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Tini a Tangaroa

Stock assessment of blue cod (*Parapercis colias*) in BCO 5 using data to 2019

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I.J. Doonan

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PO Box 2526
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EXECUTIVE SUMMARY

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The stock assessment was conducted using a Bayesian age- and sex-based model in the software Casal2. Models were constructed that allowed explicit modelling of the sex change process. This model was new and replaced the previous Bayesian length-based model. The Southern Inshore Working Group reviewed this work periodically, and all technical decisions were agreed by that group.

Separate data sets were compiled and analysed for Statistical Areas 025, 027, and 030, i.e., there were three independent stock assessments which were combined afterwards to produce the stock status for BCO 5. The data available for each of these areas differed, and few data were available for the remainder of the BCO 5 Statistical Areas. Combined, Statistical Areas 025, 027, and 030 represented about 90% of the recent commercial fishery landings. The model estimated stock size from 1900 to 2019.

The assessment included three fisheries: commercial line fishing, commercial pot fishing, and recreational fishing. Additionally, non-reported blue cod bait usage for the rock lobster fishery was estimated and included with commercial landings. Fisheries were modelled assuming length-based selectivity for catch and discards, and discard rates were estimated.

Two stock abundance indices were fitted: relative abundance indices based on standardised catch per unit effort (CPUE) from the commercial pot fishery; and estimates of fish density from a random stratified pot survey series (Statistical Area 025 only). Age composition data from the pot surveys and commercial catches were compiled and fitted. Length frequency data from commercial fishery logbook and shed sampling projects, recreational fishery catch sampling, and two mesh-size selectivity studies, were also fitted.

Numerous model runs were conducted to develop the base case, with the base case used for the final MCMC assessment and projections. Allowing for sex change did not significantly improve the fit to data, and so this assumption was excluded from the base case. Reasonable fits were obtained to all data, with no indications of model mis-specification.

MCMC results indicated that blue cod in Statistical Areas 025 and 030 were at about 30% B_0 , and that Statistical Area 027 was close to the target biomass target of 40% B_0 . Combined over the three areas gave the BCO 5 status at 36% B_0 (95% range, 31–41%).

Five- and ten-year stock projections were conducted using the last 10 years' recruitment as the distribution of future recruitment. Projections used the current catch taken as the average of catch over 2016 to 2018, all of which are consistently lower than the Total Allowable Commercial Catch (TACC) because some quota has been voluntarily shelved. At the current catch, the projections show the median stock size slowly declining in the near future, with probabilities of the mature biomass being over 40% B_0 at 29% in 5 years, and 30% in 10 years. Projections using 80% of the current catch result in an increasing median mature biomass, with a 54% probability of being at or above 40% B_0 in 5 years, and 69% B_0 in 10 years.

1. INTRODUCTION

This document describes a stock assessment of blue cod (*Parapercis colias*) in BCO 5 (Figure 1) that was completed in 2019, using data up to the 2018–19 fishing year (1 October to 30 September). The previous assessment was completed in May 2013 (Fisheries New Zealand 2019). The 2013 assessment estimated that the stock size at that time was close to the target level of depletion, which was assumed to be 40% of the pre-fishing stock size.

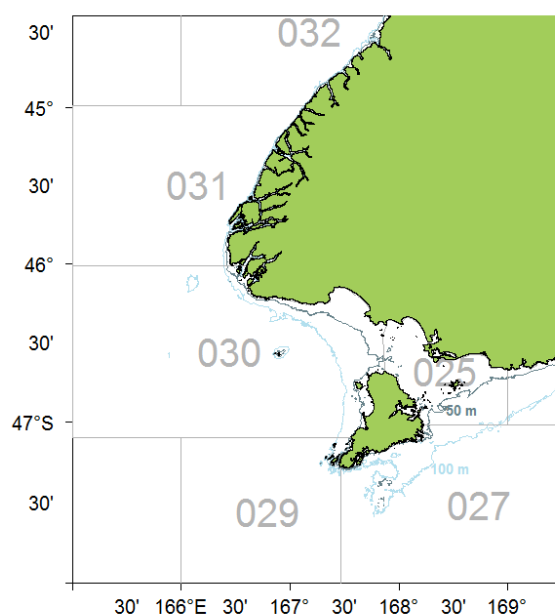


Figure 1: Blue cod BCO 5 management area showing the reporting sub-areas. Assessment were completed separately for the sub-areas: Statistical Area 025, Statistical Area 027, and Statistical Area 030, which together account for 90% of the total catch for BCO 5.

The 2019 assessment was fundamentally different to the last assessment (Haist et al. 2013, Fisheries New Zealand 2019), because it was age based instead of length based. The pot survey data were therefore included as abundance estimates and age composition of the catch. Previously, length compositions and a total mortality (Z) estimate from the age frequencies were used. The last assessment used the drift underwater video (DUV) abundance estimates, but these estimates were rejected by the Southern Inshore Working Group (SINSWG) and the series discontinued, and so they were not included in this assessment. All other data used in the previous assessment, except the Carbines (2004) sex change data, were fitted here too, as well as new data collected since 2013. Data collected since the previous assessment included: two further pot survey abundance indices and age compositions, a pot experiment on increasing the mesh size (adopted from the 2017–18 fishing year), and age compositions from the pot commercial fishing.

An important biological feature of blue cod is that they are protogynous hermaphrodites and can change sex from female to male, a behaviour that can make this species more vulnerable to heavy fishing because one sex can be preferentially depleted (Robinson et al. 2017, Easter & White 2016, Carbines 2004). Fished populations are frequently dominated by males because of the removal of the inhibitory effect of large males, resulting in a higher rate (and possibly earlier onset) of sex change by primary females (Beentjes & Carbines 2005). Mariani et al. (2013) recommended that sex change be explicitly considered in stock management and assessment. For New Zealand stocks of blue cod where biomass is very low relative to its virgin state (e.g., Motunau, an area between Clarence Point to the mouth of

the Conway River, North Canterbury), very few mature females are observed so that the sex ratio for mature fish is close to 95% male, and fish size is considerably reduced (Beentjes & Sutton 2017). This has been attributed to sex change over-compensating for the loss of males, at some (unknown) trigger threshold (Beentjes & Carbines 2005, Beentjes & Sutton 2017). Transitioning fish (i.e., individuals with both male and female reproductive tissue) have been observed in one study in 1995 (Carbines 2004), and two other studies reported very low rates, with only one such individual found in each study (Mutch 1983, Brandt et al. 2017). It is unclear how important sex change is to the BCO 5 stock dynamics, when the stock is believed to not be substantially depleted, but the 2019 assessment model was nevertheless constructed to allow sex change so the potential impact of sex change could be investigated.

Over the period February 2019 to November 2019, the SINSWG reviewed and agreed the data to be used in the stock assessment, the form of a base case, and the assumptions for stock projections.

This work was contracted by Fisheries New Zealand under contract BCO2018-01, Specific Objectives 2 & 3: (2) to undertake a quantitative stock assessment of blue cod in BCO 5 to estimate current biomass in relation to target and limit reference points; and (3) to undertake simulations predicting biomass projections under alternative catch limits (i.e., projections).

2. METHODS

2.1 Data

Data were compiled from a number of sources, including Fisheries New Zealand databases and research programmes, the field studies conducted through the Ecosystem Spatial Management programme (ESM, Middleton et al. 2013), and the characterisation work completed under Objective 1 of this contract, which is reported elsewhere (Large et al. in review).

The general categories of data used in the stock assessment models for each statistical area include: catch and landings, fishery length and age sample distributions, a catch per unit effort (CPUE) abundance index, pot survey age sample distributions and abundance indices (Statistical Area 025 only), and biological information on growth and maturation. Separate data sets were compiled and analysed for Statistical Areas 025, 027, and 030. The data available for each of these areas differed, and few data were available for the remainder of the BCO 5 Statistical Areas. Combined, Statistical Areas 025, 027, and 030 represented 90% of the commercial fishery landings for the last three years.

Catch and landings

Haist et al. (2013) constructed historical time series of BCO 5 landings for three gear types: commercial line fishing, commercial pot fishing, and recreational fishing. Additionally, non-reported blue cod catch used as bait in the CRA 8 rock lobster fishery was estimated and included with the commercial landings, and customary catch estimates were included with the recreational harvest. These estimates were up to fishing year 2011–12. Large et al. (in review) updated these series and also recalculated the entire series of recreation landings.

For the 2018–19 landings, we used the average landings over 2014–15, 2015–16, and 2017–18. In November 2019, Fisheries New Zealand supplied an estimate of landings for the 2018–19 fishing year (extracted on 10 November 2019) and this value was used in the projections.

Appendix 1 shows the full landing history used in the stock assessment.

Pot survey

There have been three random-site blue cod potting surveys in Foveaux Strait, in February 2010, 2014, and 2018 (Beentjes et al. 2019a). The surveys use eight spatial strata and, as an example, the 2018 survey used 38 random sites (6 pots per site, producing 228 pot lifts) (Figure 2). These surveys estimated both total relative biomass and scaled length sample distributions. The survey covered all of Statistical Area 025, but had only one stratum in Statistical Area 027, and a stratum consisting of half of Statistical Area 030 and half 025. Hence, these data were only used for the Statistical Area 025 assessment (excluding stratum 10 in Statistical Area 027), and for the assessment sensitivity run that covered all three sub-areas. The survey age sample distributions are given in Appendix 2.

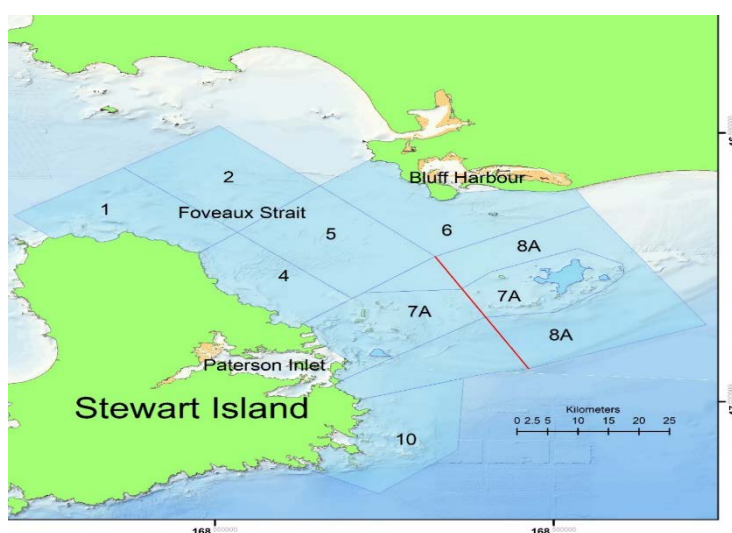


Figure 2: Foveaux Strait 2018 pot survey strata. The same design was used for 2014, but the 2010 survey had strata 7 and 8 which were left and right of the red line (from Beentjes et al. 2019a).

For this assessment, the biomasses were reworked as abundance in units of fish pot⁻¹ (Table 1).

Table 1: Blue cod abundance (fish pot⁻¹) by stratum for the three surveys in 2010, 2014, and 2018.

Year	Abundance	CV (%)
2010	11.1	12.5
2014	17.6	13.5
2018	12.5	21.5

Fisheries data

The pot fishery has operated under three different regimes of Minimum Legal Size (MLS) and mesh regulations. Before 1994, the MLS was 30 cm total length, then 33 cm from 1994 onwards. In 1994 and in 2018, the mesh regulations were changed to enforce larger mesh sizes (48 mm in 1994 and 54 mm in 2018), but the operational mesh size between 1994 and 2017 was between 50 and 52 mm.

