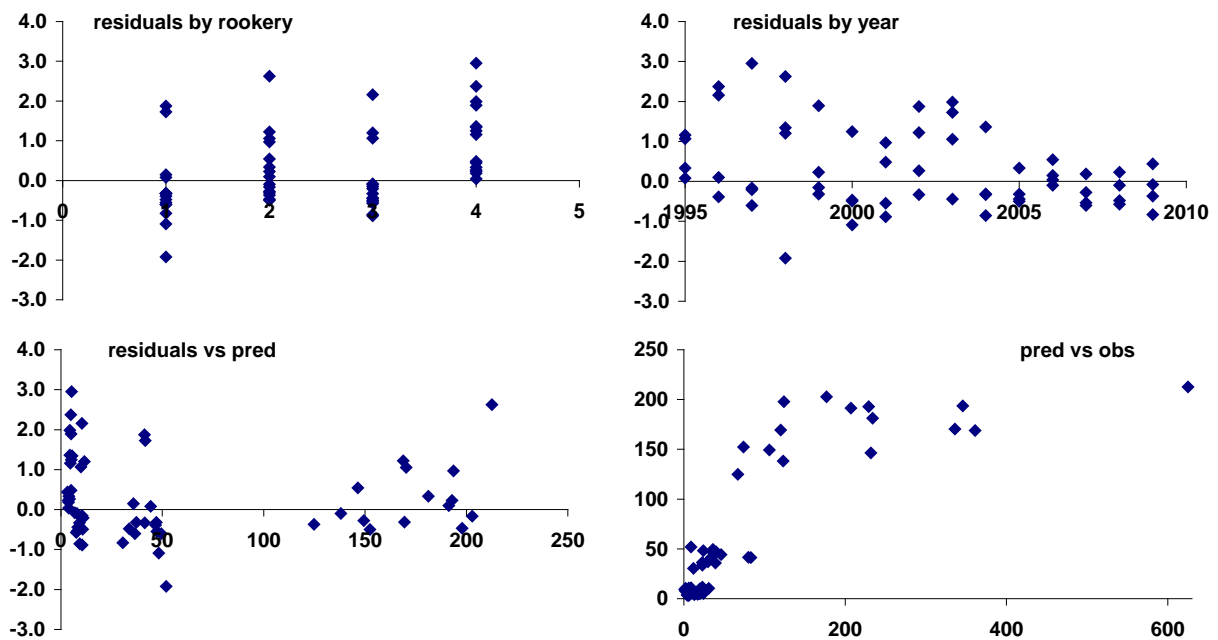


Figure 16: Residuals from the fits shown in Figure 15, plotted in various ways, and the predicted values plotted against the observed.



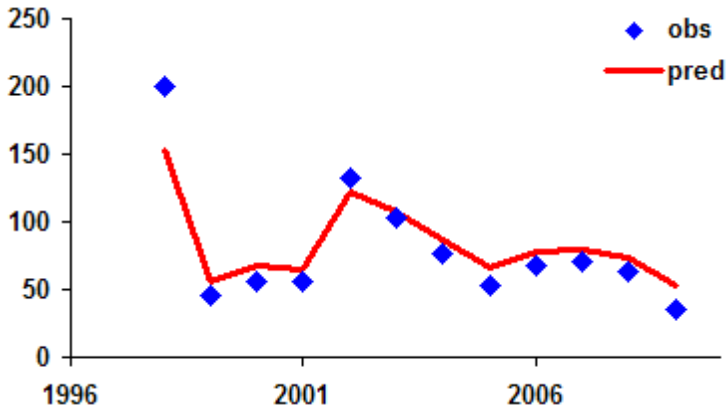


Figure 17: The fit to end of February pup mortality at Sandy Bay. Diamonds are observed data and the line connects model predictions.

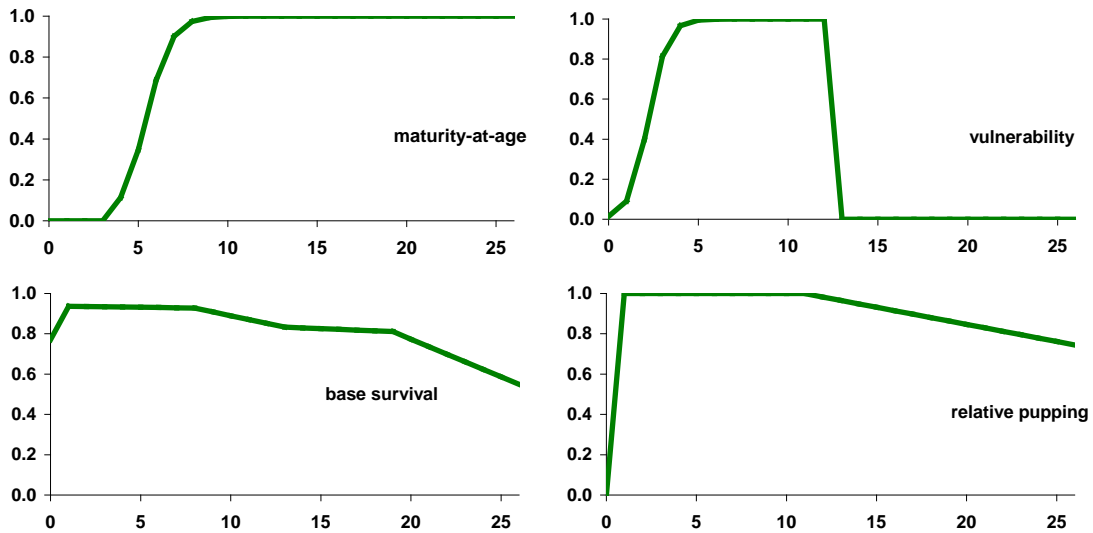


Figure 18: Some derived -at-age relations from the base case MPD. All are plotted against age: proportion mature (top left), vulnerability to capture (top right), survival before deviations are applied (bottom left) and the relative pupping rate of a mature animal.

