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Further development of models for arrow squid in New Zealand waters

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EXECUTIVE SUMMARY

Mormede, S.[1]; Dunn, A.[2]; Webber, D.N.[3] (2023). Further development of models for arrow squid in New Zealand waters.

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Arrow squid (*Nototodarus sloanii* and *N. gouldi*) generally live for one to two years. They spatially disperse and migrate throughout their short lives, and their movement and biology are strongly influenced by annually varying environmental conditions. There are no estimates of current or reference biomass available for arrow squid in New Zealand.

Two main families of population models were developed further for *N. sloanii* in the Subantarctic, capturing either the main length group of animals each year (the one-cohort model), or capturing the main length group and a secondary length group of animals born about 6 months apart (the two-cohort model). Both model types were able to capture the main biological processes of squid. Recruitment estimates were robust to model assumptions and structure, including between model types. However, several parameters in the models were highly correlated in estimation, resulting in highly uncertain absolute estimates of biomass and other parameters such as fishing pressure or escapement.

The potential for in-season management was tested. The predictability of recruitment in the fishing year was reasonable, but only once about 75% of the catch had been taken, which might preclude this type of approach. Potential proxies that could be used to compare current relative exploitation with past conditions were investigated. The use of such hindcasting tools would require the extension of the existing models back to 1990: the current models have detailed data inputs from 2011 only; higher annual catches were common in the 2000s.

Although the models developed could not be used for direct management advice at this stage, they have showed their potential to create a framework for hindcasting and investigated the requirements should in-season management be desirable. Further development work is recommended to continue improving our understanding of the fishery for squid in New Zealand, of potential stock structures, and assess the current relative exploitation level compared with that historically seen.

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1. INTRODUCTION

Arrow squid in New Zealand waters consists of two species, *Nototodarus gouldi* and *N. sloanii*. Arrow squid generally live for about one year. They spatially disperse and migrate through their short lives, and their movement and population size are likely to be strongly influenced by annually varying environmental conditions.

The annual total allowable catch limit for arrow squid was 254 664 t from 1998 to 2016, and 164 240 t since then. Total catches have been highly variable, between 32 600 t and 86 800 t per year since 2010 (Fisheries New Zealand 2023) with total catches constrained by other management measures (including incidental capture of sea lions), fishery operation, and market constraints. The last characterisation of the New Zealand squid fishery was carried out in 2022 (Mormede & Dunn 2023, Middleton et al. in prep., Neubauer et al. in press), and initial population models were developed (Mormede & Dunn 2023). Although models that predict in-season biomass have been attempted using DeLury methods, these have not been successful as yet (McGregor & Large 2016, McGregor & Tingley 2016).

The stock structure of arrow squid in New Zealand is uncertain. *Nototodarus gouldi* is assumed to be mostly distributed in the north of New Zealand although the positive identification of the two species is tricky. Mormede & Dunn (2023) suggested that differences in the timing of growth and maturity between the west coast of the South Island, the Chatham Rise, and the Subantarctic areas indicated three potential main stocks or sub-stocks of *N. sloanii*, with a potential additional cohort present only south of 49.9° S.

In the Subantarctic (which has represented about 75% of recent catches) there was evidence of one main length group (also referred as cohort) of animals progressing through the fishery each year, with sometimes a second length group with about a six-month lag in growth compared with the first length group (e.g., appearing in the fishery six months later and progressing through growth with a six-month lag), and the evidence of occasional additional length groups present in some years. However, Middleton et al. (in prep.) suggest that there was evidence for temporal separation of cohorts, but no indication that cohorts were spatially separated within the species range.

Arrow squid are semelparous: they grow, mature, spawn, and die immediately post-spawning within a period of about one year—although there is some weak evidence that multiple spawning events might occur in a short period immediately before death (Hurst et al. 2012). The rate of pre-spawning natural mortality is not known but assumed to be in the range of 0.35 to 1.8 y^{-1} (Hurst et al. 2012).

During the period that they are vulnerable to the fishery, *N. sloanii* length cohorts have an approximately linear growth rate, at about one cm per fortnight (Mormede & Dunn 2023). Although there was some evidence that the rate of growth varied annually, it was surprisingly consistent both within year and between years given these animals are likely to be highly influenced by local environmental conditions (Hurst et al. 2012). Higher growth rates have been reported for individuals over short periods of time, likely a result of high variability and spatially localised growth rates of individuals (Uozumi 1998).

Maturation likely occurs at between 25 to 44 weeks for males and 28 to 44 weeks for females; but observations of mature animals are scarce as they do not appear to be vulnerable to the fishery (Hurst et al. 2012). The biomass of squid in each year seems to be driven by environmental conditions rather than the size of the spawning population in the previous year, with no evidence of any depensation from a stock-recruit relationship (Hurst et al. 2012, Mormede & Dunn 2023).

Squid are difficult to assess and monitor using traditional stock assessment methods due to their short life cycle and the lack of pre-fishery observations on stock size, and hence robust scientific advice to inform fisheries management is not currently available. There are currently no estimates of stock status or reference biomass for any populations of squid for New Zealand (Fisheries New Zealand 2023).

Marine Stewardship Council (MSC) certification for squid fisheries has only been achieved in two North East American fisheries (DeAlteris et al. 2018), with assessments of the stocks relying on long-term pre-fishing surveys to allow the determination of stock status. Effective assessment to a standard that would achieve MSC certification for the New Zealand squid fisheries would likely require the development of a scientifically robust stock assessment, agreed reference points, and a formal harvest control rule (MRAG Asia Pacific 2017).

Previously, preliminary age-structured population models were developed for squid in the Subantarctic (Mormede & Dunn 2023). That study showed that several parameters of the models were highly correlated in estimation (e.g., mean recruitment and the catchability coefficient for catch-per-unit-effort (CPUE)), and therefore estimates of escapement biomass were potentially biased and highly uncertain. However, Mormede & Dunn (2023) found that estimates of relative recruitment were reasonably well estimated and had similar patterns between a range of models with different levels of complexity.

The overall objective of project SQU2022-01 was the "Development of harvest strategies for squid in SQU 1T and SQU 6T". The specific objective was "To utilise the best assessment and management strategy options generated from SQU2020-01 for arrow squid in SQU 1T and SQU 6T to develop and test a formal management strategy that demonstrates short- and long-term sustainability".

This report summarises the work carried out under these objectives. Although a formal management strategy was not undertaken, considerable progress was made on the development of population dynamics models, on the investigation of the potential for models to inform in-season management, and on developing indicators that could be used as hindcasting tools for management.

2. METHODS

2.1 Introduction

Models developed by Mormede & Dunn (2023) for the Subantarctic were investigated further, implemented as age-structured population dynamics models using Casal2 v23.03 (Casal2 Development Team 2023). This allowed for rapid model development of a wide range of model structures to investigate relationships between parameters and observations. Two main model structures were developed, capturing either the main length group of animals each year (the one-cohort model), or capturing the main length group and a secondary length group of animals born about 6 months apart (the two-cohort model). The increased complexity and representativeness of the two-cohort model was at the cost of a reduction in the area it covered.

For the one-cohort models, only a single area was considered: south of 45.5° S and including south of 49.5° S (the Subantarctic) and the length cohort that appears in the fishery around fortnight 8, in December (the December cohort). The second smaller cohort that appears in the fishery around June (the June cohort) was ignored in this model.

For the two-cohort models, the area south of 49.5° S was considered as the region for data used in the model, as it was plausible that the December cohorts from this area and the area south of 45.5° S could be considered as separate populations (potentially with a difference in timing of recruitment and changes in abundance from fishing).

2.2 Data inputs to the models

Commercial catch and effort data, observer data, fisheries fortnightly standardised CPUE and fortnightly scaled length compositions for this project were provided by Mormede & Dunn (2023).

Total catches of arrow squid in New Zealand have varied between 32 600 t and 86 800 t per year since 2010. The proportion of that catch included in the one-cohort model was about 75%, dropping down to

about 30% for the two-cohort model (Figure 1). Because the weight of squid was both spatially and temporally varying, the fisheries catch was provided to the models as numbers rather than weight to reduce any potential bias; these data were provided by Mormede & Dunn (2023).

Two sets of standardised CPUE indices were used: either fortnightly or annual indices (Mormede & Dunn 2023), shown in Figure 2. The fortnightly indices were used in all models, with the annual indices used as a sensitivity run when models were run over a longer time period. Fortnightly indices were available only since 2011 from Mormede & Dunn (2023), whereas annual indices were available from 1990.

Fortnightly scaled length compositions for the Subantarctic were developed by Mormede & Dunn (2023) are shown in Figure 3. These show the progression of lengths through the fishery and the presence of often two and sometimes three length cohorts progressing through the fishery in any given year.

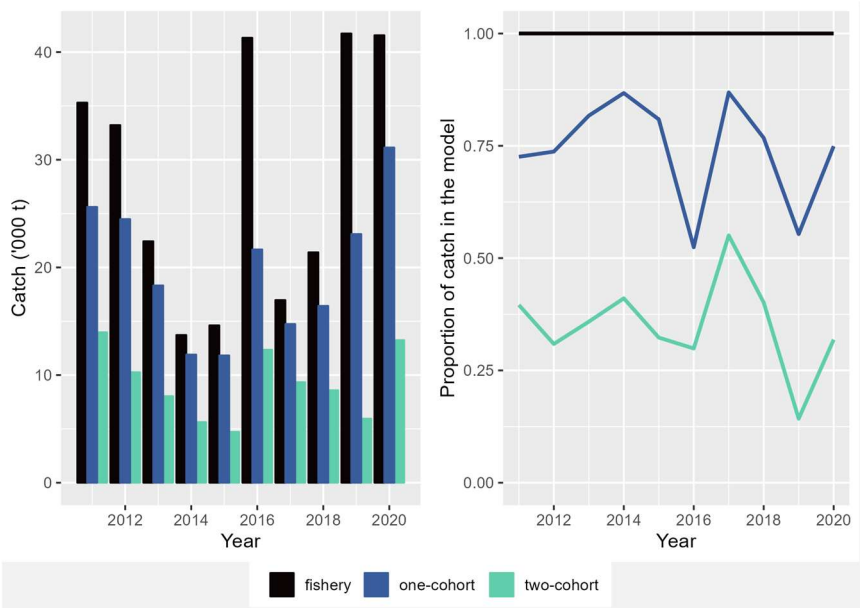

Figure 1: Annual catches of arrow squid from the fishery (black), and *N. sloanii* in the one-cohort model (blue) or two cohort model (teal) in tonnes (left) and proportion of total (right).

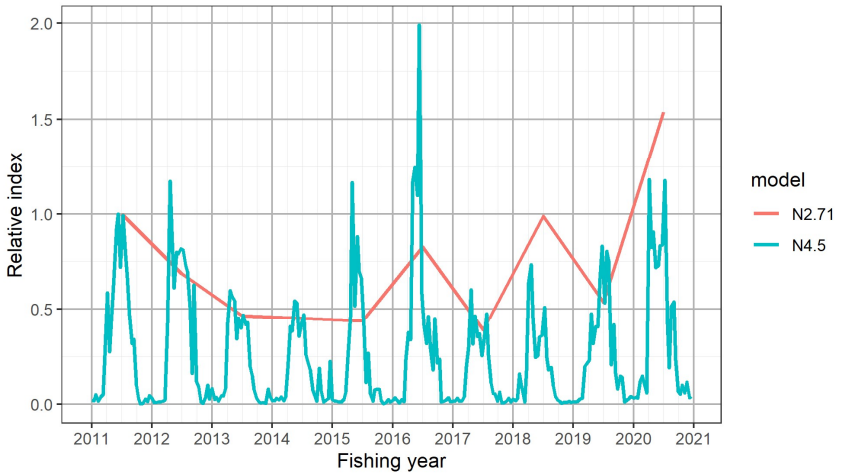

Figure 2: Standardised relative annual (model N2.71) and fortnightly (model N4.5) CPUE of squid south of 45.5° S (Mormede & Dunn 2023). For comparability, the indices were standardised to have a maximum value of 1 in in 2011.