The MLS determines which fish are landed, whereas the mesh dictates the number fish below the MLS brought on board and then discarded. It was assumed that the fraction of discards would be reduced after both introductions of increased mesh size. Thus, there were three periods with different catch selectivity: pre-1994, 1994 to 2017, and 2018 onwards. Data were needed for each period. The catch selectivity was modelled using time blocks so that different selectivity parameters could be used in each period. The alternative method would have been to split the pot fishery into three fisheries, one for each period, with each fishery having its own selectivity, and also to split the CPUE into three series (and re-standardised within each split). To keep one CPUE series throughout, the time block selectivities approach was adopted.

For the pre-1994 fishery, Haist et al. (2013) extracted the length sample distribution (LF) data from a 1986 pot mesh experiment, which was used to inform the change in mesh size and MLS in 1994. One set of pots used the pre-1994 pot design and length data from these pots were used to inform the pre-1994 selectivity. The data were collected close to Stewart Island, and also close to Bluff, so that the larger fish expected offshore were less prevalent at the experimental sites than in the fishery. Consequently, the right-hand side of the LF could not be fitted because large fish were not fully available, and therefore data for fish over 33 cm were excluded. This keeps the part of the LF that is under the influence of the catch selectivity and excludes the part that is influenced by ontogenetic migrations.

Haist et al. (2013) analysed the length data collected as part of the ESM programme with length data collected over the years 2009–2011 to produce an LF for 2010 that represented the composition of catch-on-board. There were two variations: logbooks filled out on the vessels and shed data. Shed data were collected from the last catch of the day, all of which was brought into the sheds without discarding or processing. The shed data recorded lengths as well as sex. The SINSWG judged that the logbook data were more accurate samples of the whole catch, because they were from the whole fishery. The shed data were used in an assessment sensitivity run, but were regarded as unrepresentative, because the data were collected closer to port and, hence, lacked larger fish. There was a separate LF for each assessed Statistical Area. This LF was assumed to represent selectivity of the catch for the period 1994 to 2017.

For the pot fishery post-2017, there were data from the mesh experiments conducted by G. Carbines in 2015, which were designed to quantify the effects of the new proposed mesh size (as adopted in 2018). Although more extensive than similar 1986 experiments, the 2015 experiments were nevertheless similarly restricted to sites near land, and so had the same potential bias of under-representing larger/older fish. As a result, when these datasets were used, data for fish lengths over 38 cm were excluded.

Both experimental data sets were applied to all three Statistical Area assessments.

The last data set from the commercial pot fishery comprised age and sex data collected in 2018 and the first three months of the 2018–19 fishing year (Beentjes et al. 2019b). Data were available for each of the Statistical Areas in 2018, but only Statistical Area 025 had enough data for an age sample distribution (AF) to be estimated for 2019. The data were collected from a small number of fishers who put aside the unprocessed fish from the first pot lift of the day, and the legal sized fish were landed whole and otoliths were extracted and other biological data collected. This circumvented the bias from biasing sampling areas close to port and missing the larger fish. The assessment model in 2019 did not use age data for ages 1 and 2 (see later section on sex change), so these sample distributions were truncated below age 3.

All fisheries data used in the assessment are shown in Appendix 3, where more details of the 2015 pot mesh experiments are also provided.

Haist et al. (2013) estimated the recreational fishery LF using data collected during the 2009–10 fishing year from a survey of the Southland recreational blue cod fishery (Davey & Hartill 2011). This study

included a boat ramp survey (at Bluff, Riverton/Colac, and Halfmoon Bay) and a logbook survey of charter and recreational vessels. Only logbook data are used in the 2019 assessment model to inform the selectivity for the recreational fishery.

Between October 2009 and September 2010, 1471 blue cod were measured during the boat ramp survey. Over the same period, logbook participants measured 586 fish caught by recreational vessels and 1878 fish caught by charter vessels.

Fish measured during the boat ramp survey were assumed to represent landings, and fish measured through the logbook programme were assumed to represent catch. The proportion of BCO 5 recreational catch taken by charter vessels was estimated by dividing the 1997/98 Marine Recreational Charter Vessel catch estimate by the average of the three Marine Recreational Fishery survey estimates. This proportion (27.5%) was used to weight the charter vessel and recreational vessel LFs to obtain an overall LF to represent the recreational fishery catch (Haist et al. 2013).

The same recreational fishery LF dataset was fitted in stock reconstructions for Statistical Areas 025, 027, and 030. Appendix 3 shows the recreational fishery LFs.

Biological data

Ageing error

Ageing error was estimated using the data from the commercial sampling in 2018 and 2019 (Beentjes et al. 2019b). These used two readers, and 791 fish were aged. Of these, 633 fish were assigned the same age by both readers. The model used in the assessment was the off-by-one using a probability, p , that the age differed by one from the true age. Thus, with two readers, the outcomes are:

Error in age		
Reader 1	Reader 2	Probability
0	0	$(1 - p)(1 - p)$
0	1	$p(1 - p)$
0	-1	$p(1 - p)$
1	1	$p p$
-1	-1	$p p$
1	0	$p(1 - p)$
-1	0	$p(1 - p)$

The probability to get no difference in age is: $(1 - p)(1 - p) + p p + p p$ which is equated to $633 / 791 = 0.800$. Solving for p gives $p = 12.230\%$. Because two readers were used, the chance of error by one was taken to be $12.230/\sqrt{2} = 8.6\%$. Ageing error tends to spread out age distribution, but that is corrected (partially) by specifying an ageing error.

Growth

Sex-specific von Bertalanffy (vB) growth models were fitted to age, sex, and length data from the pot surveys and the commercial fishery. All survey data were combined, because vB curves estimated from individual pot surveys all had very similar curves, only diverging at older ages for which there were few data. For the commercial data, only the female data appeared useful. The commercial female data below 15 years of age were excluded because this age is when the length-at-age distribution is fully selected into the fishery and, hence, the sampling (i.e., length at age data from the commercial fishery) would be biased for young fish). Commercial data for males appeared to be also clipped at larger lengths as a result of heavy fishing, and so they were thought to potentially bias the estimate of L_{∞} . These age estimates were all based on the new ageing protocol (Walsh 2017). The same vB curve was applied to all three assessment sub-areas. The parameter estimates were: $L_{\infty} = 40.0$ cm, $K = 0.19$, and $t_0 = -0.62$ for females; $L_{\infty} = 55.7$ cm, $K = 0.20$, and $t_0 = -0.51$ for males. Model fits are shown in Figure 3.

Male data had little information to inform the L_{∞} estimate, making it poorly determined. When the vB parameters estimated outside the model were used in the assessment, the model gave poor fits to the right-hand side of the commercial LFs. To improve fits, the male L_{∞} was estimated in one of the models leading up to the base case leaving all other growth parameters fixed at the above estimated values. Male L_{∞} was estimated to be 48.0 cm, and male L_{∞} was fixed at this value for all subsequent model runs. The length-at-age distribution was normal with a CV of 9%, allowing for ageing error.

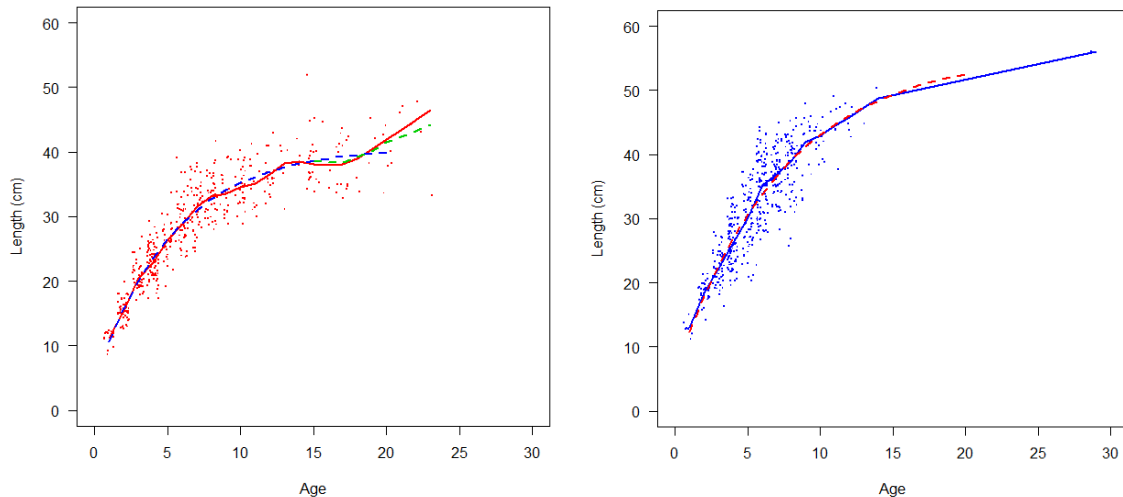


Figure 3: Fits of the estimated vB (dashed blue line) to the age-length data. Left panel, female with the red line is a smooth curve through pot survey data, green dashed line is a loess smooth curve through the commercial data. Right panel, males with the vB are shown by the dashed red line, and the blue line is a loess smooth curve.

Splitting growth into three growth paths

The fisheries selectivity was assumed to be a function of length. In an age-based model, the application of a length ogive results in an asymmetrical length-at-age distribution if the length-at-age distribution falls across the operating part of the selectivity (when selectivity is not complete). This asymmetrical nature is only preserved for one time step. In a later time step (or year), the distribution reverts to being normal again. Model runs found that the latter caused misfits in the LHS of the LF from the 2015 pot mesh experiments, because these had a relatively steep LHS to represent fewer discards from using the new 2018 pots. To preserve the distributional changes induced by length ogives, growth was divided into three paths: slow, medium, and fast (Figure 4). These divisions cannot, in general, be observed in the data except at the extremes, e.g., the very fast growers which would be at the leading edge of the length-at-age distribution, so this modelling should be viewed as an artificial modelling device to (partly) preserve LF distributional changes induced by the selectivity. Nevertheless, a wide distribution of observed length-at-age does indicate that growth rate varies substantially among individual blue cod in BCO 5.

The growth paths required some subjective decisions because only the combined distribution is observable, and this can be replicated in several different ways. Firstly, when combining the length-at-age distribution over the growth paths, the resulting combined distribution should be normal with a CV of 9% (when that age is not vulnerable, or fully vulnerable). Secondly, the medium growth vB was set using the parameters estimated above. The fast and slow paths were made inversely symmetrical about the mean length with the same initial proportions of fish in them, the same CV, and their means are the same interval from the medium mean length, but in opposite directions. Both t_0 and K are set to the same values for medium growth. To change the growth rate, the values of L_{∞} are changed in the slow and fast growth paths.

To estimate the slow and fast growth path values of L_{∞} , a fit was made to a single length distribution at one age: first with the CV of the component growth paths $cv1$ (the CV for growth paths slow and fast) and $cv2$ (CV for the medium growth path); $p1$, the proportion of fish in the slow or fast paths; the proportion in medium growth path is $1 - 2 * p1$; and the fractional change to derive the means for slow and fast paths from the medium mean length, $d\mu$. Given a $d\mu$ and $p1$, both $cv1$ and $cv2$ are varied to make the combined distribution over the three growth paths normal with a CV of 9%. To make $cv1$ and $cv2$ more general (to scale for other ages), they were re-parameterised to $\sigma1 = R_1 \sigma$ and $\sigma2 = R_2 \sigma$, where σ is the standard deviation of the full length-at-age distribution, and R_1 and R_2 are now the estimable parameters. Estimation of growth path parameters was done at a fixed mean length, but the estimated parameters scale to any mean length, e.g., the vB L_{∞} for the slow growth path is $L_{\infty} * (1 - d\mu)$.