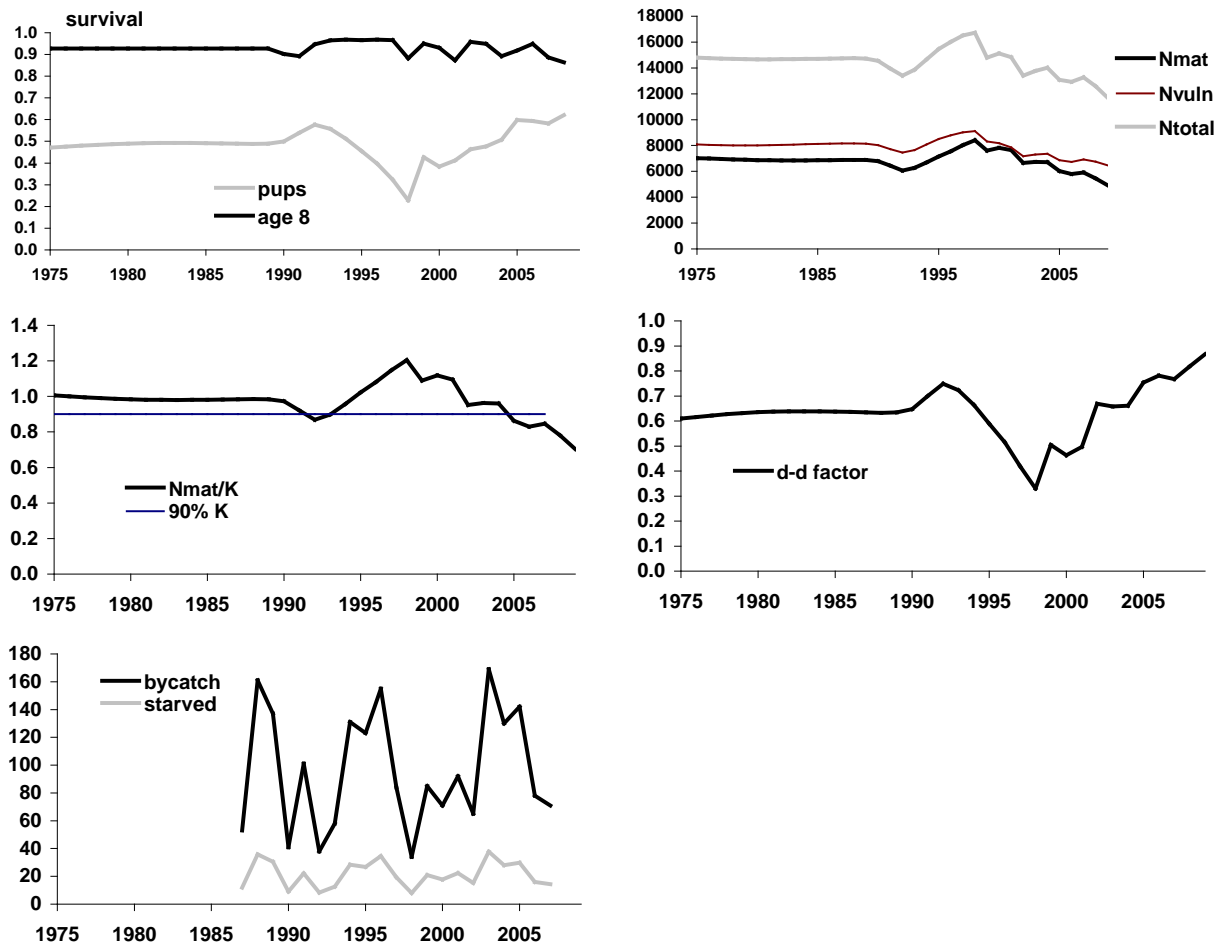


Figure 19: Some trajectories from the base case MPD. Top left: survival of pups and 8 yr-olds, top right: mature, total and vulnerable population size, middle left: mature numbers as a proportion of  $K$ , with the 90% line plotted for reference, middle right: the density dependent factor that operates on pup survival, bottom: bycatch and starved pups.