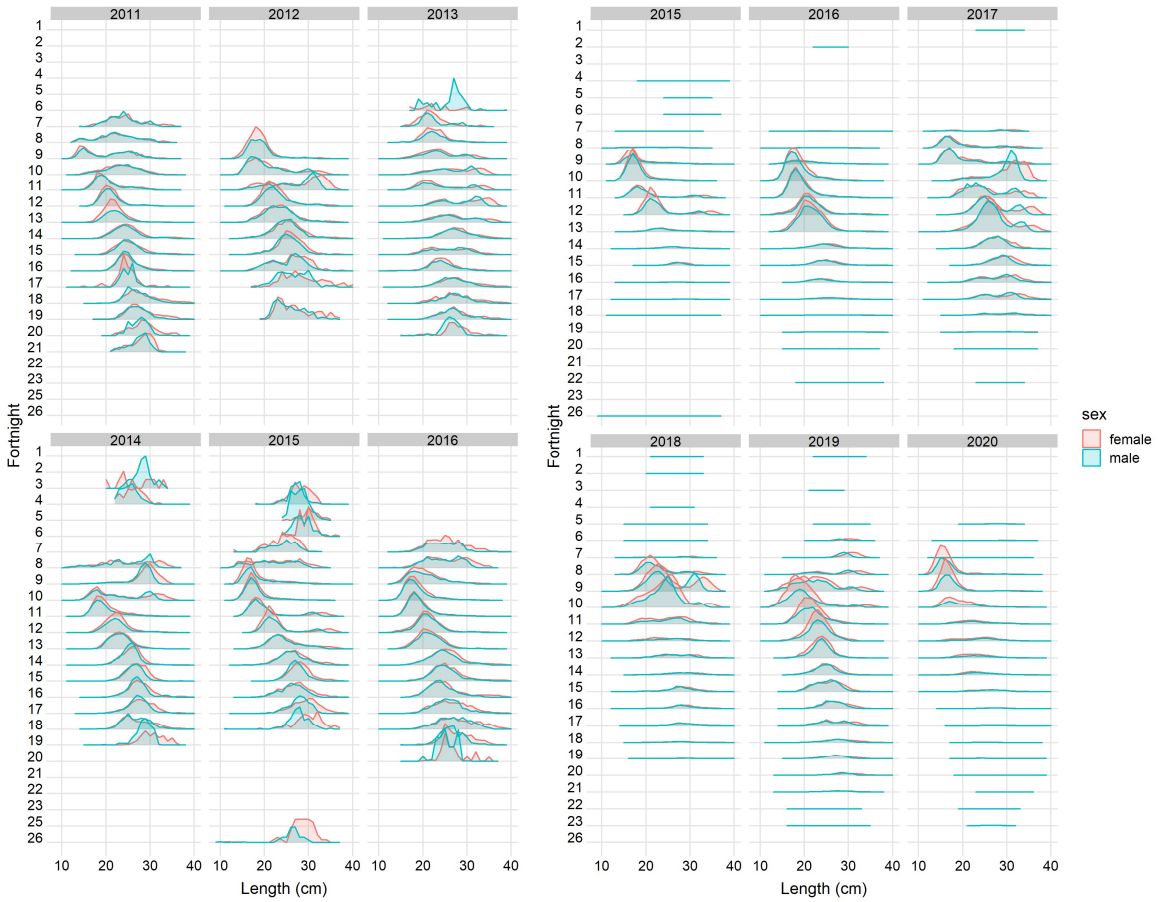

Figure 3: Scaled length compositions by fortnight for male and female *N. sloanii* in the Subantarctic (south of 45.5° S).

2.3 Population models

Maximum Posterior Density (MPD) estimates were used to compare models. For final model runs, the full posterior distribution was sampled using Markov chain Monte Carlo (MCMC) methods, based on the Metropolis-Hastings algorithm. MCMC chains with a total length of 5×10^6 iterations were constructed. A burn-in length of 5×10^5 iterations was used, with every 1000^{th} sample taken from the final iterations. Recruitment was estimated using the simplex method (Casal2 Development Team 2023), and the initial biomass was estimated using a log transformation.

Scaled length compositions were fitted as proportions at length using a multinomial likelihood. The initial effective sample size for each individual scaled length composition was estimated externally to the model from the estimated proportions and CVs. Final effective sample sizes assumed in the model down weighted these values using a multiplier of 0.01 (Mormede & Dunn 2023). The CPUE indices of biomass and associated CVs were fitted with a lognormal likelihood, by fortnight with no assumed additional process error. Sensitivities were carried out using alternative values for the additional process error.

The models were run from 2011 to 2020, the period for which the fortnightly standardised CPUE were available. Sensitivity runs were carried out using the annual CPUE as an additional series to allow model runs starting in 1990 rather than 2011. The models were assumed to be unsexed (i.e., the models did not distinguish male and female squid) with juvenile (all squid up to the point of maturity) and mature (squid that have matured) partitions. To capture the semelparous characteristics of squid, all squid were assumed to die at the end of their first year of life immediately following spawning. This model structure was used as the fishery only catches juveniles, with squid maturing from when they are about 25 weeks

old (see below). Maturation was implemented as a length-based maturity ogive. Once mature, squid effectively are not vulnerable to fishing and were assumed to spawn and die. Although the model was age-based, processes were carried out as length-based processes (e.g., growth and selectivities) with length bins of 1 cm increment from 9 to 40 cm with the 40 cm bin being a plus group.

Pre-spawning natural mortality was fixed at 1.0 y^{-1}, the mid-point of values summarised by Hurst et al. (2012), equivalent to 0.0385 per fortnight. We note that this value is lower than that used in some other squid models (for *Illex argentinus*), where values as high as 0.06 per week were used in some population models (Rosenberg et al. 1990). Natural mortality was not applied to mature animals as they were assumed to have spawned and died, and therefore represented an accounting category in the model.

Fishing mortality was applied to juvenile animals only through a length-based fishing selectivity ogive (and the length-based maturity ogive which removes larger animals from the fishery). Catch was provided in numbers of squid using the number to weight conversion carried out externally to the model (see above) as analyses showed it was spatially and temporally variable. Once spawning had occurred and spawning stock biomass calculated, all animals were removed using a terminal mortality at the end of the fishing year to represent semelparous mortality. Spawning stock biomass was assumed to be both juvenile and mature animals on the assumption that all squid would mature each year prior to spawning and then dying. In effect, spawning stock biomass in these models was the equivalent of escapement biomass: the end of year biomass which was not removed through natural or fishing mortality.

Growth was assumed constant over all the years and cohorts for juvenile animals and parameterised to be a linear growth curve using the Schnute parameterisation with fixed parameters a=0, b=1 (forcing a linear growth rate) and estimated lengths $y1$ and $y2$ at ages $\tau 1$ and $\tau 2$, respectively (Casal2 Development Team 2023). The values for $\tau 1$ and $\tau 2$ were fixed at ages 0 and 1 for the December cohort (the main length cohort) and ages 0.3 and 0.6 years for the June cohort (the second length cohort when it was estimated separately), to capture the different periods of growth and data availability of the two cohorts.

Mature animals were assumed to not grow as they would have died after maturation and spawning and were assigned the length equal to the a_{50} parameter of the maturation ogive. Recruitment was assumed independent for each cohort with initial abundance (R_0) and year class strengths (YCSs) estimated, and an assumed Beverton-Holt stock recruit relationship with steepness (h) of 0.9.

Two main structures were tested, a one-cohort model or a two-cohort model. Each model year represented a single fishing year (i.e., 1 October to 30 September) and the model was split into 26 equal time steps, each representing a fortnight. Model inputs and outputs are provided by fortnight; a translation table to calendar dates is provided (Table 1).

Table 1: Equivalent between model fortnight (FN) and date of the start of that fortnight.

Model	Date	Model	Date	Model	Date
FN1	1 October	FN10	4 February	FN19	9 June
FN2	15 October	FN11	18 February	FN20	23 June
FN3	29 October	FN12	3 March	FN21	7 July
FN4	12 November	FN13	17 March	FN22	21 July
FN5	26 November	FN14	31 March	FN23	4 August
FN6	10 December	FN15	14 April	FN24	18 August
FN7	24 December	FN16	28 April	FN25	1 September
FN8	7 January	FN17	12 May	FN26	15 September
FN9	21 January	FN18	26 May		

One-cohort model structure

To correctly model the December cohort in the single cohort model, observations of the June cohort were removed. Specifically, the scaled length compositions in 2013 and 2017, and all observations from before fortnight 10. CPUE indices before fortnight 10 and catches prior to fortnight 8 and after fortnight

20 (as fishers mostly fish on the June cohort) were also removed. The time steps were as follows, with natural and fishing mortality also happening in each time step:

- FN 1: age increment
- FN2: recruitment
- FN13–FN24: maturation
- FN24: spawning stock biomass (*SSB*) was calculated
- FN25: terminal mortality

To constrain the model and remove some of the correlations, the one-cohort model had a fixed fishing selectivity at 21 ± 1 cm with the maturation ogive estimated as a logistic curve. The CPUE indices produced by Mormede & Dunn (2023) from VAST are approximately absolute biomass indices (e.g., Thorson 2014, 2019). While this may not be exact, models were not able to calculate relative catchabilities with any reliability, and hence CPUE catchability was also arbitrarily fixed at $q = 1$ as it was confounded with absolute biomass (Mormede & Dunn 2023). The effect of these assumptions was evaluated in sensitivity model runs.

Figure 4 shows the processes captured in the one-cohort model; juvenile animals were recruited on the second fortnight of the model. Their number reduced initially due to natural mortality and then as a result of maturation. The number of mature animals increased from fortnight 13 based on the number of juvenile animals, their size, and the maturation ogive; mortality was not applied to mature animals. At fortnight 25 all animals were removed from the model, representing senescence, immediately after spawning stock biomass was calculated.