Estimation of parameters was done using a mean length of 48 cm, normal distribution, and a CV of 9%, so that σ was 4.32 cm. The objective function was the sums-of-squares of the overall normal curve from the sum of the three growth paths normal curves. Other parameters were $d\mu$, set to $\pm 5/48$ ($\sim 10\%$ shift \approx one standard deviation), and $p1$, set to 0.25 (i.e., 50% were in the medium growth path). R_1 was estimated to be 0.637, and R_2 was estimated to be 0.581. The fit is shown in Figure 4. The CVs for the three growth paths were 5.7% for the slow and fast paths, and 5% for medium growth path. The $d\mu$ meant that the largest and smallest fish in a LF were from the fast and slow growth paths exclusively.

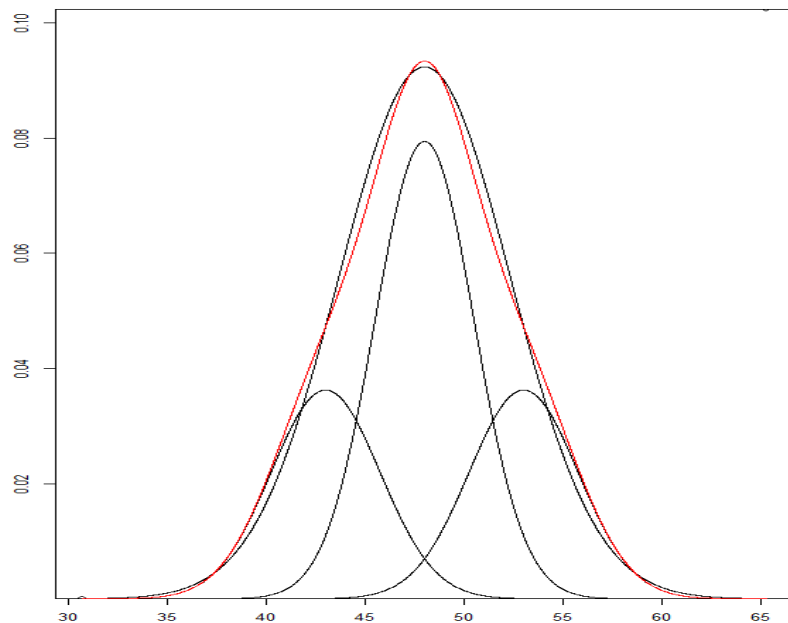


Figure 4: Best estimated growth paths (three smaller black curves), with the combined distribution over the three paths having the larger black curve, and the normal distribution with a CV of 9% (red line). $d\mu$ was set to $5/48$ and estimated parameters were: $p1 = 0.25$, $cv1$ and $cv2$ determined using $R_1 = 0.637$ and $R_2 = 0.581$.

The vB L_{∞} for the slow growth path was $L_{\infty} \times (1 - d\mu) = L_{\infty} \times 0.8966$, and for the fast path it was $L_{\infty} \times (1 + d\mu) = L_{\infty} \times 1.1034$, where L_{∞} is the value for the medium growth path.

Maturity

Age and gonad stage data came from two pot surveys that were conducted at the right time of year to detect maturing and spawning fish: Paterson Inlet in 2018 (Mike Beentjes, NIWA, pers. comm.) and Dusky Sounds in 2014 (Beentjes & Page 2016). Mature fish were taken to be those at gonad stage 2 or higher, and a logistic ogive was fitted to the proportions mature at age data, having the parameters A_{50} , age when 50% are mature, and A_{1095} , the incremental time to reach 95% mature from 50%. To fit female proportion mature at the youngest ages (ages 2 and 3), the data for age 2 had to be up-weighted (Figure 5). For males, the fits implied that 11% of age one fish were mature, but when the male A_{1095} parameter

was set to that estimated for females, 3% of the age one fish were mature; this seemed a more plausible proportion. The SINSWG decided to use one maturity ogive for both sexes, based on A_{1095} being 2.47 (female estimate) and the A_{50} being 4.1, the average of the male and female estimated values (male 4.4, female 3.7).

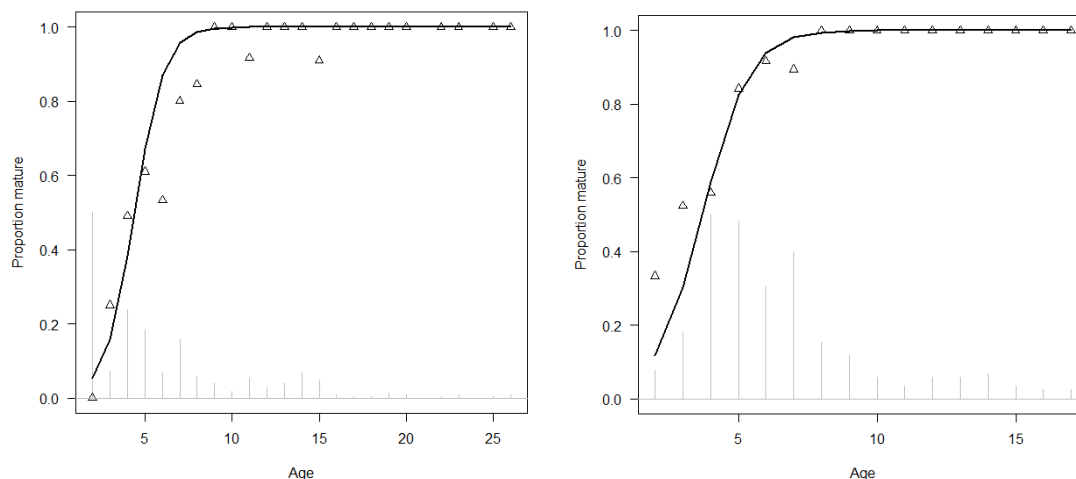


Figure 5: Fit of the maturity ogive (solid line) to the mature proportion by age data (triangles). The weights given to each point are shown as grey vertical bars. Left panel, female; right panel, male. Female parameters were: A_{50} , 3.7; A_{1095} , 2.47. Male parameters were: A_{50} , 4.4; A_{1095} , 2.47.

Natural mortality (M)

In the previous assessment (Haist et al. 2013) the value of M used was that estimated from the oldest known age, 31, using the method of Hoenig (1983); however, this age was calculated using the old, discredited, ageing protocol. This otolith was re-read using the current blue cod age determination protocol (Walsh 2017) and the age was unchanged, i.e., 31 or 32 depending on the reader.

In reviewing the M estimation, it was noted that Hoenig's (1983) method requires small sample sizes from an unfished (or nearly so) stock, and it assumes that the oldest age can be equated to the 99-percentile of the age distribution. Hoenig (1983) shows that his estimate is substantially biased (low) when sample sizes are large. For blue cod, there are surveys somewhere nearly every year, so the total sample size is in the thousands when all surveys are combined (as was implicitly done for the previous M estimate).

To estimate M , a method that explicitly corrects for sample size by using the 99-percentile age from surveys of nearly unfished stocks was used in Hoenig's (1983) equation, with ages obtained using the currently ageing protocol. There was only one survey that met both criteria; Banks Peninsula, offshore strata, completed in 2016 (Beentjes & Fenwick 2017). The 1% oldest age is the 4.5th oldest age, 27, which gives an M of 0.17.

Sex change

Although blue cod are known to change sex from female to male (i.e., are protogynous hermaphrodites), sex ratios vary spatially and the mechanisms causing sex change are not well understood. There are insufficient data from studies on blue cod in New Zealand to model reliably the impact of sex change on blue cod dynamics in specific regions.

A management concern about sex change in blue cod is that under heavy fishing, large males will be preferentially depleted in the stock because they grow faster and are larger, which could lead to an

imbalance in the sex ratio, instability in sex ratio, and insufficient numbers of each sex for reproduction, making blue cod more vulnerable to fishing than “normal” fish stocks (Reinboth 1980, Huntsman & Schaaf 1994). The blue cod fishery is controlled by the MLS, which means males also enter the fishery at an earlier age than females because they have faster growth. Depending on the mechanism, sex change can make species more vulnerable to fishing than “normal” species, and there may be a compounding effect from sperm limitation (Robinson et al. 2017, Easter & White 2016, Provost 2013). Some authors advocate a revision of reference points to account for this effect (Brooks et al. 2008).

The concern about sex change dynamics does have a basis in observations from severely depleted stocks, e.g., Motunau, in which males dominate and mature fish have smaller average sizes than other stocks and a very low proportion of mature females, about 5% in Motunau (Beentjes & Sutton 2017). At some point in the stock dynamics, blue cod in this stock manifest a nearly total transition of females to males. What the threshold is and why it occurs this way is largely unknown, but, as mentioned earlier, the removal of the inhibitory effect of large males is thought to result in a higher rate (and possibly earlier onset) of sex change by primary females (Beentjes & Carbines 2005).

Blue cod belong to the family Pinguipedidae or sandperches of which there are four genera including *Paraperis*, all members of which are all thought to be protogynous hermaphrodites (Randall 1995). In New Zealand, transitional blue cod gonads (having both male and female parts in the ovaries) have been identified in three studies using microscopic methods to evaluate the gonads (more accurate, but more time consuming than using macro gonad staging). The study that first suggested that blue cod is a protogynous hermaphrodite was by Mutch (1983), but this was based on one transitional fish, a rate of 0.2% of the females sampled (site in Leigh Reserve). The Carbines (2004) study collected data in 1995 at sites just outside Paterson Inlet, off Stewart Island and found 28 females that were judged to be transitional female, which represented an average of 20% of all females. These data were fitted in the previous 2013 assessment (Haist et al. 2013), but the fit was poor, even using penalties to force a fit. The third study was by Brandt et al. (2017) using data collected in a pot survey in Marlborough Sounds in 2013. Again, only one transitional female was found, less than 1% of the female sample; according to Carbines, there should have been 10 such fish, other things being equal. This transitioning fish was not reproductively active (M. Dunn, NIWA, pers. comm.). It seems very hard to reconcile these observations without further information and a clear mechanism for sex change in blue cod.

The 2013 assessment (Haist et al. 2013) used a sex ratio at birth of 20% male, based on a regression fit of sex ratio against length, extrapolated back to age zero. To find the fraction male at birth for the model, the sex ratio at age from the three pot surveys were each extrapolated back to age zero, which gave a wide range of values. The SINSWG was uncomfortable with this analysis because recruited fish were not dominated by males as occurs in other blue cod areas so there is little evidence of sex change in BCO 5. The SINSWG was also concerned with the effect of the pot selectivity on the youngest fish. The SINSWG initially decided to start the model at age three with a 1:1 sex ratio. However, this led to problems with fits to the recreational LF, which had lengths consistent with age one and age two fish, and so this LF could not be fitted at all well. The model was started at age one, but age data for ages one and two were excluded.

For BCO 5, the assumption made from the available evidence was that sex change occurred primarily in the first two years of life, and it was unimportant as a dynamic element in maturity, at least at the densities that currently occur in this stock. As such, the assessment model assumes that the stock dynamics operate as a conventional separate-sex model over the ages selected by the fishery (i.e., blue cod is gonochoristic rather than hermaphroditic; hypotheses about the direction and magnitude of sex change are irrelevant). A sensitivity model was run using sex change, where the sex change rate from female to male was modelled as a capped logistic ogive and the cap, A_{50} , and A_{1095} parameters estimated.

2.2 Assessment modelling

Model structure and assumptions

A Bayesian statistical catch-at-age model was implemented in Casal2 (Doonan et al. 2016) independently for each Statistical Area: 025, 027, and 030. Casal2 is the replacement package for NIWA's CASAL assessment package, and this is the first assessment to use this software outside testing. Unlike CASAL, Casal2 can accommodate sex change and allow time blocks for parameter estimates (needed here to keep the CPUE as one series because the selectivity changed in 1994 and 2018). For the BCO 5 management area, the estimates were added over the three assessments to get overall stock status.