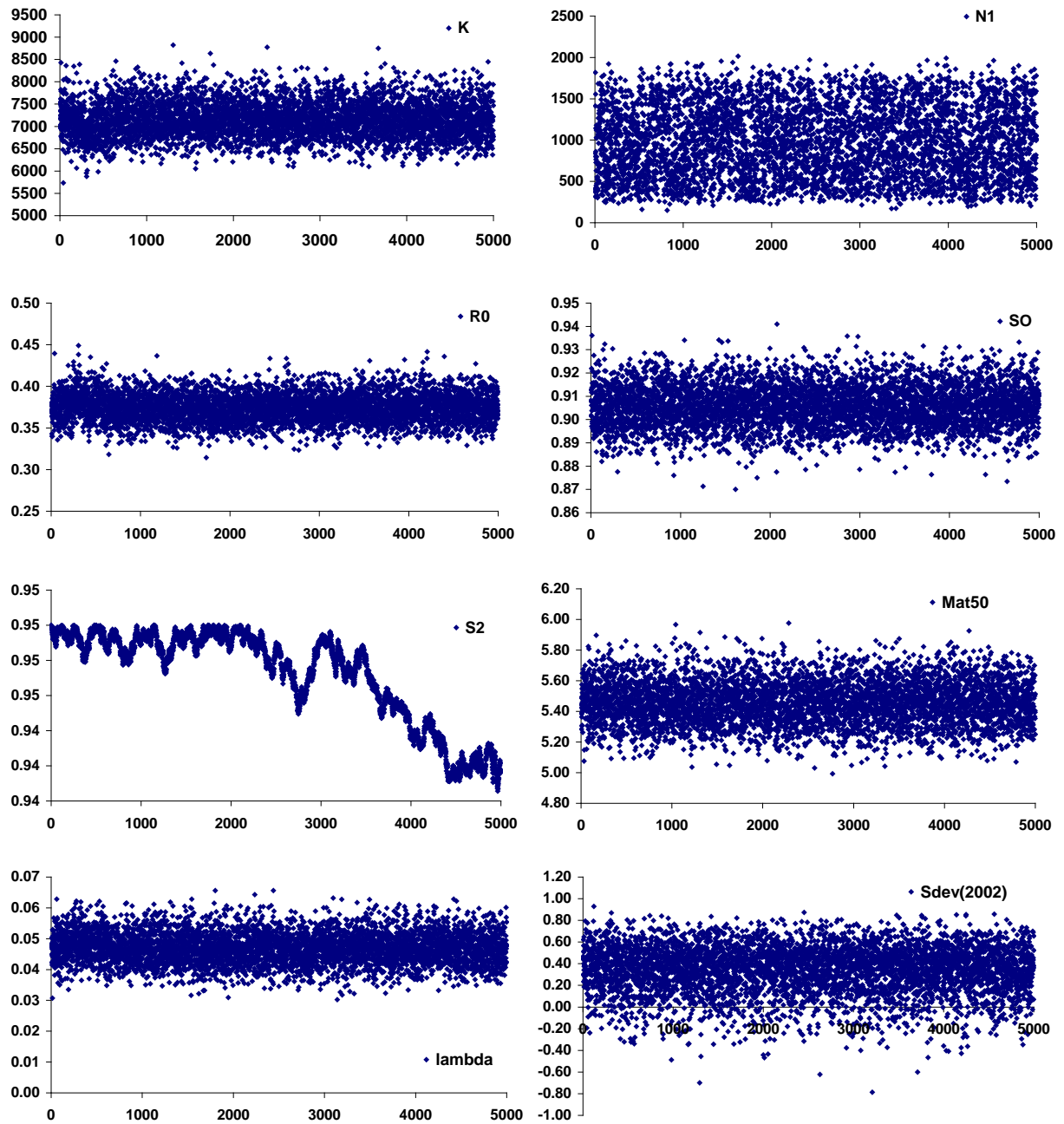


Figure 20: Traces of some major and representative parameters from the base case operating model MCMC. For “lambda” on the bottom left read “*Rmax*”. Some x-axes are truncated.

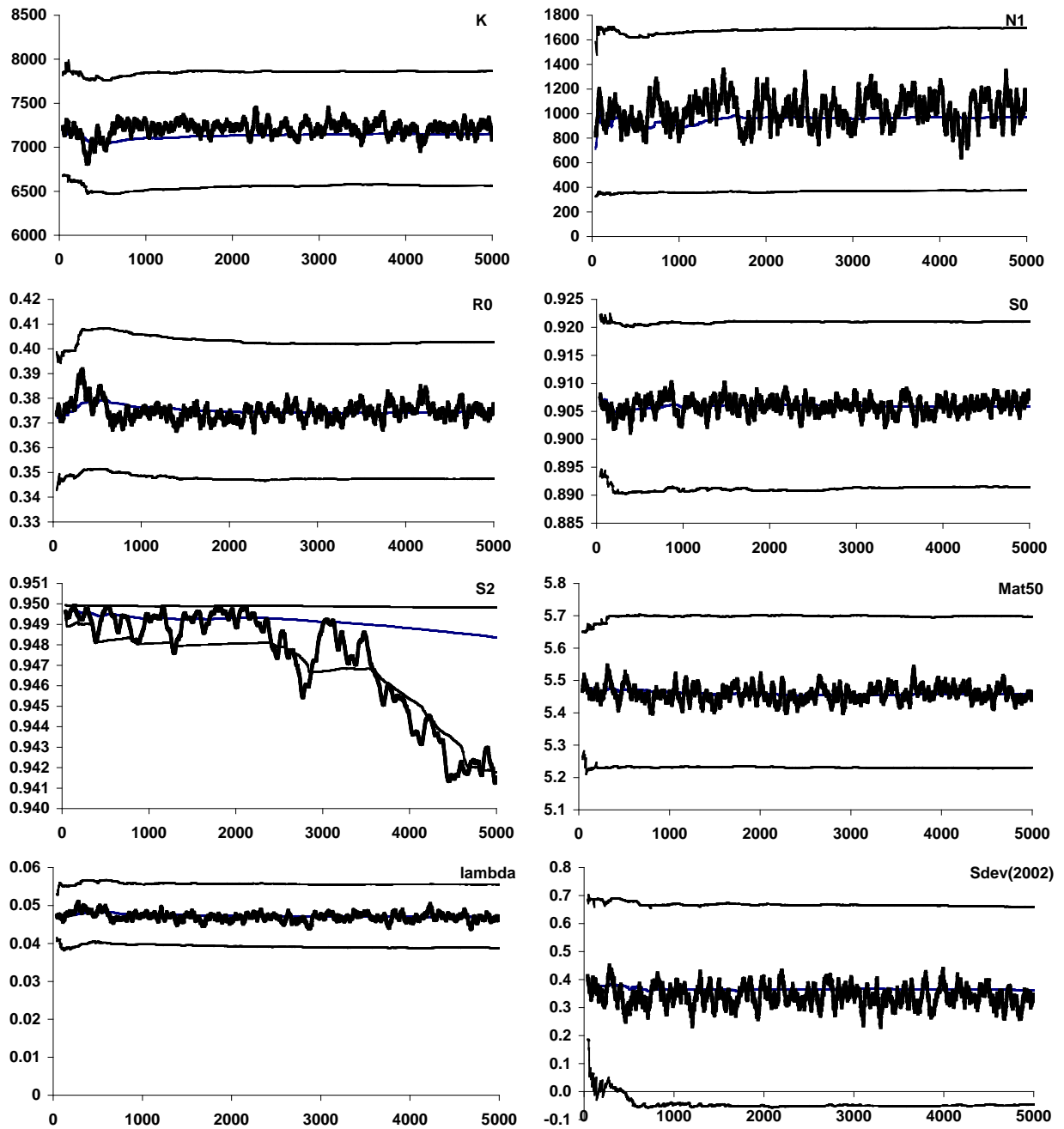


Figure 21: Simple diagnostic plots for the traces seen in Figure 20. The thin black lines are the running 5th, 50th and 95th quantiles (respectively from lowest to highest), and the heavier black line is the moving (over 40 samples) mean. For “lambda” on the bottom left read “*Rmax*”. Some x-axes are truncated.