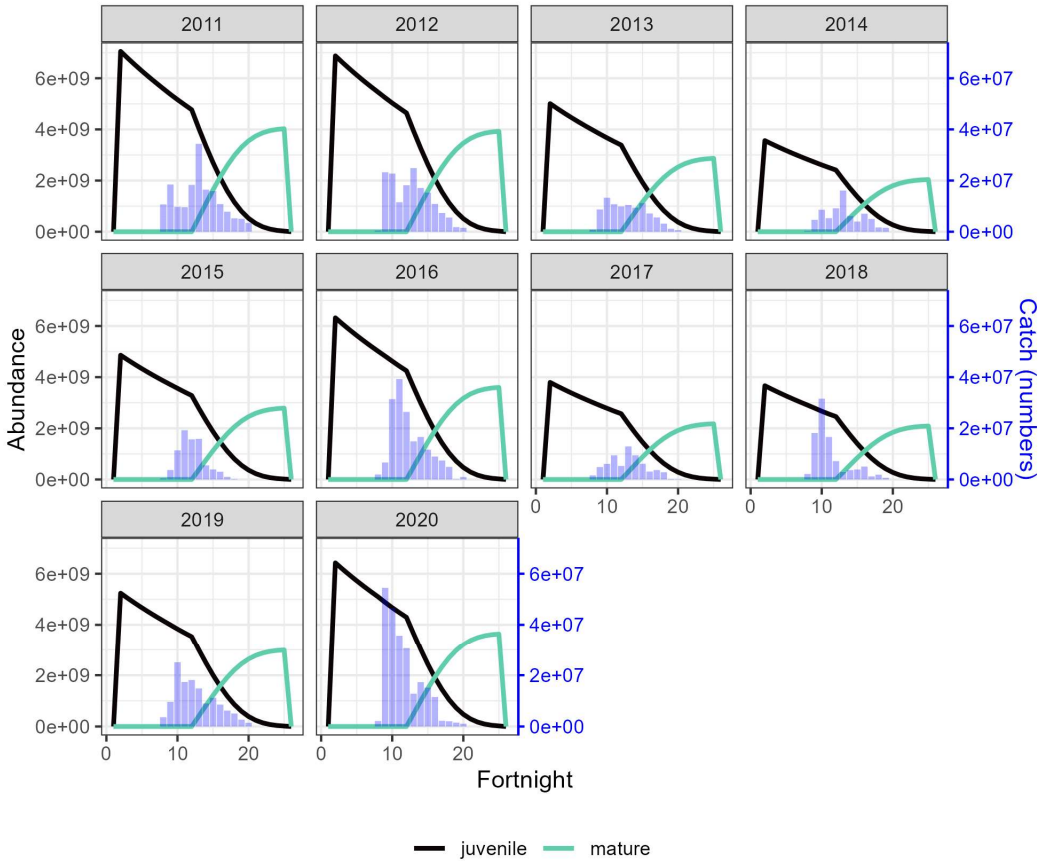

Figure 4: Process in the one-cohort model: abundance in numbers of juvenile and mature animals and catch in numbers.

Two-cohort model structure

For the two-cohort model, observations of CPUE and length compositions were limited to the area south of 49.5° S. The two-cohort models had included both the December and June length cohorts. Each was considered a separate population with independent R_0 and YCS parameters with fishing mortality applied to both cohorts combined. The time steps for the December cohort were assumed to be the same as for the one-cohort model. The time steps for the June cohort were as follows, with natural and fishing mortality also happening in each time step:

- FN16: age increment
- FN17: recruitment
- FN1 the following year to FN12 the following year: maturation
- FN13 of the following year: *SSB* was calculated
- FN14: terminal mortality

To constrain the two-cohort model and remove some of the correlations between parameters, fishing selectivity was estimated for the two cohorts separately and maturity was fixed. CPUE catchability was also arbitrarily fixed at 1 as it is confounded with initial biomass (Mormede & Dunn 2023). The effect of these assumptions was evaluated in sensitivity model runs.

In the two-cohort model, the biological process for the December cohort was identical to that in the one-cohort model (Figure 4). The process for the June cohort was the same but was about 6-months delayed, resulting in that cohort overlapping into the following model year (Figure 5).

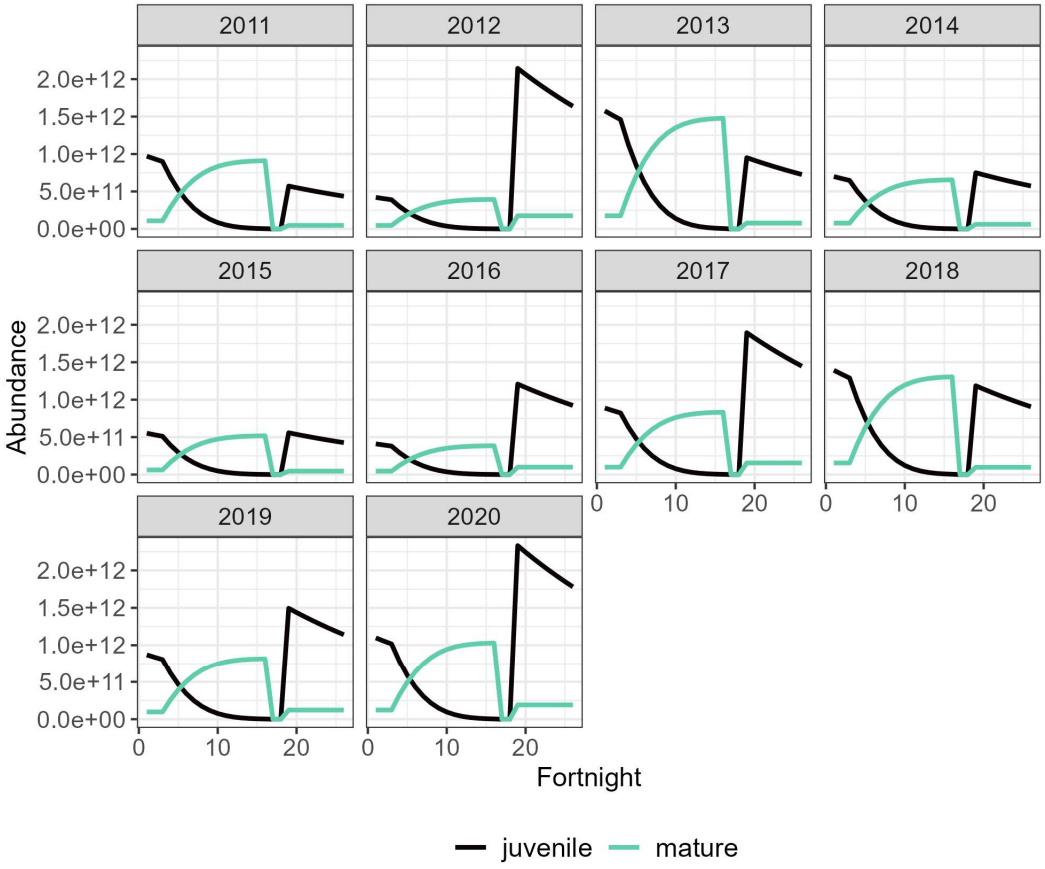

Figure 5: The June cohort process in the two-cohort model: abundance in numbers of juvenile and mature animals and catch in numbers.

2.4 Retrospective analysis

Because squid live for one year only, predicting biomass in future years would rely on predicting future recruitment and in-season management is more likely to be tractable (e.g., Falkland Islands Fisheries Department 2017, DeAlteris et al. 2018). However, there are no pre-season estimates of squid biomass nor squid recruitment, and DeLury methods using in-season CPUE have not yet been successful (McGregor & Large 2016, McGregor & Tingley 2016).

A retrospective analysis was performed using the final two-cohort model. The aim was to investigate how early in the season recruitment strength, and hence relative abundance, could be estimated. If this could be successfully estimated early in the season, an in-season management approach, based on the strength of recruitment in the year in progress, could be considered. The best-case scenario was considered initially, whereby data access was assumed instantaneous and fortnightly CPUE and length frequency (LF) observations were available for the assessment in each fortnight of the fishery.

The model was run with an increasing number of fortnightly data for the latest year of the model. The estimated YCS using the sequential increase in fortnightly data were compared with the YCS estimated when all data were available for that year. This was then replicated for each of the most recent five years of the model. For example, the model was run to the end of 2016, with data up to fortnight 11 only in 2016 (but all previous data included in the model), then up to fortnight 12 and so forth, and the estimated YCS were compared with the YCS from the model using all data.

3. RESULTS

3.1 Two-cohort model investigations

The two-cohort model was initially updated to attempt to capture as much of the complexity of the fishery and the stock as possible, even though this only represented 30–40% of the total arrow squid catches across all areas in recent years (Figure 1). The rationale was that, if successful, this could be extended to include data from other areas.

Maturation and natural mortality

The effect of different assumptions for maturation and natural mortality were investigated. Specifically, models assumed that maturity was estimated and growth fixed ('Mat est growth fixed' in Figure 6), maturity was fixed as a logistic selectivity with parameters 35 ± 8.5 cm and growth was estimated ('Mat fixed tight growth est' in Figure 6), maturity was fixed as a logistic selectivity with parameters 37 ± 24 cm and growth was estimated ('Mat fixed flat growth est' in Figure 6), and maturity was fixed as a logistic selectivity with parameters 37 ± 24 cm, natural mortality was increased from 1 y^{-1} to 2 y^{-1} and growth estimated ('Mat fixed flat double M growth est' in Figure 6).

Estimating the maturation ogive resulted in a left shift of the June fishing selectivity and a right shift of maturation with 50% maturity estimated at about 75 cm. This was not considered biologically realistic; however, it would be similar in effect to the assumption in the DeLury models (DeLury 1947, McGregor & Large 2016, McGregor & Tingley 2016) that allocated all of the in-season change in vulnerable abundance to just fishing and natural mortality. The estimation of maturity also resulted in a change to the estimated values of YCS, although the pattern of strong and weak year classes was similar (Figure 6). This highlights the correlation in the model between maturation and the fishing selectivity of the June cohort. Changing the shape of maturation to a less steep ogive, similar in shape to that estimated in some previous models (Mormede & Dunn 2023), resulted in little change in the estimated selectivities or the relative strengths of annual recruitment (Figure 6). Spawning stock biomass (*SSB*) estimates were all highly influenced by the different parameter assumptions (not shown). The model run with a less steep maturation ogive ('Mat fixed flat growth est') resulted in models with the lowest negative log-likelihood (3720 instead of 4165 for the 'Mat fixed tight growth est' model). Model 'Mat fixed flat growth est' was used as the basis for further investigations described below.