The models were age-based (1–20 years with a plus group) with a partition made up of sex (male and female) and three growth paths (slow, medium, and fast). The model was run for the years 1900 to 2019. A single time step each year was used, and the fisheries were assumed to be year-round. There were three fisheries: line, pot, and recreational. Spawning was taken to occur after 93% of the natural mortality, and 100% of mature fish were assumed to spawn each year. Natural mortality was assumed to be constant at 0.17 y^{-1} and the stock-recruitment relationship was assumed to follow a Beverton-Holt function with steepness of 0.75. Relative year class strengths (YCS) were parameterised in the model such that the mean was equal to one. Recruits entered the model at age one, and the sex ratio was assumed to be 1:1. Ageing error was assumed to be 8.6% for a one-off error. Retained catch selectivity for fisheries were knife-edged at the MLS. Estimated model parameters and priors are summarised in Table 2; and observations, their distribution, and process error used are given in Table 3.

Table 2: Estimated model parameters for the BCO 5 assessments. “All” means Statistical Areas 025, 027, and 030.

Parameter	Number of parameters	Statistical areas	Prior	Comments
B_0	1	All	Uniform-log	–
Base case				
Pot fishery selectivity	6	All	Uniform	Three time blocks, length-based logistic
Recreational selectivity	2	All	Uniform	Length-based logistic
Pot survey selectivity	4	025	Uniform	Age-based, separate sex versions
Year class strengths	35	All	Lognormal, CV 0.6; Haist parameterisation	Estimated from 1980 to 2014
Pot abundance q	1	025	Uniform	Nuisance
CPUE q	1	025	Uniform	Nuisance
Sensitivity models				
Sex change	3	025	Uniform	Capped logistic
Proportion of recruitment for males	1	025	Uniform	

Table 3: Observations and their distributions and process error. AF is age sample distribution; LF is length sample distribution.

Observation	Likelihood	Process error	
		CV	N
Pot survey abundance	Lognormal	20	-
CPUE	Lognormal	10	-
			Re-weighted following Francis (2011)
AF, pot survey	Multinomial		100
AF, pot fishery	Multinomial		100
		(2019, 5)	Down-weighted because it was just from 3 months. Poor sampling for females
LF, logbook	Multinomial		100
LF, shed	Multinomial		100
			Used in a sensitivity run as a replacement to logbook LF
LF, 1986 experiment	Multinomial		20
LF, 2015 experiment	Multinomial		20

Lengths-at-age were converted to weights-at-age in the model using the length-weight relationship estimated by Beentjes et al. (2019b), i.e., assuming the relationship, $\text{weight} = a \times \text{length}^b$ for length in centimetres and weight in kilograms. The parameters $a = 0.000007289$, and $b = 3.2055$ were assumed for both sexes for all model years.

Penalty functions were used to constrain the model so that any combinations of parameters that did not allow the historical catch to be taken were strongly penalised. A small penalty was applied to encourage the estimates of year class strengths to have mean equal to one.

Maximum of posterior distribution model runs

Maximum of posterior distribution (MPD) model runs were conducted on each Statistical Area (025, 027, and 030) to assess fits to the observations. Establishing a base model was done with the Area 025 model because it had the most data and largest catches. Model runs were also used to determine the data weighting for the CPUE, using the Francis (2011) method. The CPUE was the only observation with a long enough series to warrant a formal data weighting analysis. All other data were assigned a process error: usually $N = 100$ for multinomial distributions (following the practice by Haist et al. 2013) and 20% for the pot survey abundance, the default choice recommended by Francis et al. (2001). Three data sets were down-weighted further: the two mesh experiments, and the age sample distribution (AF) for the pot fishery in 2019. The mesh experiments had much fewer data collected than the other data sets and they were in the model primarily to estimate pot fishery selectivity, so they should not out-weigh other data sets (i.e., influence on YCS); a somewhat arbitrary N of 20 was used for these data. The 2019 commercial AF was down-weighted with an N of 5, because it covered just the first three months of the 2019 fishing year, and the female AF had an influential but unwarranted effect on the fits in the other commercial AFs. Specifically, the 2018 AF had a strong cohort at age eight in both the male and female AFs. The 2019 male AF had a strong cohort at age 9, i.e., it was internally consistent. However, the 2019 female AF did not have a strong cohort at age 9, but it did have one at age 15+. Because the AFs were entered as a single joint sex sample distribution, the entire 2019 AF was down-weighted ($N = 5$).

To explore potential uncertainties in the assessment model structure, sensitivities were conducted on the Area 025 model. The previous assessment by Haist et al. (2013) found little effect on results when they varied the re-constructed catch history, and so these were not repeated here. The following sensitivities conducted were:

1. Change M by ± 0.02 ,
2. Set pot discard mortality to 50%,
3. Replace logbook LF with shed sampling LF,

4. Single growth path,
5. Single stock assessment covering all three areas, and
6. Allow sex change (this necessitated using a single growth path).

MCMC runs

To estimate the joint posterior distribution of the parameters in a Bayesian analysis, Casal2 uses a straightforward implementation of the Metropolis algorithm (Gelman et al. 1995, Gilks et al. 1998) to execute the Markov chain Monte Carlo (MCMC). The initial covariance matrix comes from the MPD run, from inverting the Hessian matrix.

MCMC runs were conducted on each Statistical Area model for 1 M iterations, keeping every 1000th value for the posterior. The covariance matrix was recalculated twice, using the MCMC parameters of the previous run, the samples from which were then discarded, i.e., only the samples after the second recalculation of the covariance (and burn-in) were used. Plots of the MCMC trace, dividing the final chain into three sections and over-plotting the three resultant cumulative parameter distributions, and the posterior distributions were generated. For acceptance, the trace should have no long-term drift and the overlaid cumulative curves should be “tight”, especially for parameters of interest, e.g., B_0 and $B_{current}$ (% B_0).

Summary statistics for BCO 5 were calculated by summing across the Statistical Areas 025, 027, and 030. The BCO 5 catch was calculated assuming these areas account for 90% of the BCO 5 stock.

Projections

Parameter samples obtained from the MCMC posterior distribution were used to run the model into the future for 10 years using a specified constant future catch, i.e., there were 1000 runs, one for each parameter set. Summary statistics at the end of 5 and 10 years were calculated for BCO 5 by summing B_0 estimates and projected biomass estimates across the three Statistical Areas. Summary statistics are the probabilities that B_{xx} was below 10 and 20% B_0 , and above 40% B_0 , where xx is either 2024 or 2029.

In the stock assessment, the 2018–19 commercial catch level was set at the average of the years 2015–16, 2016–17, and 2017–18. This level of catch was also used in projections of current catch for the years 2019–20 onwards. For 2018–19, catch was recalculated based on returns-to-date (804.8 t as of 8 November 2019), which were allocated to the assessment areas based on the fraction of catch in each. An alternative catch scenario was simulated with the commercial catch reduced by 20%.

Future recruitment was simulated by randomly re-sampling (with replacement) from the 2005–2014 YCS, applied to the stock-recruitment relationship. The alternative method was to use all the estimated YCS, i.e., from 1980 to 2014, but the SINSWG decided that the 2005–2014 YCS represented “normal” conditions, and that YCS variability for these had also been estimated using age data. The YCS from 1980 to 1995 were not determined by age data, but by fitting to the initially flat then increasing section of the CPUE series, which resulted in a period of much lower than average YCS, followed a period of much higher YCS.

3. RESULTS

3.1 MPD

The base model provided good MPD fits to the data (Figures 6, 7, 8, 9, and 10).

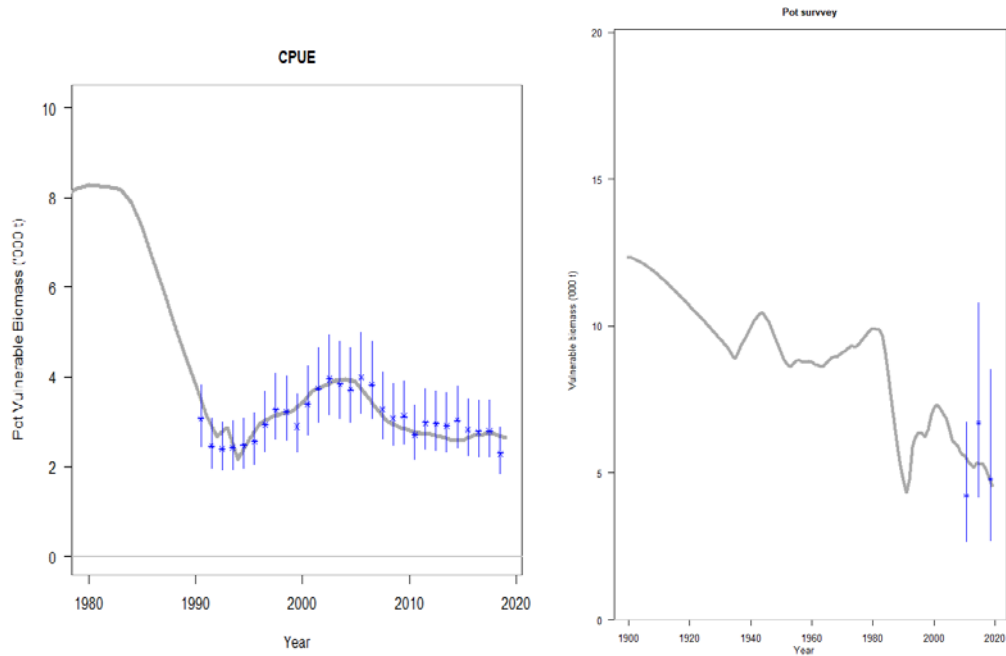


Figure 6: MPD fits to abundance indices for Area 025, base model run: (*, observations; vertical line, 95% CI; grey thick lines, predictions): (left) commercial catch per unit effort; (right) pot survey catch abundance.