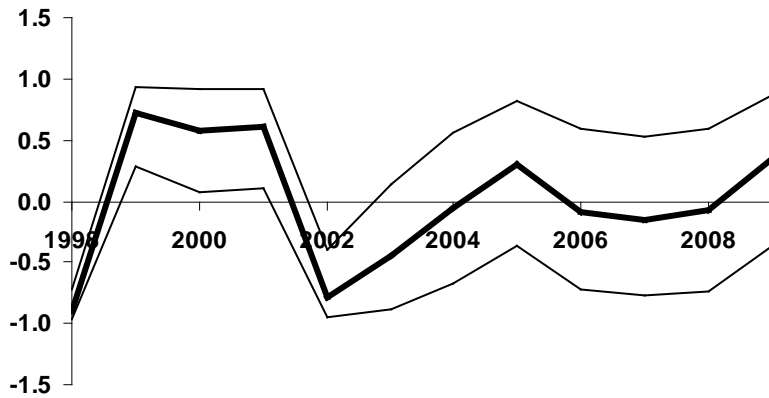


Figure 22: A summary of the posterior distribution of *S1devs* - survival deviations that apply to pups – from the base case model McMC: the thick line is the median and thinner lines are 5th and 95th quantiles.

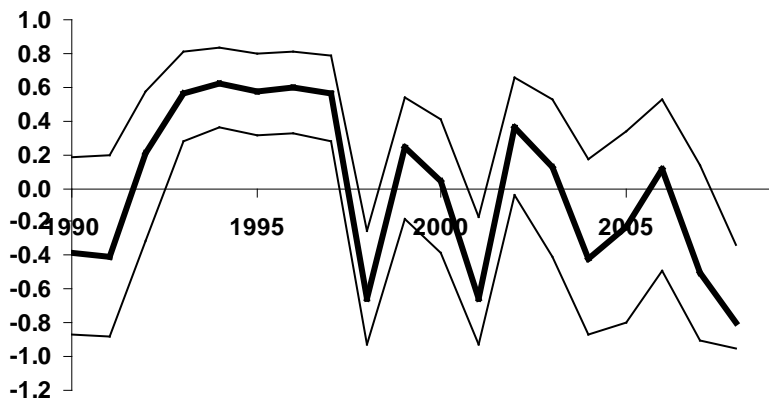


Figure 23: A summary of the posterior distribution of *Sdevs* - survival deviations that apply to adults – from the base case model McMC: thick line is the median and thinner lines are 5th and 95th quantiles.

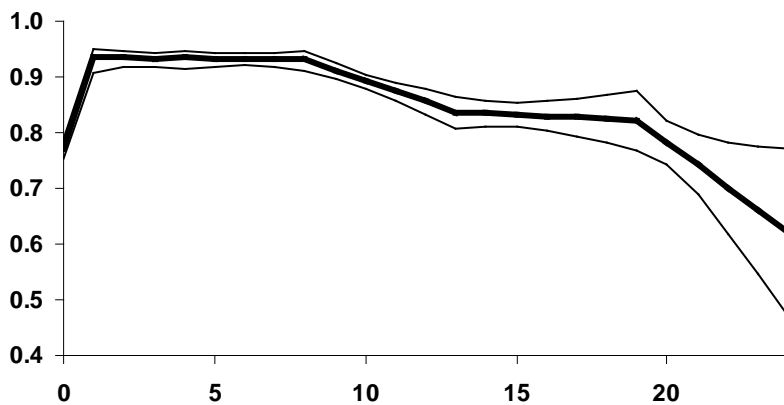


Figure 24: A summary of the posterior distributions of survivals-at-age from the base case model McMC: thick line is the median and thinner lines are 5th and 95th quantiles.

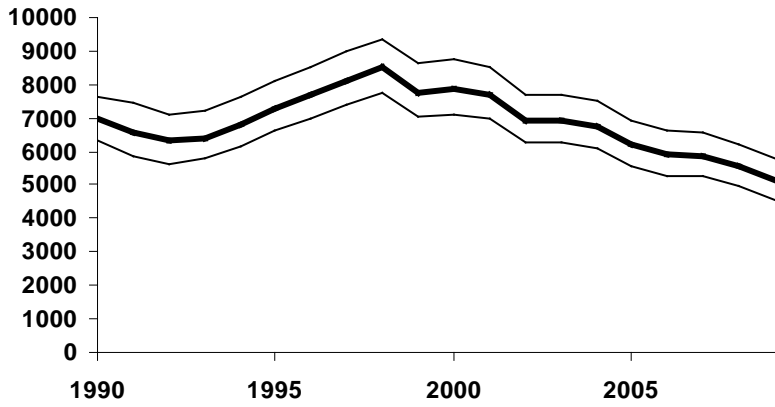


Figure 25: Posterior trajectory of mature numbers from the base case model McMC.

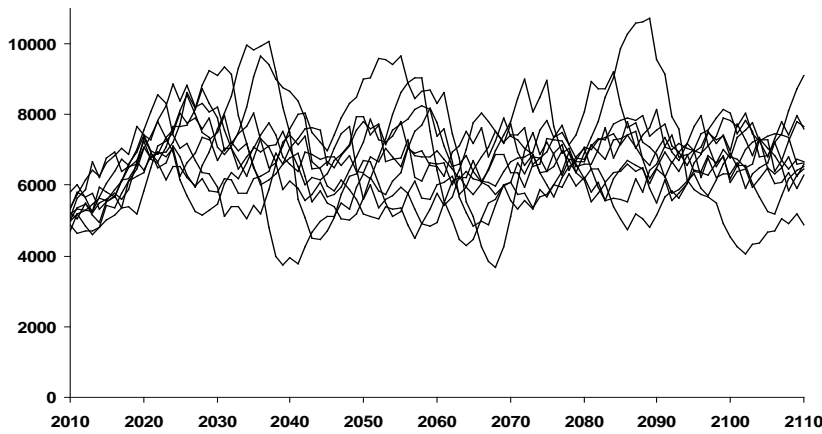


Figure 26: From the base case operating model, ten random projected mature numbers trajectories obtained under rule 0 (no fishing).