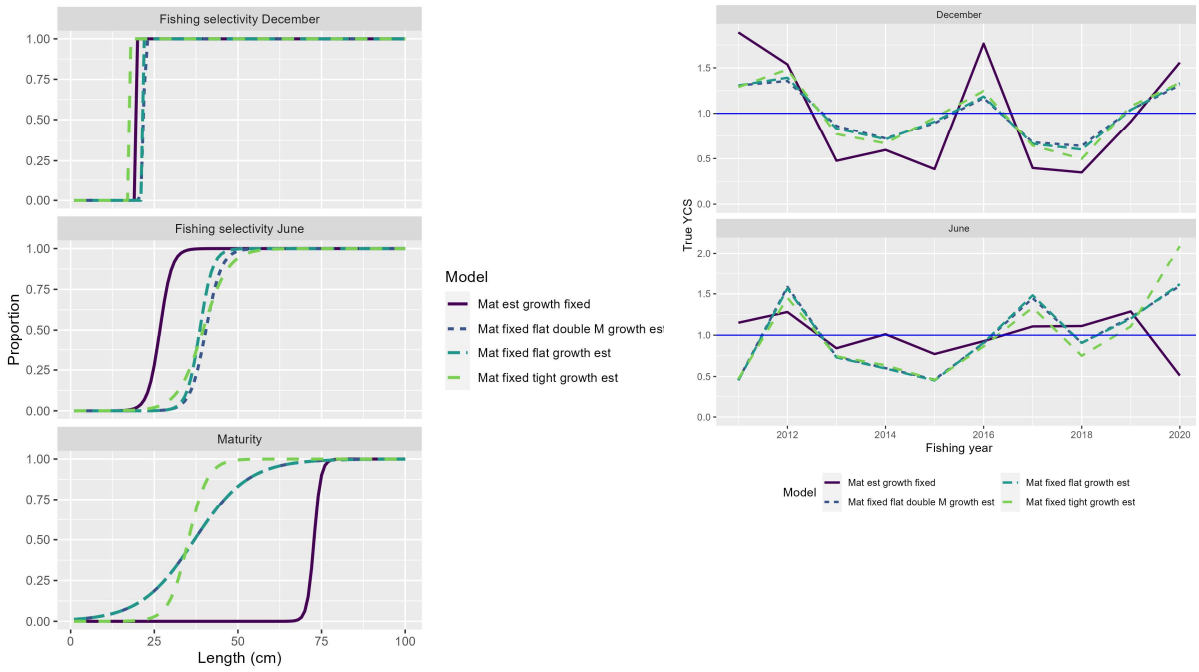

Figure 6: Effect of various assumptions of maturity and natural mortality on estimated selectivity parameters and year class strengths (YCS). Models assume that maturity was estimated and growth fixed (Mat est growth fixed), maturity was fixed as a logistic selectivity with parameters 35 ± 8.5 cm and growth was estimated (Mat fixed tight growth est), maturity was fixed as a logistic selectivity with parameters 37 ± 24 cm and growth was estimated (Mat fixed flat growth est), and maturity was fixed as a logistic selectivity with parameters 37 ± 24 cm, natural mortality increased from 1 y^{-1} to 2 y^{-1} and growth was estimated (Mat fixed flat double M growth est).

Data weighting

The effects of assigning different data weightings to the CPUE and length composition data were also investigated. The length composition data was down weighted by a factor of 0.01 in the base case model (Mormede & Dunn 2023). Increasing that weight resulted in the right shift of the June fishing selectivity and an increase in YCS and *SSB* variability as well as a clear reduction in the fits to the CPUE data. This analysis confirmed that there is some level of conflict between the two datasets given the model construct, but the effects on the model were much smaller than that of the assumptions about the maturation ogive or natural mortality. The model with down-weighted length data was used as the basis for further investigations described below.

The construct of the model could partly cause this effect: the expected length compositions are a combination of the fishing selectivity which controls when animals appear in the length composition, and the maturation which controls when animals leave the length composition. The variability in the timing and rate of growth between years were also not captured in this model.

Catchability

CPUE catchability was shown to be directly correlated with initial biomass as the model has no information to distinguish the two (Mormede & Dunn 2023) so was arbitrarily fixed at 1 to constrain the model. The effect of this value was investigated by running models with catchability fixed at either 0.25, 0.5, 1, 5, 10, 12.5, 25, or 50. The objective function was flat until q = 12.5 but then increased steadily based on deteriorated fits to the CPUE observations. The effect on YCS was small (Figure 7). Catchability values are directly correlated with spawning stock biomass so those were highly influenced by the value of q. A value of q = 10 was used as the basis for further investigations described below.

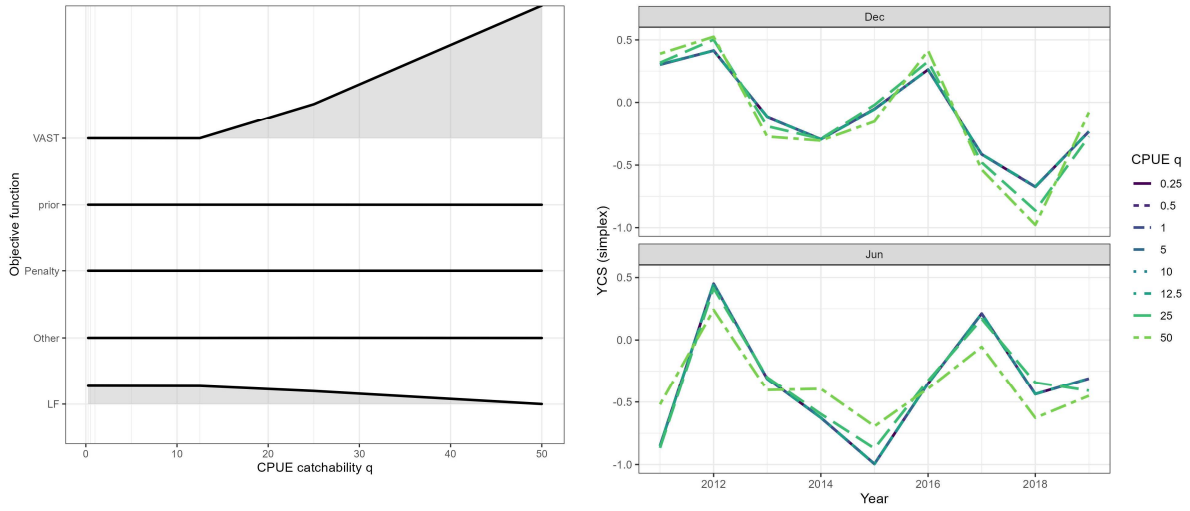

Figure 7: Effect of the value of the CPUE catchability *q* on the objective function (left) and estimated year class strengths (YCS, right).

Updated model

The updated model was constrained enough to present good MCMC performance (Figure A.1). Spawning stock biomass was relatively stable although the June cohort presented an unlikely high initial biomass due to the right shift in the fishery selectivity, probably driven by the fact the June cohort is only rarely fished (Figure A.2). Fits to the fortnightly CPUE were adequate (Figure A.3) and confirmed that the June cohort is expected to make a very small contribution to the CPUE (Figure A.4). Fits to the length composition were generally acceptable, although there is evidence of inter-annual variability which could warrant the investigation of annually varying growth parameters (Figure A.5). Year class strengths for the two cohorts were estimated with narrow credible intervals and differed between the two cohorts in some years (Figure A.6).

The June cohort was only present south of 49° S, which required the two-cohort model to be limited to that area. The June cohort was found to be a small contributor to the CPUE. Moreover, it was only intermittently sampled by the fishery leading to poor model behaviour. Consequently, the one-cohort model was deemed more desirable at this stage to further investigate arrow squid in New Zealand.

3.2 One-cohort model investigations

The one-cohort model developed previously was updated with catchability *q* fixed at 10. The YCS estimations of the December cohort were almost identical to those of the two-cohort model and stable with different model configurations but deemed to be not variable enough for such a dynamic species. For example, the spawning stock biomass of the US Northeast longfin squid was estimated through surveys to vary between about 30 000 and 170 000 tonnes a year (DeAlteris et al. 2018). Ways of increasing uncertainty/variability in the estimates of recruitment were investigated.

Extension of the model

The models were developed initially for fishing years 2011 to 2020, for which fortnightly standardised CPUE were available (Mormede & Dunn 2023). This also correlates with a period when squid catches in New Zealand have been variable but not at the levels seen in the early 2000s.

One-cohort models were extended back to 1990, with fortnightly scaled length composition when available (there were no length data for the 2000 to 2007 fishing years), fortnightly standardised CPUE from 2011 to 2020 (fortnightly standardised CPUE were not available for 1990 to 2010), and annual standardised CPUE from 1990 to 2020. As expected, the variability of recruitment between 1990 and 2010 was much higher than seen since 2011. However, they were completely correlated with the annual

CPUE series prior to 2011 whereas from 2011 the annual and fortnightly CPUE values were not necessarily in agreement (Figure 8). The variability of the fortnightly CPUE observations from one fortnight to the next (e.g., Figure A.3 for the two-cohort model) shows the importance of using fortnightly CPUE rather than a single annual CPUE. This result confirmed the need for the fortnightly CPUE series to have a better handle on recruitment strength. This model was not used as the basis for further investigations.

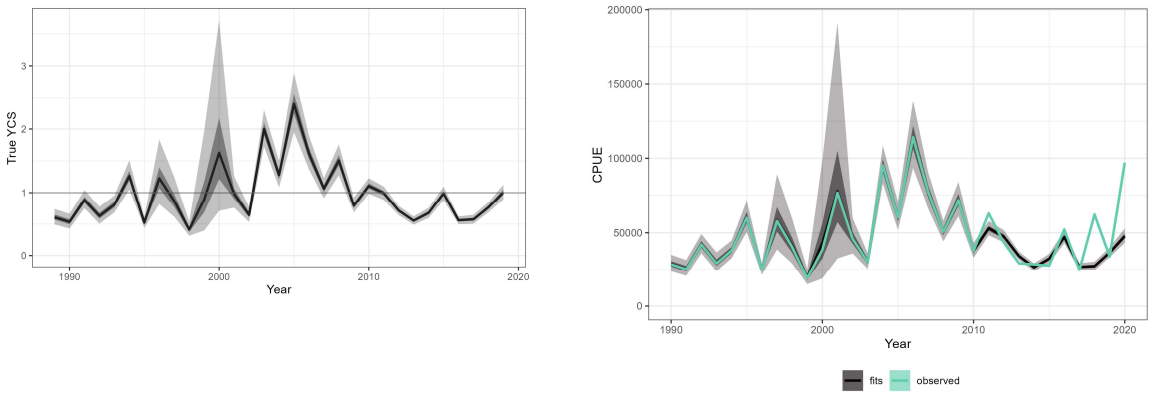

Figure 8: Estimated year class strength (YCS) for the extended one-cohort model (left) and fits to the annual CPUE series (right), with interquartile range (dark grey) and 95% credible interval (light grey).

Increased model uncertainty

In an attempt to increase the variability and uncertainty of the model and in particular of the estimated recruitment, changes to the assumption of the catchability parameter were tested. Firstly, instead of being fixed at 10, catchability was instead estimated with a lognormal prior of mean 10 and CV 0.2. Consequently, the uncertainty in the spawning stock biomass increased, which is not surprising given *SSB* and *q* are directly correlated. However, the estimates of recruitment remained identical, including their credible intervals (Figure 9).

Secondly, a 20% process error was added to the fortnightly CPUE observations. This resulted in an increase in the uncertainty of all estimated parameters, including the estimates of recruitment. This additional process error was used as the basis for further investigations described below.

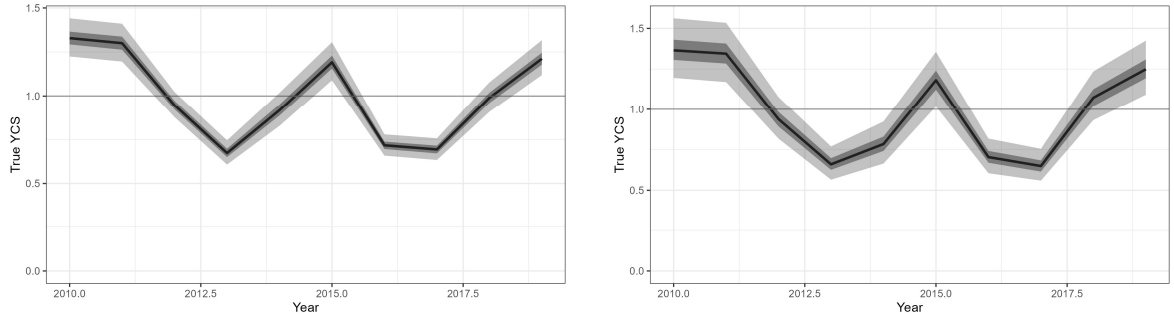

Figure 9: Estimated year class strength (YCS) for model without CPUE process error (left) or with 20% process error (right), with interquartile range (dark grey) and 95% credible interval (light grey).