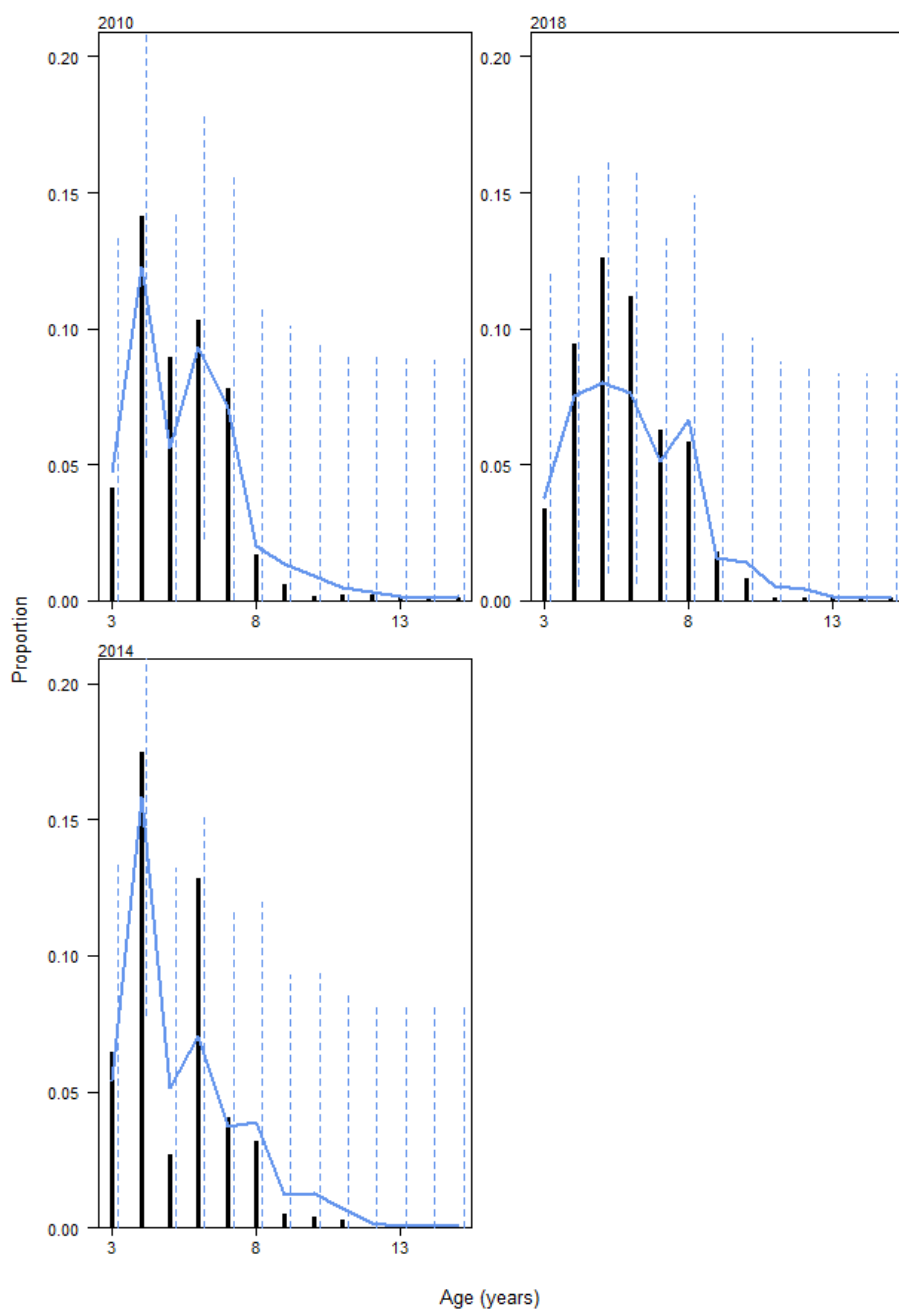


Figure 7: Pot survey female age data MPD fits for Statistical Area 025, base model run: (solid vertical bar, observations; vertical dotted line, 95% CI; blue thick lines, predictions).

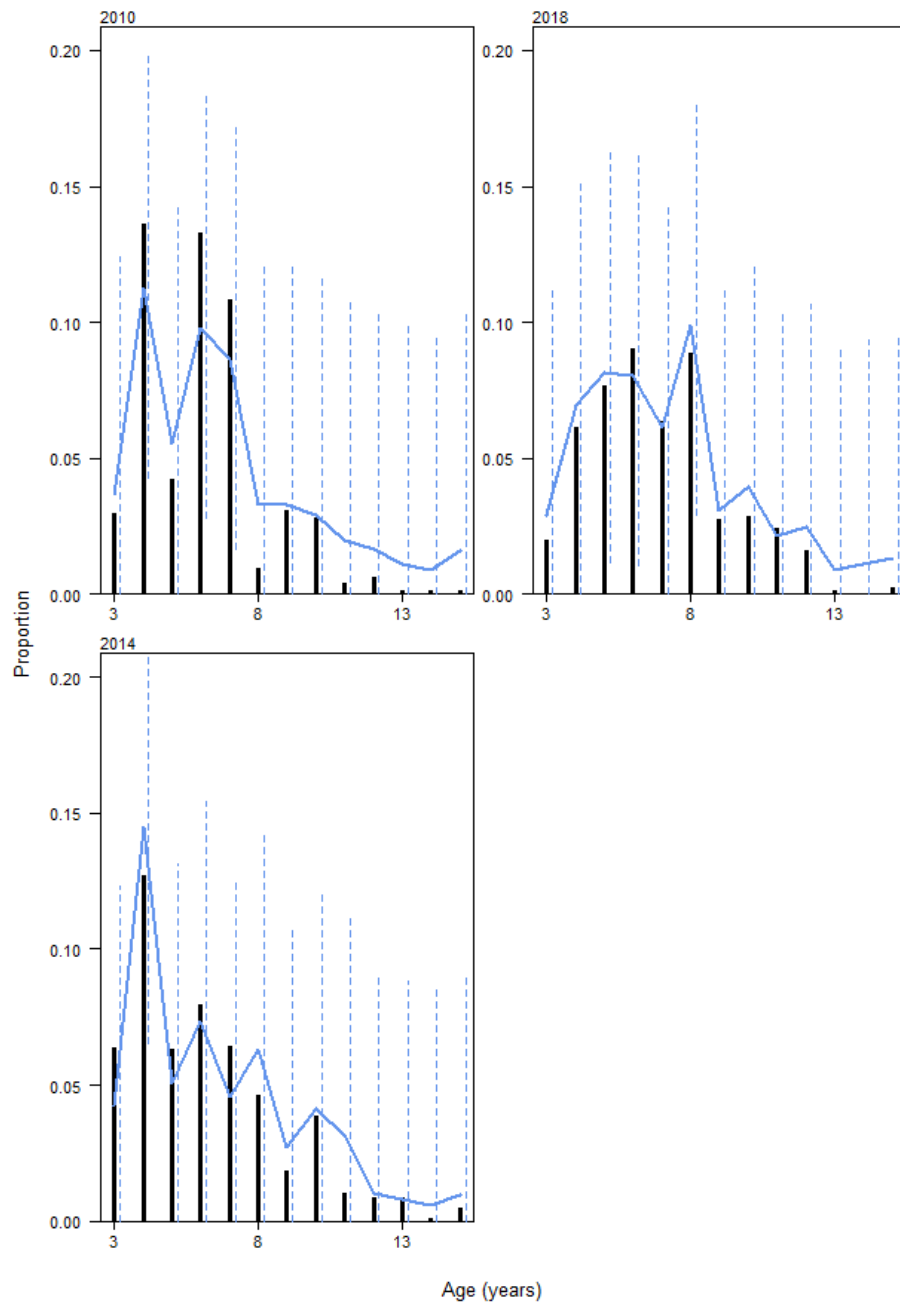


Figure 7 (cont.): Pot survey male age data MPD fits for Statistical Area 025, base model run: (solid vertical bar, observations; vertical dotted line, 95% CI; blue thick lines, predictions).

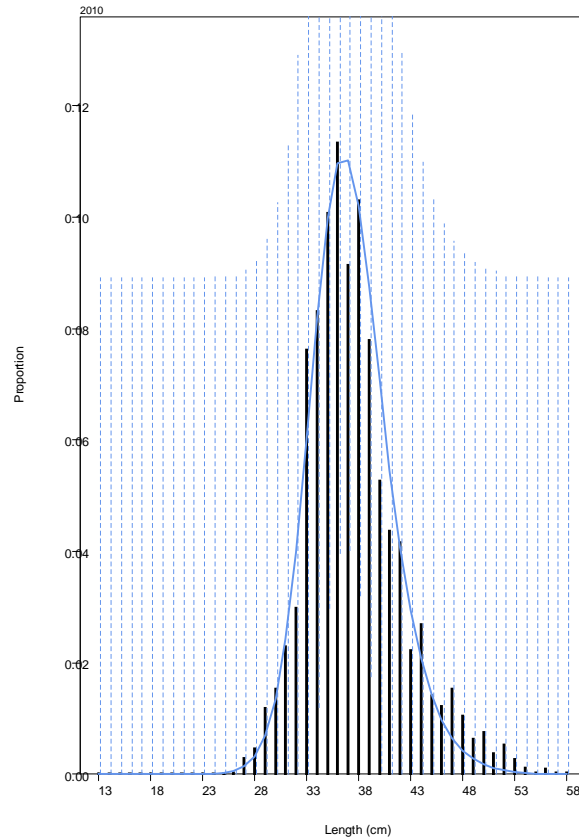


Figure 8: Logbook LF MPD fits for Statistical Area 025, base model run: (solid vertical bar, observations; vertical dotted line, 95% CI; blue line, prediction).

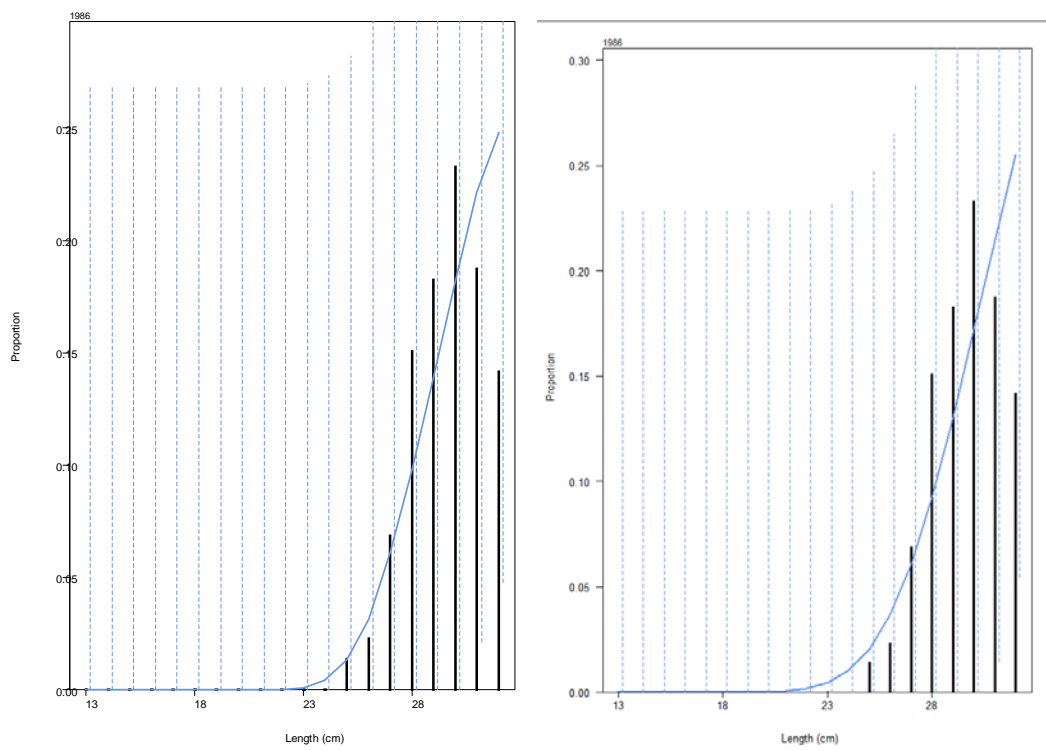


Figure 9: Pot mesh experimental LF data MPD fits for Statistical Area 025, base model run: (solid vertical bar, observations; vertical dotted line, 95% CI; blue lines, predictions): (left) 1986 data; (right) 2015 data.