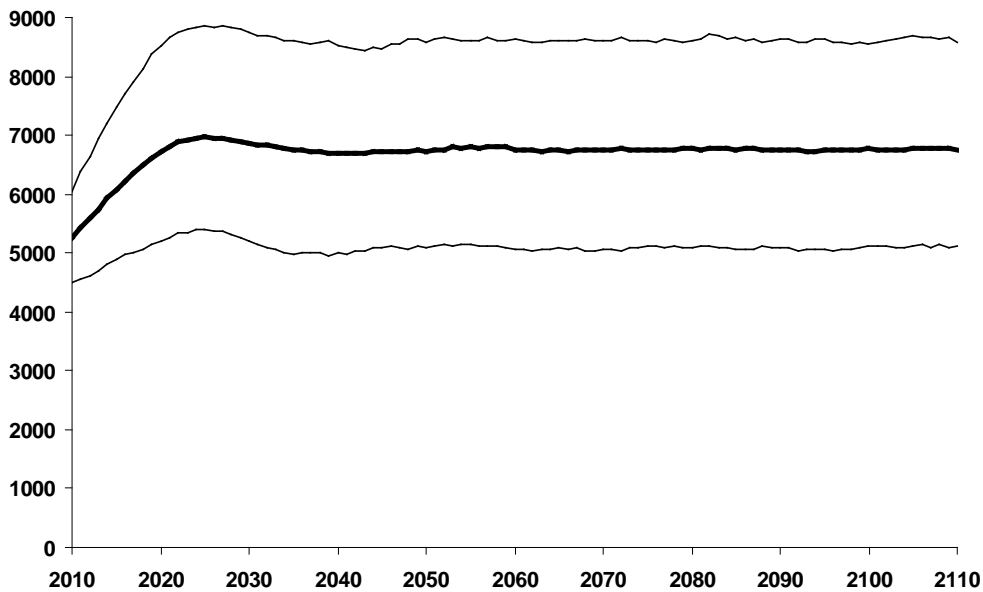
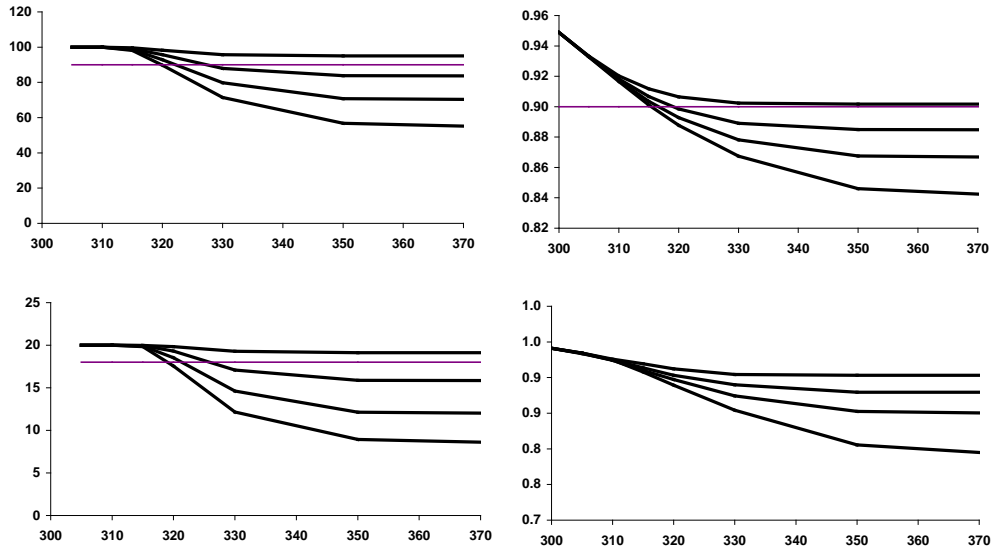
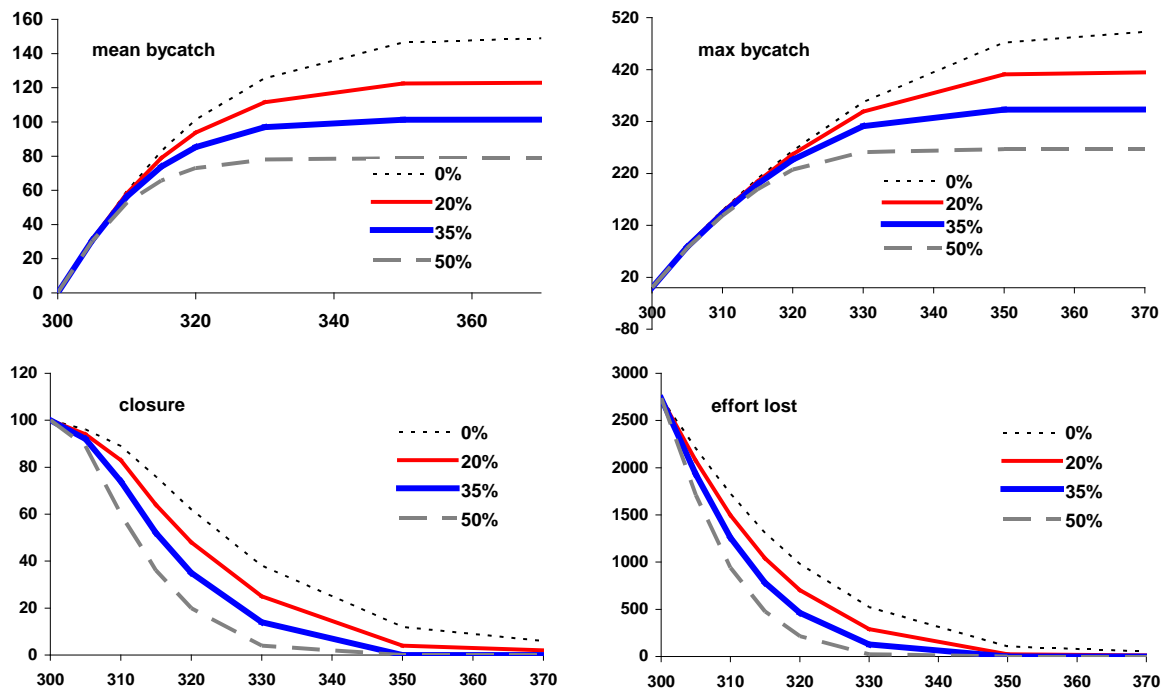