Annually varying growth

Another source of variability not considered in previous models is the variation in the timing of the cohorts between years, and their speed of growth. This is shown in the fits to the length composition, which are to the left of the observed in some years and to the right in others (Figure A.5).

Growth was parameterised to be a linear growth curve using the Schnute parameterisation with fixed parameters a=0, b=1 (forcing a linear growth rate) and estimated lengths *y1* and *y2* at ages 0 and 1, respectively (see section 2.3 for further details, and Casal2 Development Team 2023 p. 62, section 5.6.3). Allowing varying annually as *y1* and *y2* allows cohorts to appear in the fishery at different times of the year and to grow at different rates.

Annually varying growth was applied to the one-cohort model. The fits to the length composition were improved (Figure B.1). Estimated growth parameters indicated quite variable growth between years, with years of obvious faster growth such as 2015 and years of much slower growth such as in 2012 (Figure 10). The estimated recruitment strength was slightly different from that estimated in the previous models (Figure 10 vs. Figure 9). This model was used as the basis for further investigations described below.

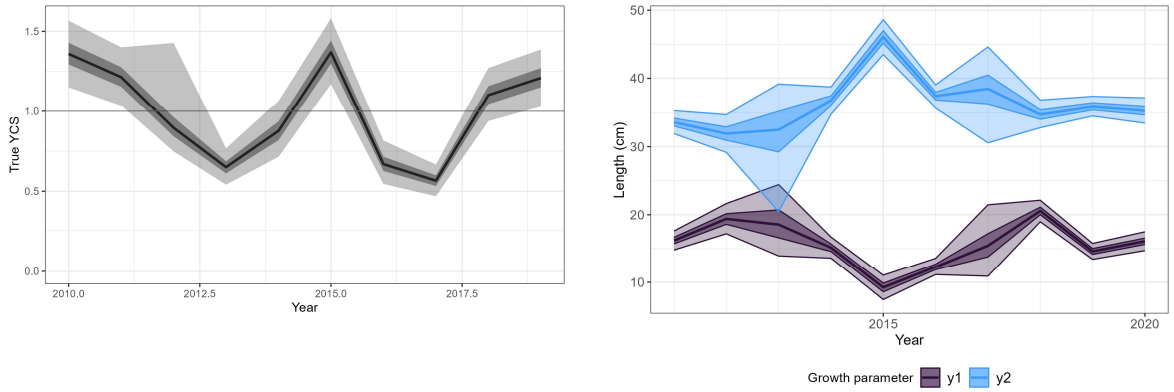

Figure 10: Estimated year class strength (YCS) and estimate of growth parameters *y1* and *y2* (right), with interquartile range (dark shading) and 95% credible interval (light shading).

Updated model

The updated model was constrained enough to present relatively good MCMC performance (Figure B.2). The 50% maturation was estimated at about 34 cm (Figure B.3). Fits to the fortnightly CPUE were adequate (Figure B.4), although they indicated that a higher process error might be warranted to capture more of the variability of the observations. Fits to the length composition were generally acceptable, although the presence of a second length cohort in some fortnights (for example fortnight 10 in 2014) affected the fits and should probably be removed from the observations in future models (Figure B.1). Year class strengths were estimated with an increased credible interval compared with previous models although the range of values was still relatively limited, only varying between 0.5 and 1.5 (Figure 10).

3.3 Retrospective analysis

A retrospective analysis was carried out over the last 6 years of the model using the two-cohort model. For the December cohort, four out of the six years were within the 95% credible interval of the final YCS estimated for that year, at a time when between 25 and 60% of the catch had already been caught. This value increased to five out of six at fortnight 15 when 75% of the catch had been caught (Figure 11). It is unclear that such late predictability in terms of catch taken would be operationally useful at this stage.

Furthermore, no correlation was found between annual CPUE and YCS or fortnightly CPUE at any fortnight and YCS, precluding the use of standardised CPUE throughout the season as a useful indicator of abundance.

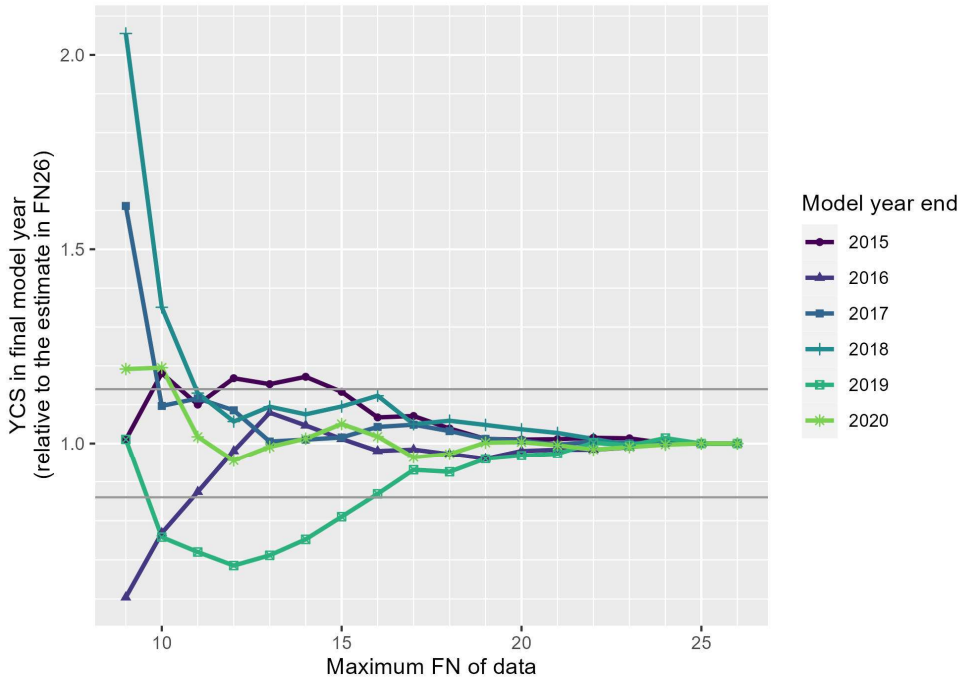

Figure 11: Estimated year class strength (YCS) estimated at between fortnight (FN) 9 and 26 of the final model year, simulating in-season estimation of YCS in 2015 to 2020. The grey lines represent the 95% credible interval of YCS estimation of about 0.14.

4. POTENTIAL MANAGEMENT

Absolute spawning stock biomass could not be estimated at this stage: there is no absolute index of abundance (such as a trawl survey), no fluctuating stock with many age classes, and each year of recruitment is independent of the previous year, likely driven by annual environmental parameters. Therefore, management based on absolute value of biomass, of escapement, or fishing pressure was not possible. However, other short-lived species are managed based on relative proxies in relation to past values. For example, octopus in Australia is managed based on hindcasting CPUE and has attained MSC certification (Daume et al. 2018).

4.1 Potential proxies

CPUE is both spatially and temporally variable for squid and, as shown above, the annual index was not always consistent with the equivalent fortnightly index when integrated in a model (Figure 8) and was not correlated to the model estimates of recruitment strength. Therefore, standardised CPUE was not proposed as a potential proxy of population status.

Model-based estimates of recruitment appeared to be reasonably robust to various model assumptions. Although absolute estimates of biomass were not possible, representations of relative exploitation rates were proposed: either expressed on an annual basis as total catch divided by spawning stock biomass, or as a fortnightly exploitation rate (Figure 12). Absolute values for those proxies were not provided because they were deemed relative, with the absolute value driven by model assumptions and in particular the assumed value of catchability q.

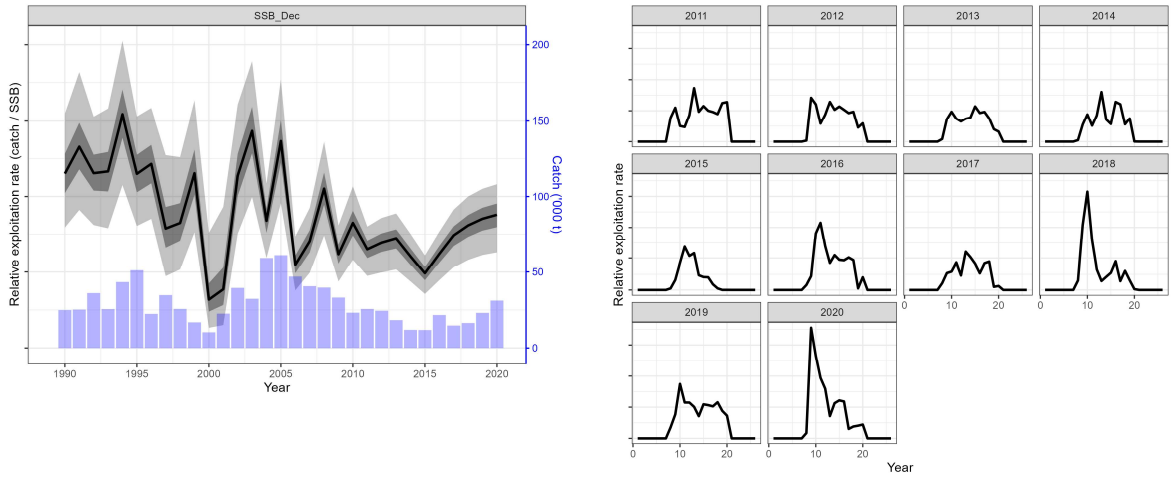

Figure 12: Estimated annual relative exploitation rate and catch for the extended one-cohort model (left), and fortnightly relative exploitation rate for the one-cohort model starting in 2011 (right). Absolute values for those proxies were not provided because they were deemed relative, with the absolute value driven by model assumptions and in particular the assumed value of catchability *q*.

4.2 Potential application of those proxies

Although the proxies proposed are relative indices, their recent range can be compared with historical ranges, assuming no significant changes in underlying productivity that might affect this comparison. If proxies from the models were used in this way, then fortnightly standardised CPUE should be developed for the 1990–2010 years to extend the current series. Since 2011, effort has been stable and catch was likely driven largely by annual changes in abundance (Figure 13). However, we note that higher variability of effort and catch was likely to have been present in the past.

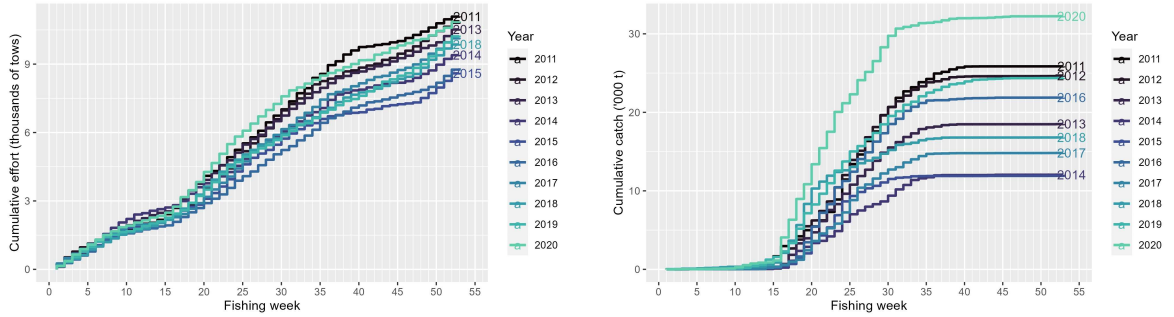

Figure 13: Annual cumulative effort (left) and catch (right) of squid in the Subantarctic region which forms the basis for the standardised CPUE and catch values in the one-cohort model.