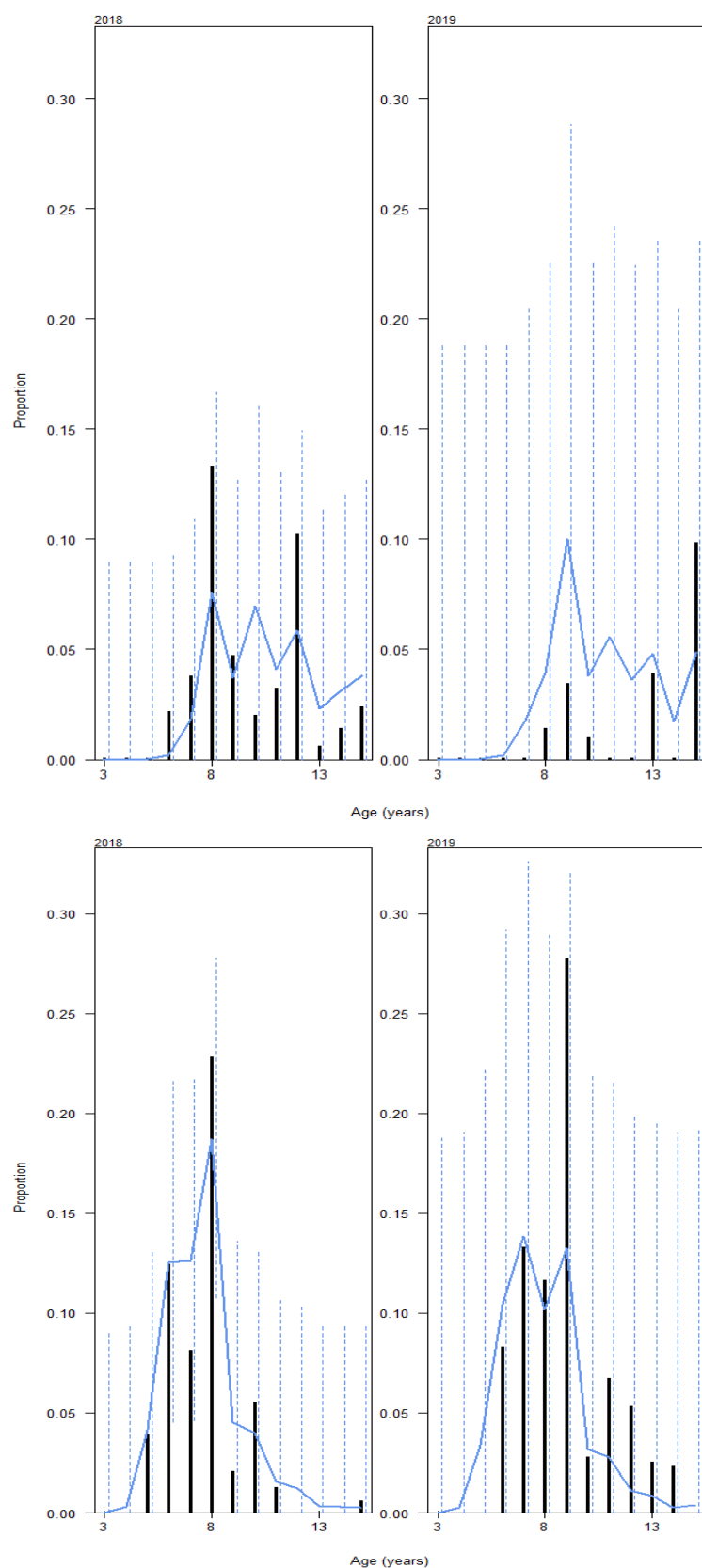


Figure 10: Pot fishery age data MPD fits for Statistical Area 025, base model run: (solid vertical bar, observations; vertical dotted line, 95% CI; blue lines, predictions): (top) female data; (bottom) male data.

The estimated B_0 and $B_{current}$ (% B_0) for the base case, BCO 5, was 20 682 t and 32.4 %. The estimated $B_{current}$ (% B_0) for each Statistical Area were: 025, 31.2%; 027, 31.5%; and 030, 38%.

Apart from the run using the shed sampling LF, $B_{current}$ from the sensitivity runs varied little from the base case, i.e., from 29.4 to 33.1 % (Table 4). The largest change occurred when the LF data from the logbook programme were replaced with data from the shed sampling programme which reduced $B_{current}$ to 23.9%. However, the SINSWG considered this run to be less credible, because the shed length data had a lower proportion of large fish than that from the logbook data because of the differences in the way they were sampled. The logbook length data were preferred by the WG. Adding sex change changed the log-likelihood by a trivial amount, and so it was not needed to get a better fit; it estimated the rate of change as 0.2% for all ages. When the proportion of males entering as 1-year olds was also estimated, the sex change rate was zero, with a proportion of males being 55%. In this case, the effect of sex change was to compensate for the 1:1 initial sex ratio assumed in the model.

Table 4: The $B_{current}$ estimated from the sensitivity runs for BCO 5.

Sensitivity	$B_{current}$ (% B_0)
$M = 0.19$	33.1
$M = 0.15$	29.4
Commercial discard mortality of 50%	31.6
Replace logbook LF with shed sampling LF	23.9
Single growth path	31.6
Single stock assessment	33.0
Sex change in model (also single growth path)	32.0 Minor change in the log-likelihood

3.2 MCMC runs

Convergence seems to be achieved for B_0 and $B_{current}$ (% B_0) (Appendix 4). Some parameters had problems, but these had few data to estimate them, e.g., the L_{50} for the pot fishery selectivity before 1994 which only had the 1986 mesh experiment LF to fit to. Spawning stock biomass (SSB) trajectories for the three Statistical Areas and overall are shown in Figure 11 and YCS distribution is shown in Figure 12.

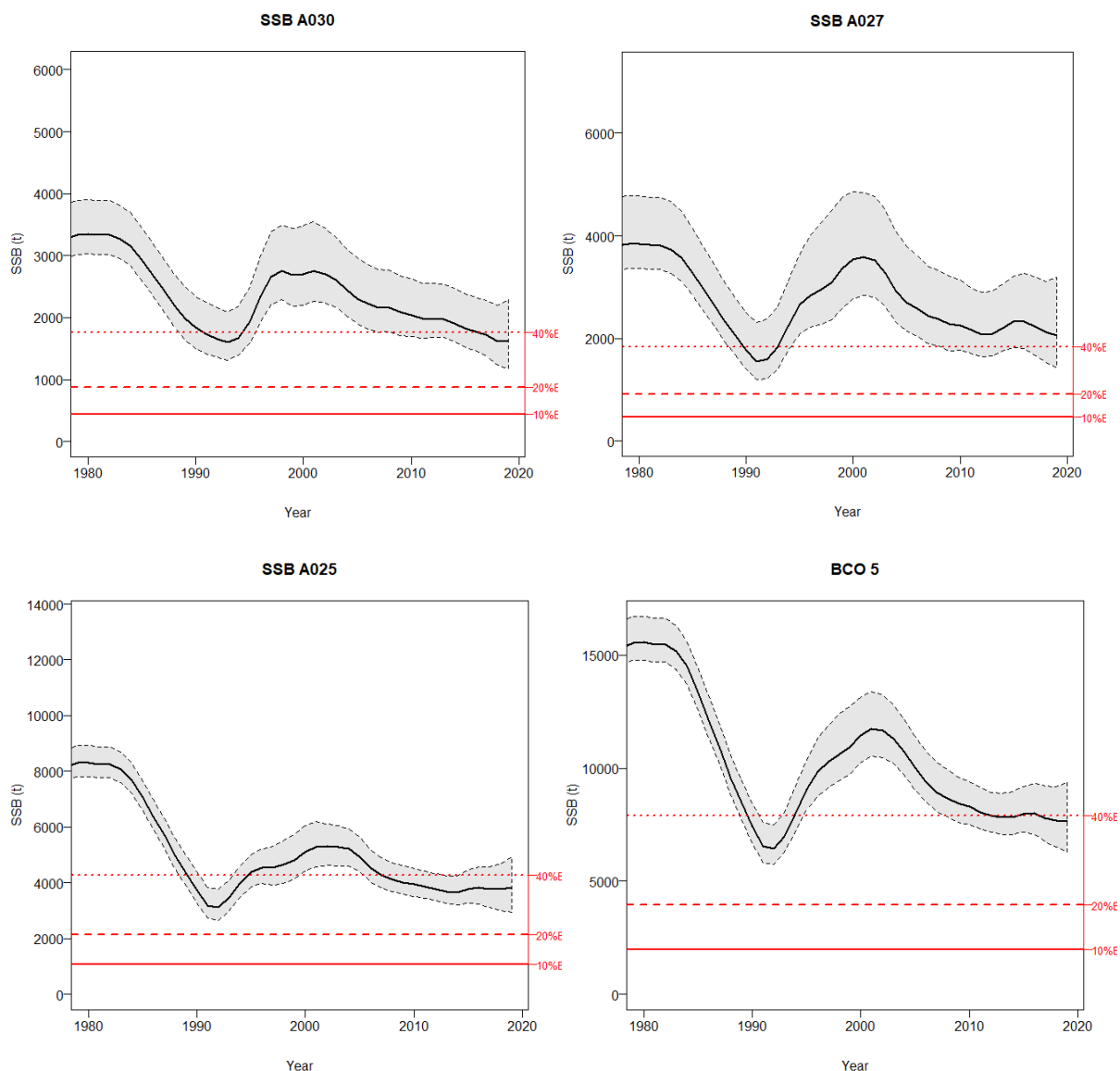


Figure 11: Median estimates of spawning stock biomass for Statistical Areas 025, 027, 030, and the combined areas, for the base case, 1900–2019.

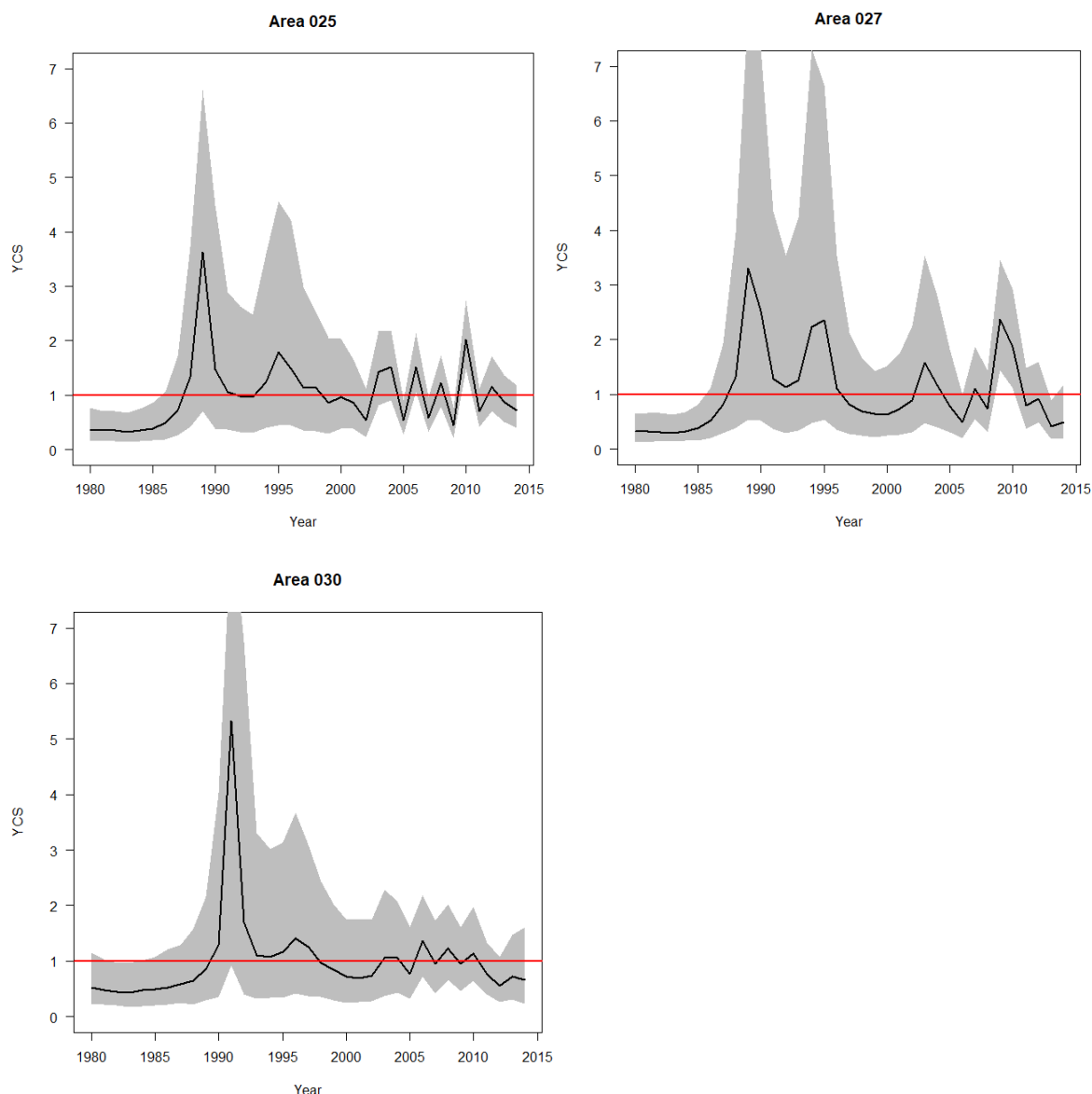


Figure 12: Year class strength from the base case runs for Statistical Areas 025, 027, and 030, 1980–2014. Medians are shown by the black line and the shaded areas show the 95% range limits. The red line is at a YCS of one, the long-term average by definition.