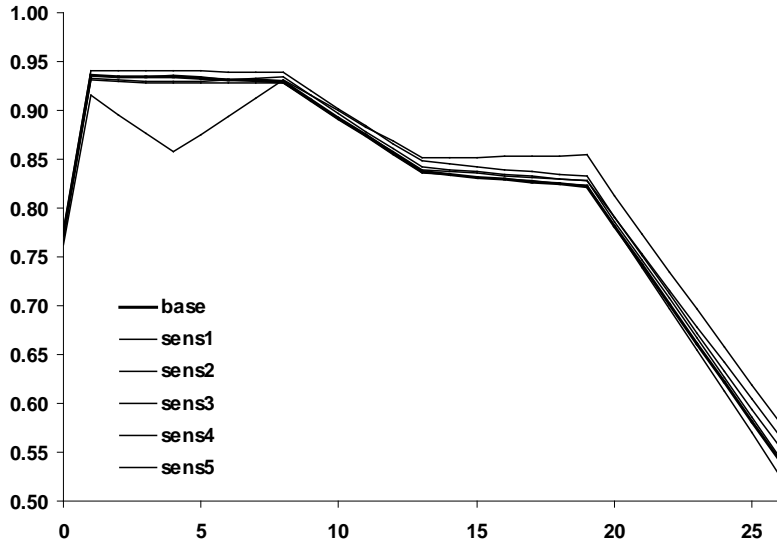
Figure 27: From the base case operating model, the posterior trajectory of projected mature numbers obtained under rule 0 (no fishing). Heavy line is the median and lighter lines are the 5th and 95th quantiles.



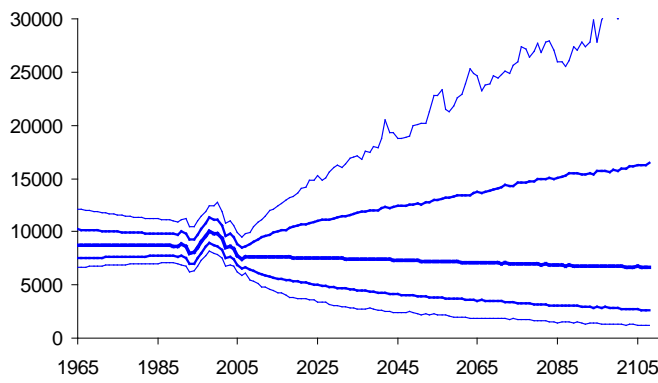
**Figure 28:** From the base case operating model, a comparison of the effects of the discount rate assumptions on the four key indicators. Note truncated y-axes. Top left: the *MFish1* criterion, top right: *MFish2*, lower left: *DOC1* and lower right: *DOC2*. In each figure the lines from upper to lower show results from assuming 50%, 35%, 20% and 0% discount rates. The light horizontal lines show the critical point: 90 for *MFish1*, 0.90 for *MFish2*, 18 for *DOC1* and 0.5 (out of range) for *DOC2*.



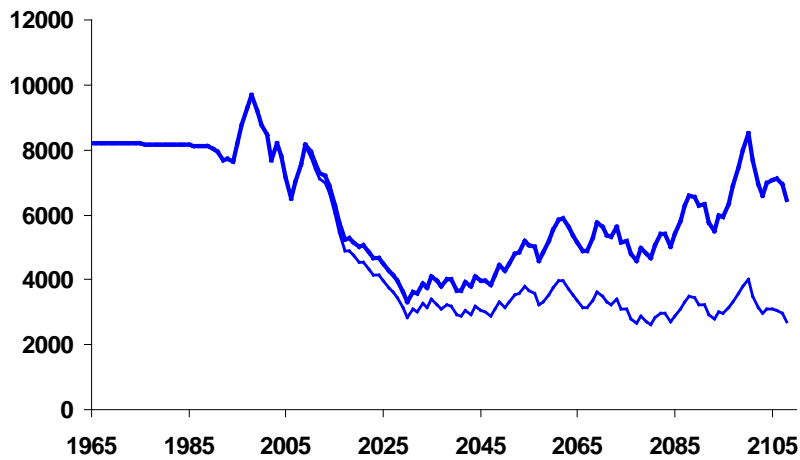
**Figure 29:** From the base case operating model, a comparison of the effects of four discount rate assumptions on four other indicators. The y-axis is the rule 300 family rule number.



**Figure 30: Median survival-at-age curves from the base case (heavier line) and the alternative operating models. The odd one out is sens2.**



**Figure 31: The minimum and maximum, 5th and 95th quantiles and the median of the mature numbers trajectory distribution from rule 0 in the no-density-dependence sensitivity trial (trial 6) from the 2008 study.**



**Figure 32: For the no-density-dependence sensitivity trial from the 2008 study, a comparison of the mature numbers trajectory from run 2557 with rules 0 and 1.**