5. DISCUSSION

Age-structured population models were developed further for squid in the Subantarctic. Many of the model parameters were highly correlated in estimation (e.g., mean recruitment and the catchability coefficient for CPUE), and therefore estimates of escapement biomass were highly uncertain, precluding the use of standard assessment models as information for management at this stage. However, the estimates of recruitment were reasonably well estimated and had a consistent pattern between different models with different levels of complexity.

The models presented have limitations, such as the need to assume many parameters as fixed and not estimated, to stabilise the model. This led to a consequent likely underestimate of model uncertainty in parameter estimates. These models should be developed further, as should length-based models which might better capture the length observations and underlying cohorts present in each year. Alternative model structures should also be investigated. For example, these models assume the mature biomass is effectively not vulnerable to fishing. An alternative extreme that could be tested is having no maturity (although fits to length data would be compromised), which is equivalent to the assumption made in DeLury analyses.

The models developed were used to investigate the potential for in-season management of squid. Given the short season of the fishery, it is unlikely that in-season predictions could be made early enough to be useful for in-season management at this stage. Proxies for relative fishing pressure were developed and could be used as hindcasting tools to confirm if the fishery operated within known ranges of relative fishing pressure. The use of such hindcasting tools would require the extension of the existing models back to 1990; the current models have detailed data inputs from 2011 only and higher annual catches were common in the 2000s.

6. FULFILLMENT OF BROADER OUTCOMES

Whakapapa links all people back to the land, sea, and sky, and our obligations to respect the physical world. This research aims to ensure the long-term sustainability of squid stocks, for the good of the wider community (including stakeholders and the public) and the marine ecosystems that squid inhabit. This project supports Māori and regional businesses, diversity, and inclusion, and our research is inextricably linked to the moana from the work it carries out and the tangata whenua it supports.

As part of this project, the team has continued to build capacity and capability in fisheries science and stock assessment, its commitment to zero waste and carbon neutrality, environmental stewardship, and social responsibility.

7. ACKNOWLEDGEMENTS

We thank Dragonfly Data Science for providing the dataset used by Mormede and Dunn (2023) (as part of contract SQU2020-01) and hence in this report. We also thank the members of industry, Fisheries New Zealand management, and the Fisheries New Zealand Deepwater Working Group for their input and discussions on this work, in particular Geoff Tingley and Richard Wells. This work was funded by the Fisheries New Zealand project SQU2022-01.

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Appendix A – Two-cohort final population model results

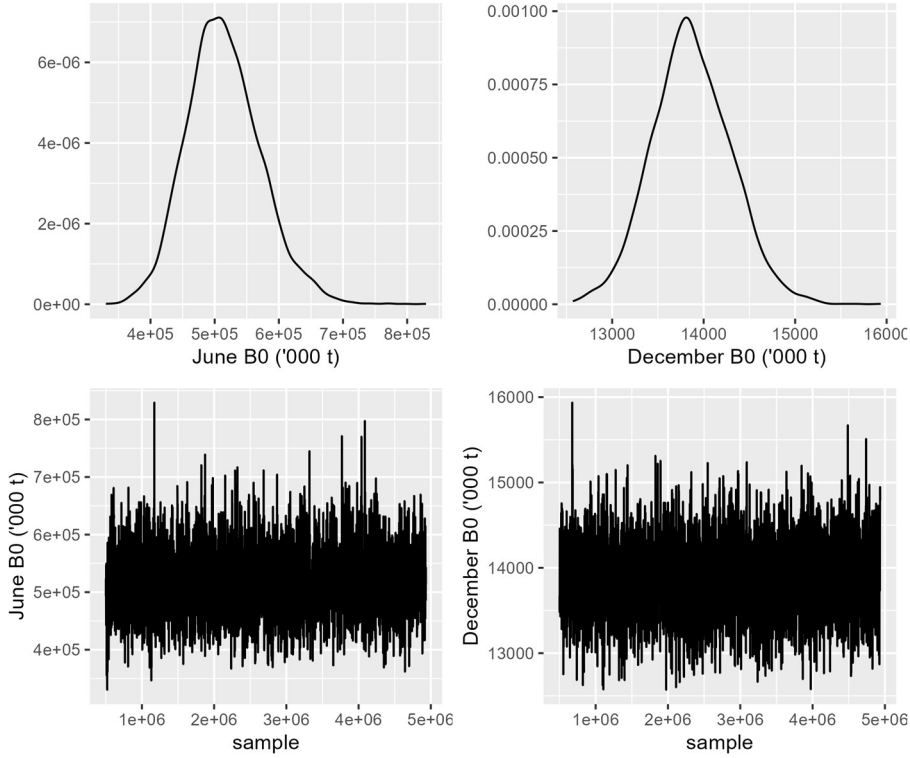

Figure A.1: Two-cohort model MCMC traces for the *SSB* parameters.

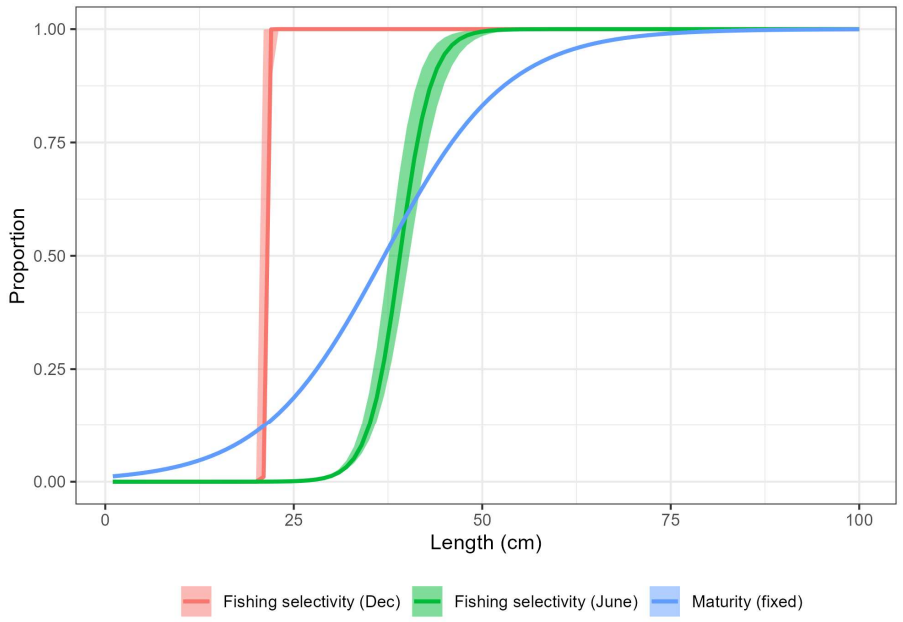

Figure A.2: Two-cohort model MCMC estimation of fishing selectivities, with 95% credible interval. The maturity ogive was fixed in this model.

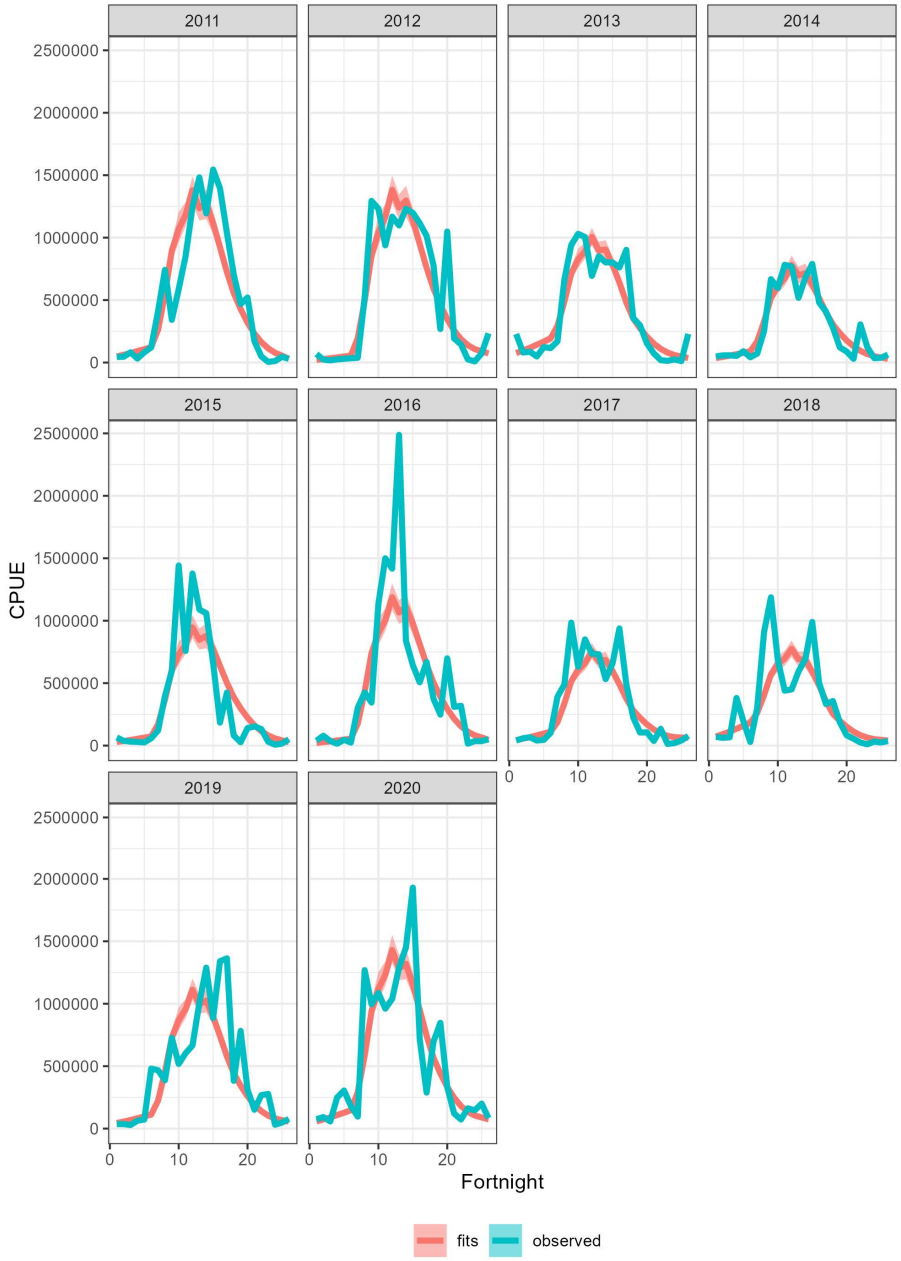

Figure A.3: Two-cohort model fits to the CPUE at MCMC level, with 95% credible interval.