The MCMC estimate of $B_{current}$ for BCO 5 and the base model run was 35.7 (% B_0) with 95% credible intervals of 31–41%.

3.3 Projections

With catches at current levels, the median SSB was projected to slowly decline over the next 10 years, but at 80% of the current catch, the median SSB was projected to increase (Figure 13).

With catches at current levels, the probability of the stock being less than either the soft or hard limit over the next five years was negligible (Table 5).

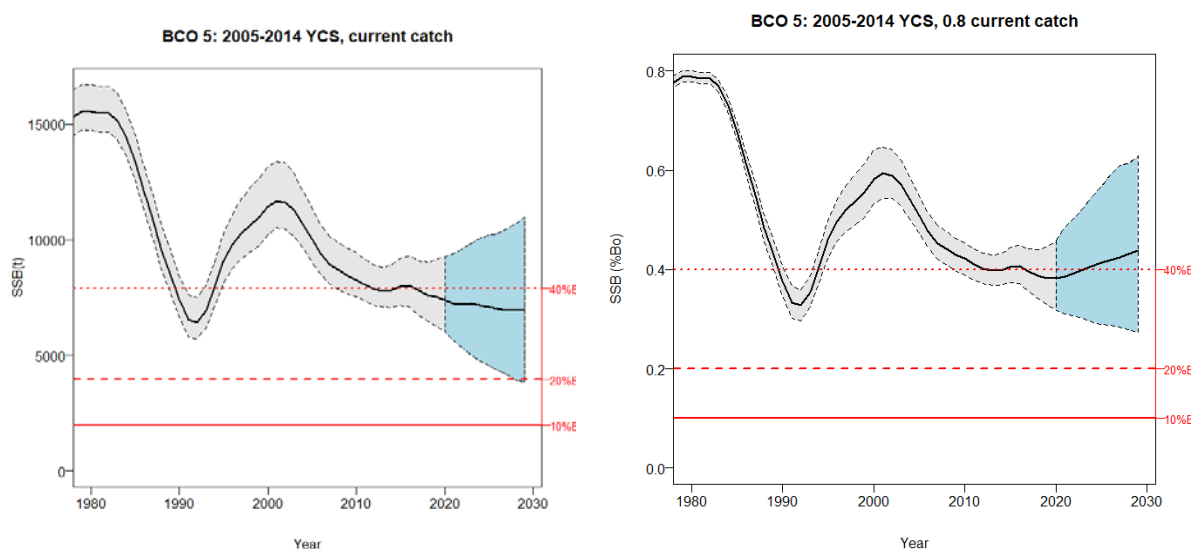


Figure 13: Projected BCO 5 spawning biomass (% B_0) assuming recent recruitment and catch at current levels (left) and at 80% of current levels (right) for the base case run. Median estimates are shown as solid lines and 95% confidence intervals as shaded polygons. Projections start in 2020.

Table 5: Probabilities of SSB being below B_0 reference levels in 2019, 2024, and 2029 at alternative catch levels for the base case projections. Projected recruitment simulated from the 2004–2014 estimated YCS.

Run	Base		
	TACC	Current	0.8×Current
Current			
$P(B_{2019} < 0.1 B_0)$	NA	0	0
$P(B_{2019} < 0.2 B_0)$	NA	0	0
$P(B_{2019} \geq 0.4 B_0)$	NA	0.279	0.269
5 year projection			
$P(B_{2024} < 0.1 B_0)$	NA	0	0
$P(B_{2024} < 0.2 B_0)$	NA	0.004	0
$P(B_{2024} \geq 0.4 B_0)$	NA	0.286	0.535
10 year projection			
$P(B_{2029} < 0.1 B_0)$	NA	0	0
$P(B_{2029} < 0.2 B_0)$	NA	0.024	0.001
$P(B_{2029} \geq 0.4 B_0)$	NA	0.301	0.69

4. DISCUSSION

The fishery independent abundance indices, from the pot surveys, begin after the model SSB trajectory had flattened out, or was declining slowly, and therefore had little leverage in the model. Only the CPUE series covered the time period of stock decline and heavy fishing. However, the CPUE started to flatten and then increased over the period when catches were at their highest, which in this model could only be “explained” by a pattern of very low recruitment followed by a period of very high recruitment, with the latter recruiting into the fishery in the period when catches were highest yet CPUE increased. Figure 12 shows that YCS medians were about one third of mean levels for seven years, followed by very good YCS that peaked at five times the average. The age data from the pot survey and the commercial sampling occurred so long after the period of high YCS that the cohorts from these high YCS were not present in the age data and so had little constraining or confirming influence on the initial pattern of YCS. The B_0 was most influenced from the period of declining CPUE (starting in 2006), under the influence of the (lower) catches attributed to this period along with more normal recruitment (less extreme and fluctuating about some mean with no time trend). This defines the productivity needed to observe the decline under normal conditions. The CPUE series was truncated to begin at the peak in

CPUE, as a sensitivity run, but similar results in productivity were estimated (but are not reported here because it occurred in a preliminary model leading up to the base case).

It is notoriously hard to evaluate CPUE accuracy, especially with no fishery independent surveys over the same period. In the author's experience, CPUE can be maintained at some nearly constant rate over year blocks before it steps downwards, so it can often appear as a series of "steps", i.e., the declining part of the CPUE may under-estimate the decline and so over-estimate the productivity.

Adding sex change resulted in trivial changes in the fits to observed data (log-likelihood) and so it appears the hypothesis of sex change, as parameterised in the model, was not supported by the data; specifically, sex change is not needed to get a better fit to the currently collected data at the current state of the stock. Although sex change does not seem dynamically relevant under normal circumstances in the adult BCO 5 blue cod population, the model did not have a density dependent mechanism for sex change as postulated in the literature. The sex ratios by age from the Foveaux Strait pot surveys (Statistical Area 025) seemed to suggest that sex change occurs only at age one or age two. Paradoxically, Carbines (2004) found 20% of females from one site in the BCO 5 area were transitional and these were all larger females (all considered mature), which is hard to reconcile (although there is a time gap of 15 years between Carbines' data collection and the first pot survey). Comparison of sex ratios from potting surveys in Statistical Area 025, with those from potting surveys at other locations around the South Island, suggested that sex change in Foveaux Strait was much less prevalent than in other areas.

5. MANAGEMENT IMPLICATIONS

Although a sex change mechanism exists in blue cod, in assessment modelling it played no part in the population dynamics in the current state of BCO 5. The stock can be managed without including sex change implicitly, which is possible as long as the biomass is increasing from the current level. However, for declining biomass it is more uncertain because there will, or may be, a point when sex change will severely influence the stock. This point is unknown, and more research is needed if this mechanism is deemed important to management. Currently, the very poor understanding of sex change in blue cod hampers any modelling of sex change in the population dynamics. Future potting surveys in Foveaux Strait should, nevertheless, indicate if sex change increases.

Given the central importance of the CPUE in determining productivity, and that its estimated decline may be under-estimated, it would be advantageous to do inter-sessional work to check and perhaps revise the CPUE. Interviewing fishers about changes and factors adopted over time that they think helped keep catch rates profitable would be an essential element.

6. ACKNOWLEDGMENTS

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APPENDIX 1: LANDINGS USED IN THE MODEL

Table 1.1: Statistical Area 027 landings (t) for the line, pot, and recreational fisheries.

Year	Line	Pot	Recreational	Year	Line	Pot	Recreational
1900	0	0	0	1943	29.5	0	3
1901	2.2	0	2	1944	81.7	0	3
1902	4.5	0	2.1	1945	94.8	0	3
1903	6.8	0	2.1	1946	107.3	0	3
1904	9.2	0	2.2	1947	147.6	0	3
1905	11.6	0	2.2	1948	132	0	3.1
1906	14.1	0	2.3	1949	151.3	0	3.2
1907	16.6	0	2.3	1950	163.6	0	3.2
1908	19.2	0	2.4	1951	143	0	3.3
1909	21.8	0	2.4	1952	153.2	0	3.3
1910	24.5	0	2.5	1953	83.5	0	3.4
1911	27.2	0	2.5	1954	93.6	0	3.4
1912	30	0	2.5	1955	101.9	0	3.4
1913	32.9	0	2.5	1956	147.1	0	3.5
1914	35.7	0	2.5	1957	126.2	0	3.6
1915	38.7	0	2.6	1958	117.2	0	3.7
1916	41.6	0	2.6	1959	105.6	0	3.8
1917	44.7	0	2.6	1960	148.9	0	3.9
1918	47.8	0	2.6	1961	119.7	0	4
1919	50.9	0	2.6	1962	137.9	0	4.1
1920	54.1	0	2.6	1963	135.4	0	4.1
1921	57.3	0	2.7	1964	102.2	0	4.2
1922	60.6	0	2.7	1965	75.1	0	4.3
1923	63.9	0	2.7	1966	87.5	0	4.4
1924	67.3	0	2.7	1967	112.9	0	4.4
1925	70.7	0	2.8	1968	105.3	0	4.4
1926	74.2	0	2.8	1969	80.3	0	4.5
1927	77.7	0	2.8	1970	101.1	0	4.5
1928	81.3	0	2.8	1971	92.3	0	4.5
1929	85	0	2.8	1972	51.7	0	4.5
1930	88.6	0	2.8	1973	126.9	0	4.6
1931	92.4	0	2.9	1974	107.9	0	4.6
1932	95.9	0	2.9	1975	56.2	0	4.6
1933	106.2	0	3	1976	64.4	0	4.6
1934	141.4	0	3	1977	53.1	0	4.6
1935	37.4	0	3.1	1978	55.6	0	4.6
1936	15.3	0	3.1	1979	43.3	0	4.6
1937	22.5	0	3.1	1980	83	11.8	4.6
1938	12.8	0	3.1	1981	82.4	27.3	4.6
1939	18.6	0	3.1	1982	50.8	30.2	4.6
1940	5.8	0	3.1	1983	70.2	69.4	4.6
1941	17.4	0	3.1	1984	64.2	105.4	4.5
1942	19	0	3.1	1985	51.9	152.1	4.5

Table 1.1: continued.