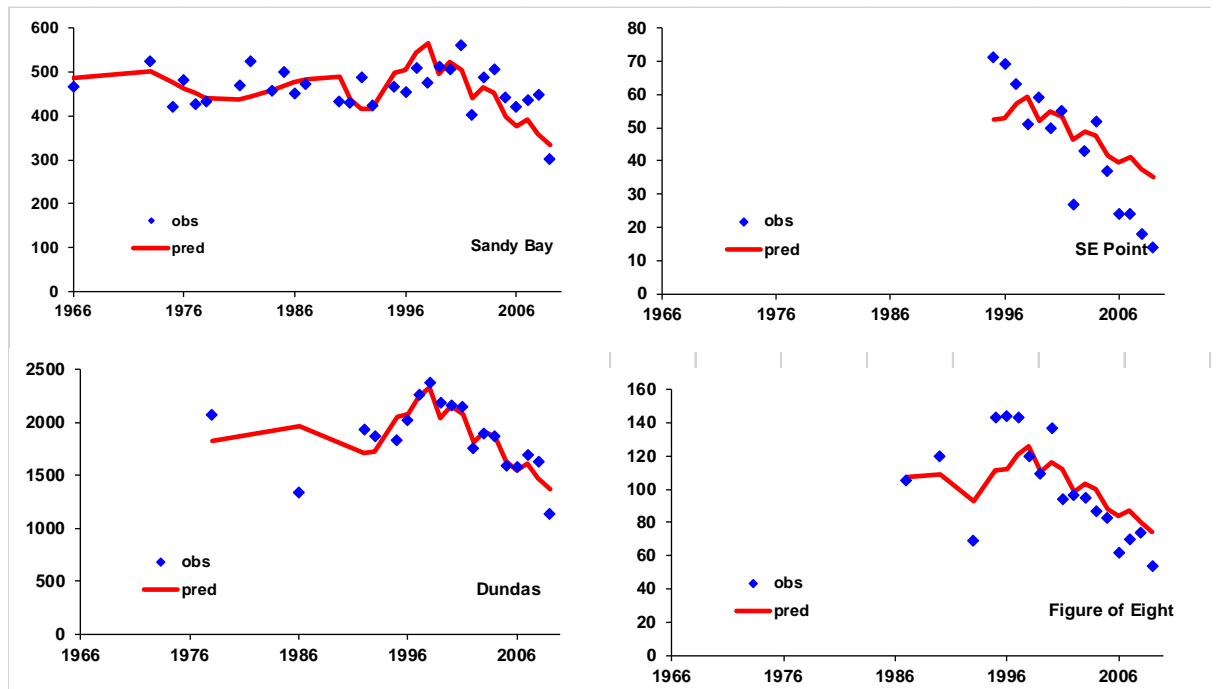


Figure 33: The fits to pup counts from each of the four rookeries in the 2013 noSbound trial MPD (compare with Figure 5). Diamonds are observed data and the line connects model predictions.

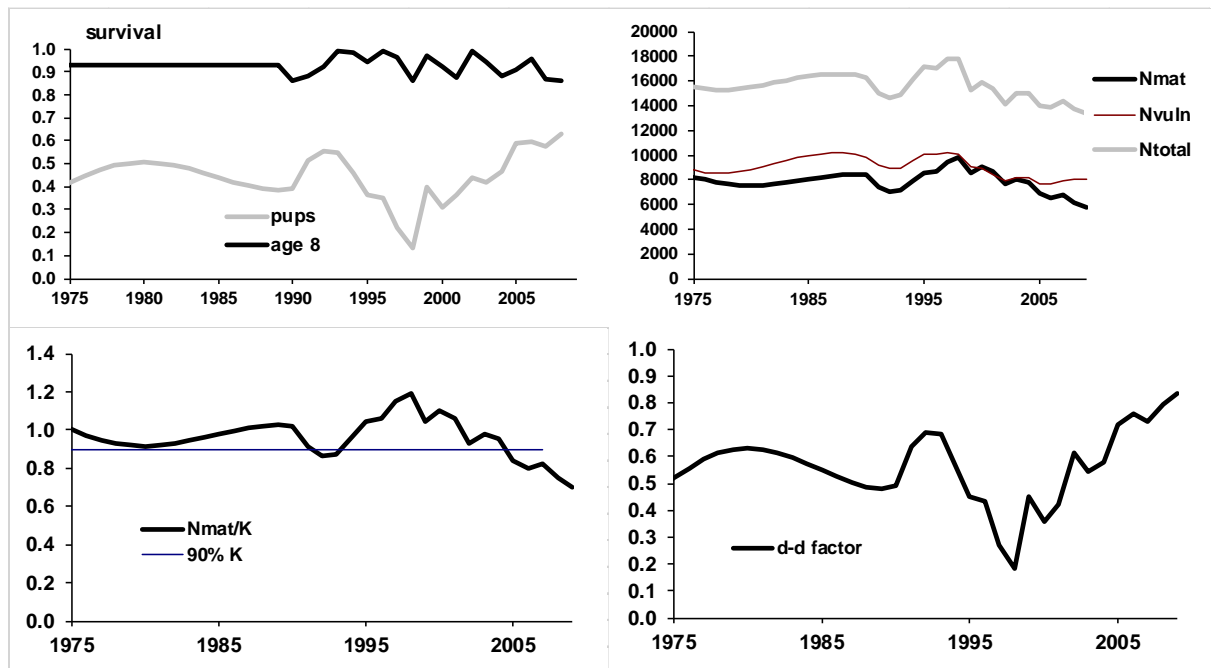


Figure 34: Some trajectories from the 2013 noSbound trial MPD (compare with Figure 18). Top left: survival of pups and 8 yr-olds, top right: mature, total and vulnerable population size, middle left: mature numbers as a proportion of  $K$ , with the 90% line plotted for reference, middle right: the density dependent factor that operates on pup survival, bottom: bycatch and starved pups.