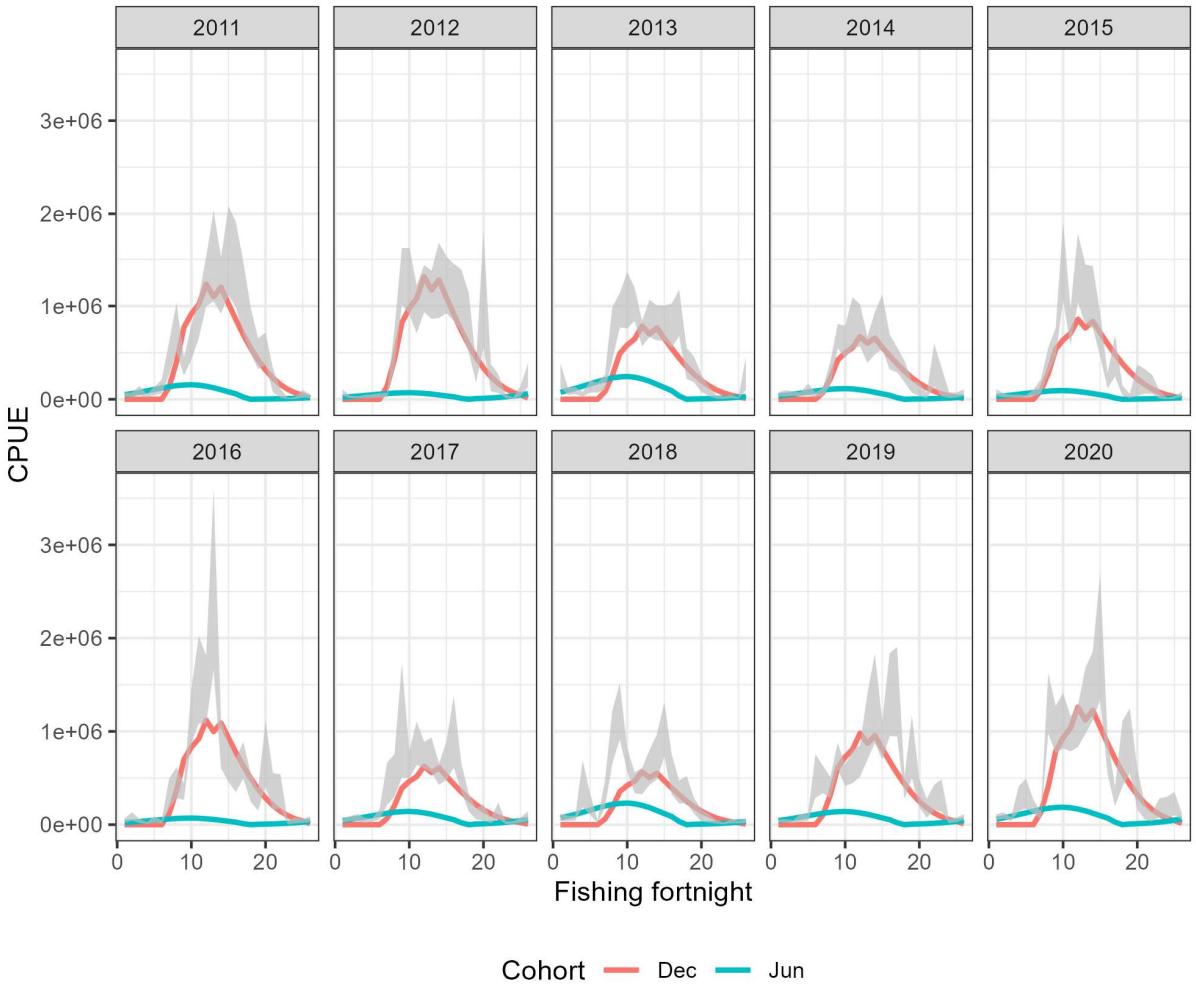

Figure A.4: Contribution of each of the cohorts to the CPUE at MCMC level, with 95% credible interval.

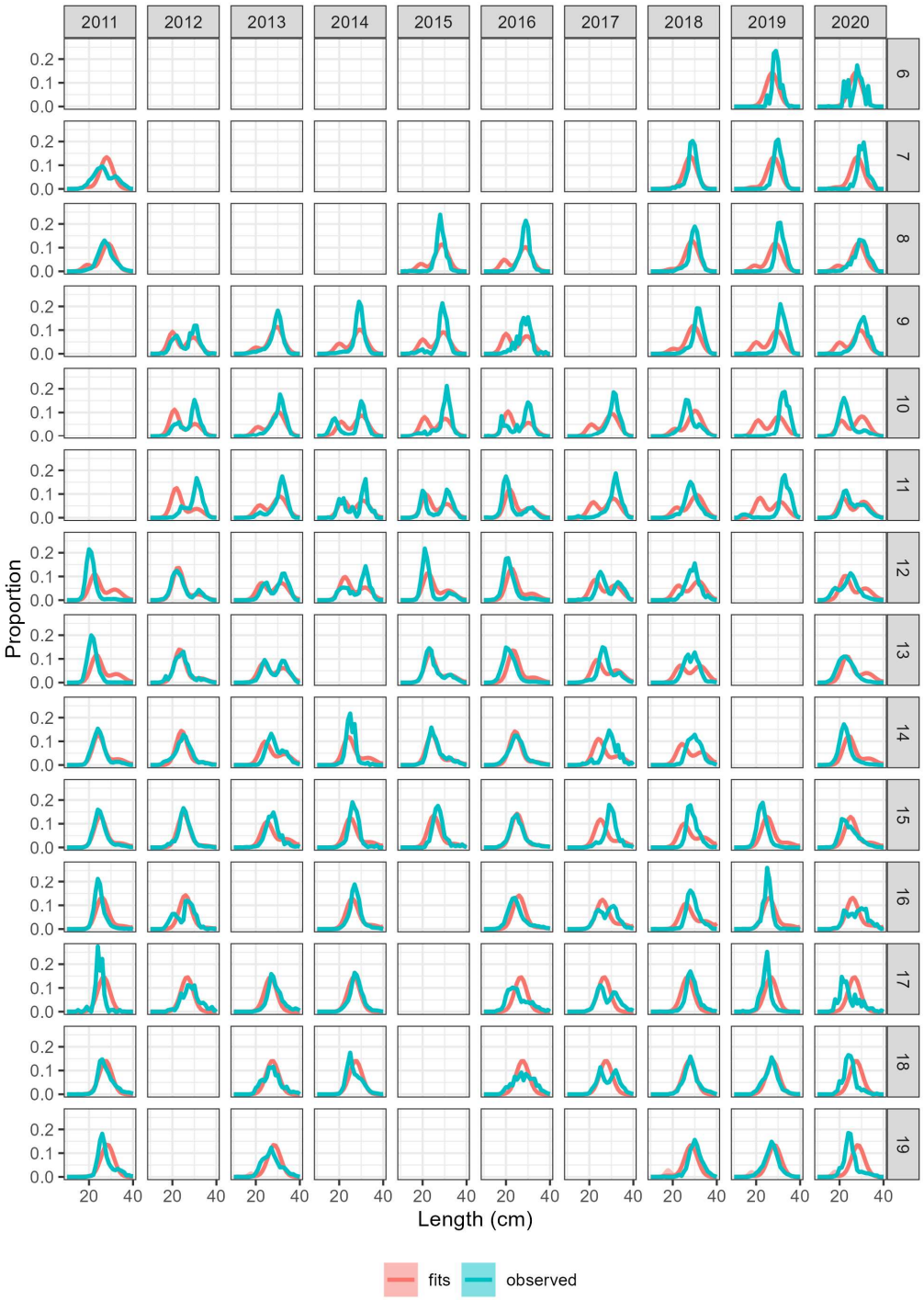

Figure A.5: Two-cohort model fits to the length composition at MCMC level. The 95% credible interval is within the width of the plotted lines.

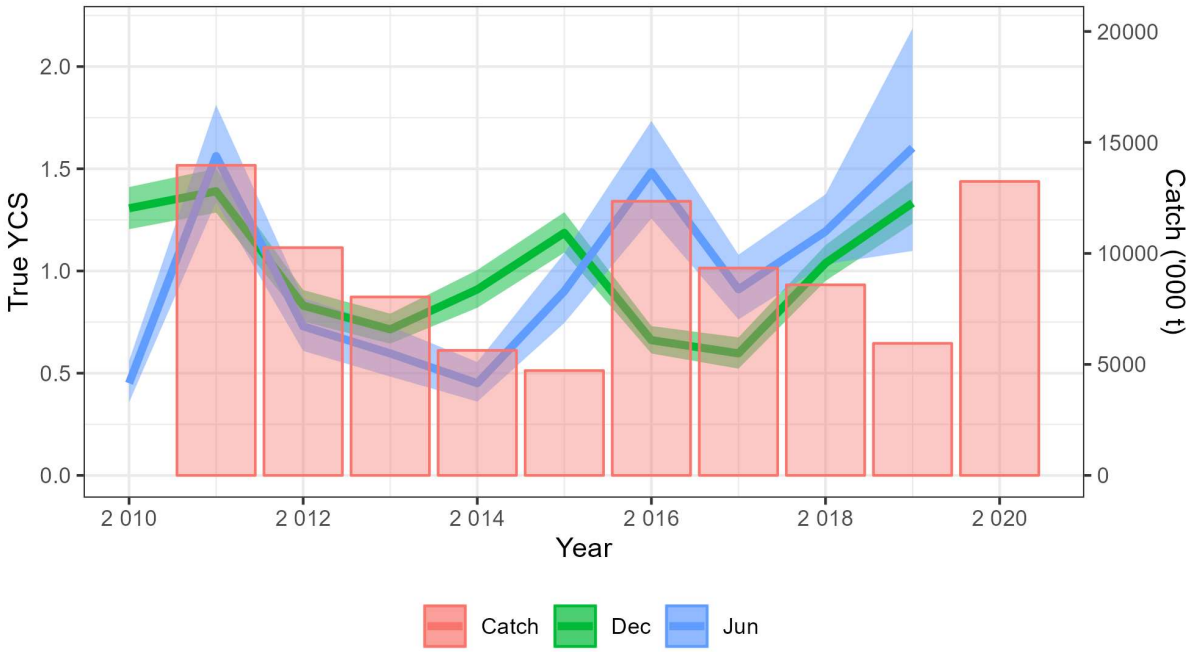

Figure A.6: Two-cohort model MCMC estimates of year class strengths, with 95% credible interval. Also plotted the annual catches included in the model.