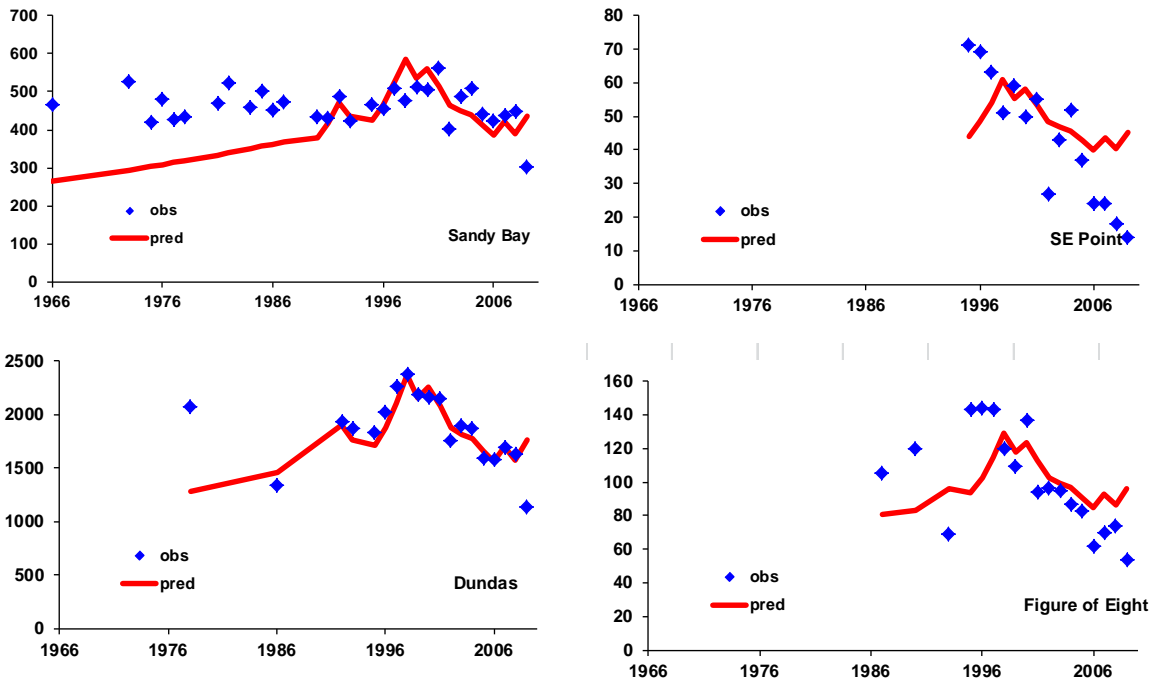


Figure 35: Fit to pup counts for the 2013 noDD trial.

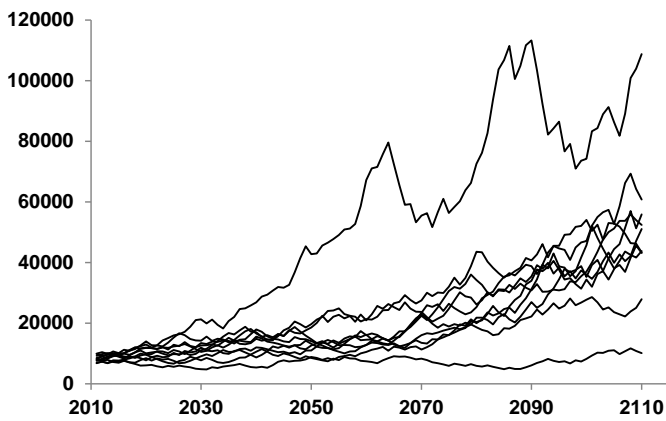


Figure 36: Ten random runs from the 2013 noDD trial with no fishing.

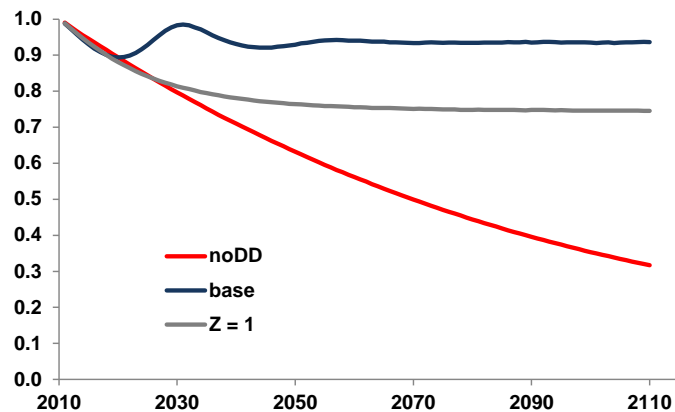
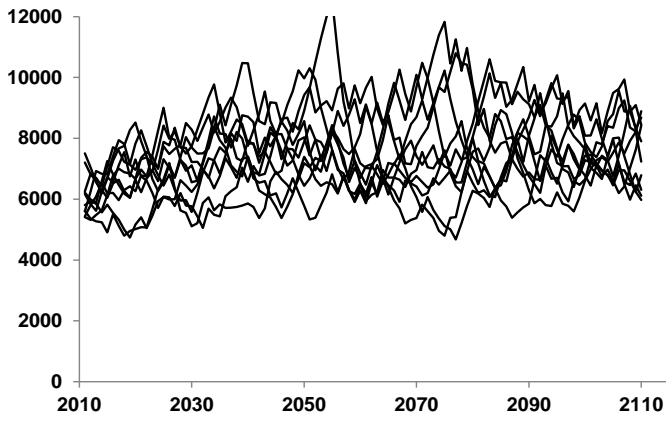
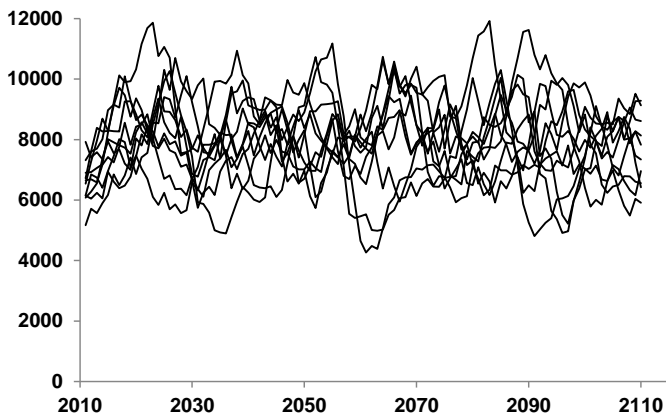


Figure 37: With discount rate 0 and unconstrained fishing, the median of the ratio of  $N_{mat}$  under rule 1 to  $N_{mat}$  under no fishing (calculated for each year) for the 2013 noSbound (base), noDD and Z1 trials.



**Figure 38: Ten random runs from the Z1 trial with no fishing (the same 10 runs as in Figure 36).**



**Figure 39: Ten random runs from the vuln26 trial with no fishing (the same 10 runs as in Figure 36).**