Appendix B – One-cohort final population model results

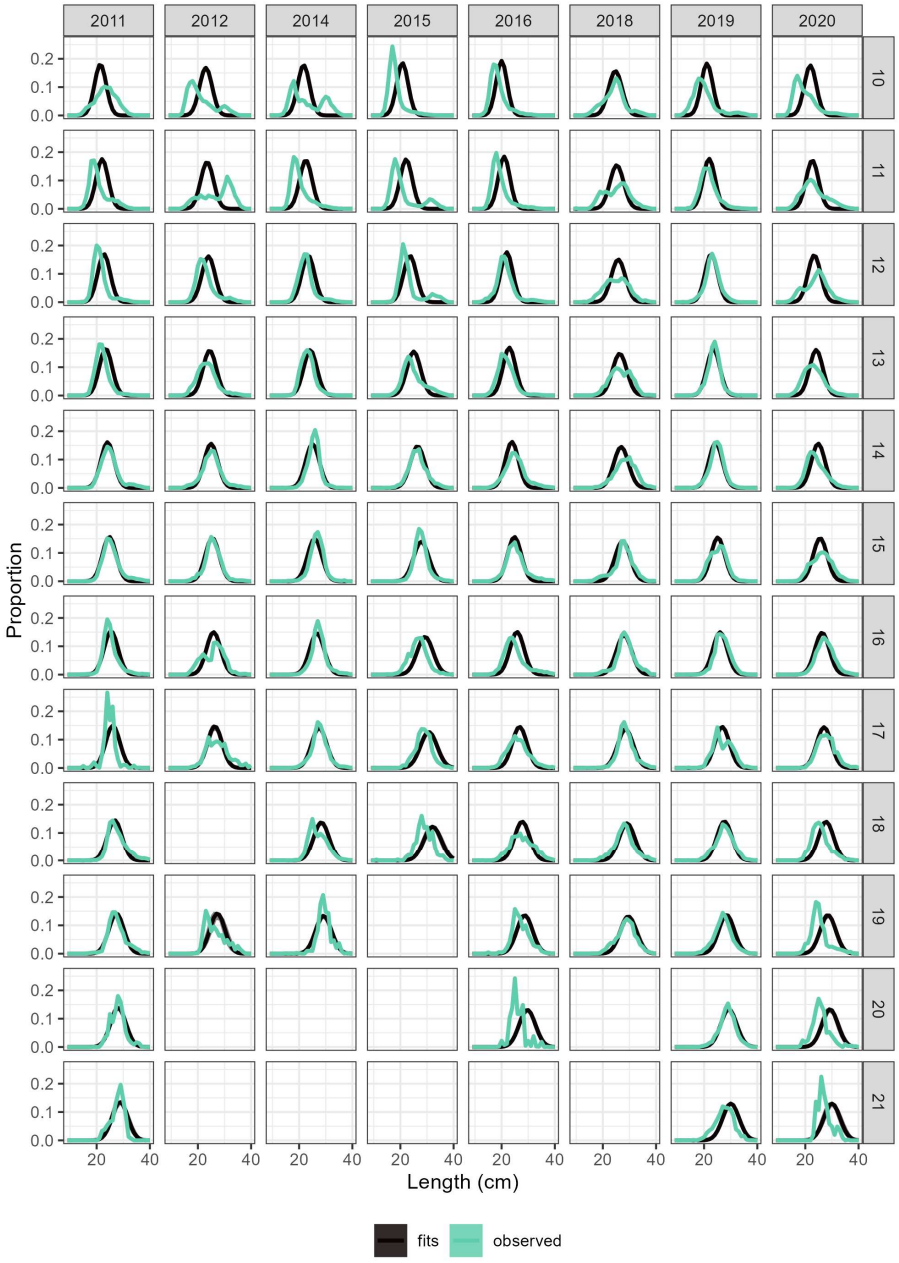

Figure B.1: One-cohort model fits to the length composition at MCMC level. The 95% credible interval is within the width of the plotted lines.

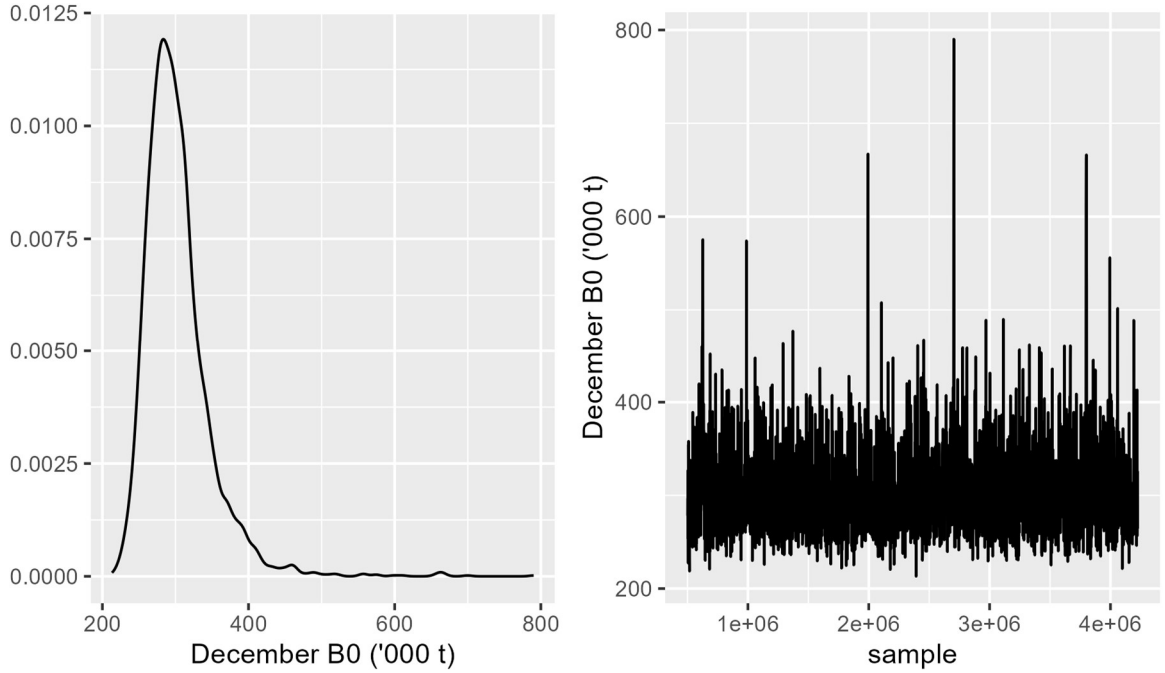

Figure B.2: One-cohort model MCMC traces for the *SSB* parameter.

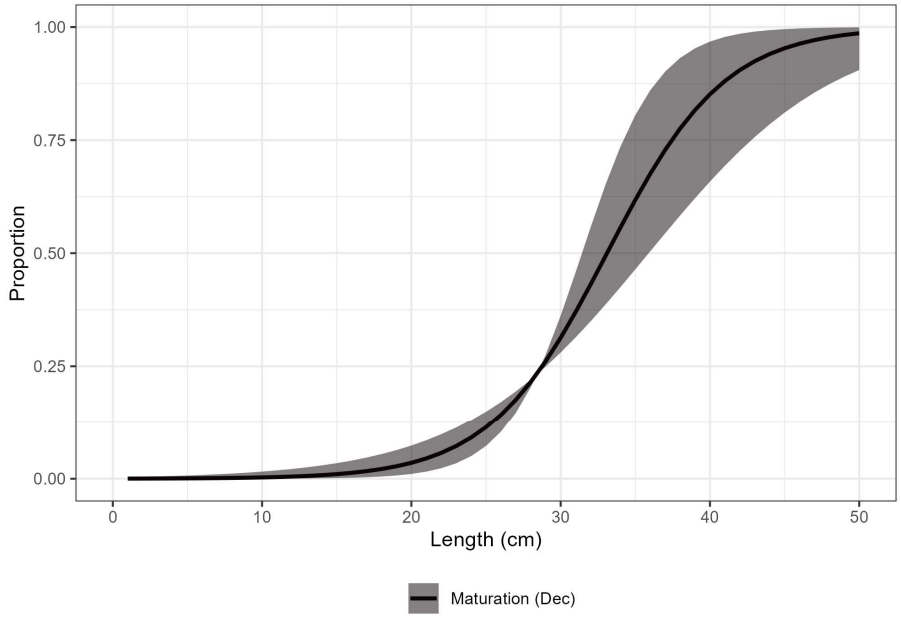

Figure B.3: One-cohort model MCMC estimation of the maturation ogive, with 95% credible interval.

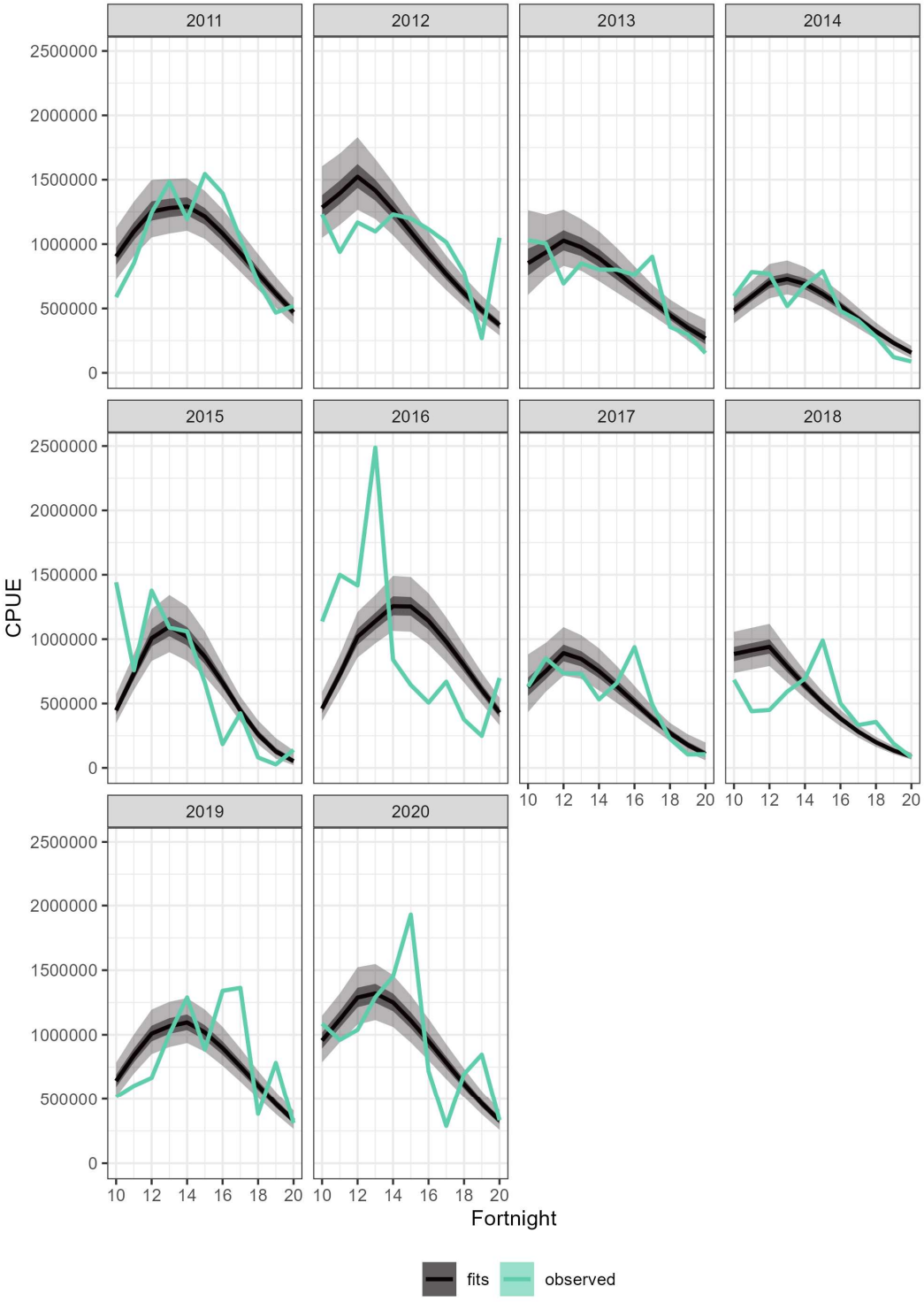

Figure B.4: One-cohort model fits to the CPUE at MCMC level, interquartile range (dark grey) and 95% credible interval (light grey).