Year	Line	Pot	Recreational	Year	Line	Pot	Recreational
1986	24.1	161.4	4.5	2003	0	362.2	4
1987	1	180.3	4.5	2004	0	412.7	4
1988	0	199	4.5	2005	0	273.5	4
1989	0	167.8	4.4	2006	0	214.8	4
1990	0	252.7	4.4	2007	0	336.5	4
1991	0	259.3	4.4	2008	0	291	4
1992	0	157.7	4.4	2009	0	327.9	4
1993	0	183.2	4.4	2010	0	190.8	4
1994	0	164.2	4.4	2011	0	269.2	4.1
1995	0	203.1	4.4	2012	0	284	4.1
1996	0	330.1	4.2	2013	0	256.7	4.1
1997	0	329.7	4.1	2014	0	250.2	4.1
1998	0	311	4.1	2015	0	248.4	4.1
1999	0	263.8	4	2016	0	253.1	4.2
2000	0	317.1	3.9	2017	0	270.4	4.2
2001	0	312.1	4	2018	0	228.1	4.2
2002	0	267.9	4				

Table 1.2: Statistical Area 025 landings for the line, pot, and recreational fisheries.

Year	Line	Pot	Recreational	Year	Line	Pot	Recreational
1900	0	0	0	1943	112.5	0	34.2
1901	13.2	0	22.9	1944	309.1	0	34
1902	26.4	0	23.5	1945	350.3	0	33.7
1903	39.6	0	24	1946	394.4	0	33.5
1904	52.7	0	24.6	1947	539.3	0	34.2
1905	65.8	0	25.1	1948	477.4	0	34.9
1906	78.8	0	25.6	1949	536	0	35.7
1907	91.9	0	26.2	1950	571	0	36.4
1908	104.8	0	26.7	1951	488.8	0	37.1
1909	117.8	0	27.3	1952	513.9	0	37.5
1910	130.7	0	27.8	1953	245.9	0	37.8
1911	143.6	0	28.3	1954	249.7	0	38.2
1912	156.5	0	28.3	1955	266.1	0	38.6
1913	169.3	0	28.5	1956	409	0	39
1914	182.1	0	28.6	1957	354.2	0	40.1
1915	194.8	0	28.8	1958	331.6	0	41.3
1916	207.6	0	28.9	1959	299	0	42.5
1917	220.3	0	29.1	1960	444.5	0	43.6
1918	232.9	0	29.2	1961	345.2	0	44.8
1919	245.5	0	29.4	1962	397	0	45.6
1920	258.1	0	29.5	1963	375.3	0	46.5
1921	270.7	0	29.8	1964	276.1	0	47.3
1922	283.2	0	30.1	1965	184.9	0	48.2
1923	295.7	0	30.4	1966	219.4	0	49
1924	308.2	0	30.7	1967	309.7	0	49.4
1925	320.6	0	31	1968	286.1	0	49.7
1926	333	0	31.3	1969	208.7	0	50.1
1927	345.3	0	31.5	1970	262.6	0	50.4
1928	357.7	0	31.7	1971	231.5	0	50.8
1929	370	0	31.8	1972	120.3	0	51
1930	382.2	0	32	1973	339.2	0	51.3
1931	394.4	0	32.2	1974	289.6	0	51.5
1932	405.3	0	32.7	1975	137.3	0	51.8
1933	444.7	0	33.2	1976	156.2	0	52
1934	586.5	0	33.8	1977	126.4	0	52
1935	153.5	0	34.3	1978	125.8	0	52
1936	62.5	0	34.8	1979	93.8	0	52
1937	90.7	0	34.8	1980	205.4	29.2	51.9
1938	51	0	34.7	1981	211.2	69.9	51.9
1939	73.5	0	34.7	1982	125	74.3	51.6
1940	22.6	0	34.7	1983	183	180.9	51.3
1941	67.7	0	34.6	1984	167.6	275.1	51
1942	73.2	0	34.4	1985	135.1	396.3	50.7

Table 1.2: continued.

Year	Line	Pot	Recreational	Year	Line	Pot	Recreational
1986	61.2	409.9	50.4	2003	0	683	44.9
1987	2.6	455.5	50.1	2004	0	625.3	44.9
1988	0	519.3	50	2005	0	775.7	44.8
1989	0	425.7	49.7	2006	0	856.5	44.5
1990	0	566.9	49.5	2007	0	759.6	44.5
1991	0	756.2	49.4	2008	0	773.7	44.6
1992	0	576.6	49	2009	0	751.8	44.9
1993	0	660.5	49	2010	0	704.7	45.2
1994	0	738.2	49	2011	0	665.7	45.7
1995	0	739.3	48.9	2012	0	614.4	45.8
1996	0	767.9	47.3	2013	0	623.9	45.9
1997	0	749.9	46.5	2014	0	631	46.1
1998	0	617.8	45.6	2015	0	535.6	46.5
1999	0	698.4	44.8	2016	0	572.2	46.8
2000	0	636.7	44.3	2017	0	623.5	47
2001	0	807.7	44.6	2018	0	475.2	47.3
2002	0	782.9	44.7				

Table 1.3: Statistical Area 030 landings for the line, pot, and recreational fisheries

Year	Line	Pot	Recreational	Year	Line	Pot	Recreational
1900	0	0	0	1943	41.7	0	5.7
1901	4.9	0	3.8	1944	114.5	0	5.7
1902	9.8	0	3.9	1945	132.7	0	5.6
1903	14.7	0	4	1946	148.6	0	5.6
1904	19.5	0	4.1	1947	202.3	0	5.7
1905	24.4	0	4.2	1948	179.7	0	5.8
1906	29.2	0	4.3	1949	205.7	0	5.9
1907	34	0	4.4	1950	221.5	0	6.1
1908	38.8	0	4.5	1951	193.7	0	6.2
1909	43.6	0	4.5	1952	207.4	0	6.2
1910	48.4	0	4.6	1953	121.1	0	6.3
1911	53.2	0	4.7	1954	141.7	0	6.4
1912	58	0	4.7	1955	154.8	0	6.4
1913	62.7	0	4.7	1956	214	0	6.5
1914	67.5	0	4.8	1957	180.8	0	6.7
1915	72.2	0	4.8	1958	165.4	0	6.9
1916	76.9	0	4.8	1959	147.4	0	7.1
1917	81.6	0	4.8	1960	198	0	7.3
1918	86.3	0	4.9	1961	161.4	0	7.5
1919	91	0	4.9	1962	184.2	0	7.6
1920	95.6	0	4.9	1963	184	0	7.7
1921	100.3	0	5	1964	140.1	0	7.9
1922	104.9	0	5	1965	108.7	0	8
1923	109.5	0	5.1	1966	124	0	8.2
1924	114.2	0	5.1	1967	147.9	0	8.2
1925	118.8	0	5.2	1968	137.5	0	8.3
1926	123.3	0	5.2	1969	107.6	0	8.3
1927	127.9	0	5.2	1970	134.2	0	8.4
1928	132.5	0	5.3	1971	124.8	0	8.5
1929	137	0	5.3	1972	73.5	0	8.5
1930	141.6	0	5.3	1973	158.2	0	8.5
1931	146.1	0	5.4	1974	132.2	0	8.6
1932	150.2	0	5.5	1975	74.5	0	8.6
1933	164.7	0	5.5	1976	85.2	0	8.7
1934	217.3	0	5.6	1977	70.7	0	8.7
1935	56.9	0	5.7	1978	76.7	0	8.7
1936	23.1	0	5.8	1979	56.4	0	8.7
1937	33.6	0	5.8	1980	94.1	13.4	8.7
1938	18.9	0	5.8	1981	96.2	31.8	8.7
1939	27.2	0	5.8	1982	62.5	37.2	8.6
1940	8.4	0	5.8	1983	81.6	80.6	8.6
1941	25.1	0	5.8	1984	71.3	117	8.5
1942	27.1	0	5.7	1985	57.2	167.9	8.5

Table 1.3: continued.

Year	Line	Pot	Recreational	Year	Line	Pot	Recreational
1986	26.1	174.5	8.4	2003	0	328.6	7.5
1987	1.1	196.9	8.4	2004	0	361	7.5
1988	0	209.8	8.3	2005	0	297.3	7.5
1989	0	180.7	8.3	2006	0	222.3	7.4
1990	0	138.1	8.3	2007	0	232.3	7.4
1991	0	126.2	8.2	2008	0	184	7.4
1992	0	138.5	8.2	2009	0	288.9	7.5
1993	0	195.5	8.2	2010	0	263.9	7.5
1994	0	232.6	8.2	2011	0	299.9	7.6
1995	0	326.5	8.2	2012	0	258.5	7.6
1996	0	353.8	7.9	2013	0	262.2	7.6
1997	0	355	7.8	2014	0	305.7	7.7
1998	0	409	7.6	2015	0	308.5	7.7
1999	0	484.3	7.5	2016	0	218.1	7.8
2000	0	317.2	7.4	2017	0	219.5	7.8
2001	0	266.7	7.4	2018	0	262.8	7.9
2002	0	354.4	7.4				

APPENDIX 2: POT SURVEY AGE SAMPLE DISTRIBUTION

Table 2.1: Age sample distribution from the pot surveys: 2010, 2014, and 2018. Data for ages 1 and 2 are discarded because the model assumes a 50:50 sex ratio, but sex change may occur in these ages.

Age	Male			Female		
	2010	2014	2018	2010	2014	2018
3	0.04055	0.06416	0.03324	0.02885	0.06291	0.01937
4	0.14075	0.17413	0.09360	0.13561	0.12624	0.06046
5	0.08901	0.02622	0.12520	0.04168	0.06260	0.07586
6	0.10256	0.12801	0.11103	0.13222	0.07898	0.08982
7	0.07751	0.04001	0.06209	0.10759	0.06385	0.06270
8	0.01632	0.03130	0.05761	0.00883	0.04581	0.08819
9	0.00554	0.00446	0.01703	0.03039	0.01772	0.02661
10	0.00082	0.00311	0.00744	0.02731	0.03783	0.02783
11	0.00164	0.00238	0.00010	0.00329	0.00954	0.02345
12	0.00164	0.00010	0.00031	0.00554	0.00808	0.01519
13	0.00051	0.00010	0.00010	0.00041	0.00798	0.00051
14	0.00010	0.00010	0.00031	0.00072	0.00031	0.00010
15	0.00021	0.00010	0.00010	0.00041	0.00394	0.00173

APPENDIX 3: FISHERIES DATA

Table 3.1: Standardised CPUE for each Statistical Area and combined over all three Statistical Areas, 1990–2018.

Year	Statistical Area				Year	Statistical Area			
	025	027	030	025 + 027 + 030		025	227	030	025 + 027 + 030
1990	1.01	0.59	1.04	0.92	2004	1.23	1.63	1.23	1.22
1991	0.81	0.62	0.97	0.84	2005	1.32	1.25	1.24	1.28
1992	0.79	0.66	1	0.82	2006	1.26	1.18	1.27	1.20
1993	0.8	0.85	0.89	0.85	2007	1.09	0.96	1.14	1.06
1994	0.81	0.61	0.65	0.83	2008	1.02	0.88	0.95	0.97
1995	0.84	0.91	0.69	0.86	2009	1.03	0.88	1.04	0.98
1996	0.97	1.07	0.7	0.95	2010	0.9	0.82	1.01	0.87
1997	1.08	1.24	1.15	1.12	2011	0.98	1.01	0.86	0.99
1998	1.06	1.13	1.2	1.12	2012	0.98	0.98	0.81	0.96
1999	0.96	1.11	1.32	1.04	2013	0.96	0.92	0.91	0.92
2000	1.12	1.32	1.13	1.13	2014	1	0.84	0.96	0.97
2001	1.23	1.65	1.18	1.23	2015	0.93	0.92	0.96	0.95
2002	1.31	1.75	1.35	1.28	2016	0.92	0.97	0.85	0.91
2003	1.27	1.51	1.35	1.23	2017	0.92	1.01	0.89	0.95
					2018	0.76	0.9	0.82	0.85

Table 3.2: 1986 pot mesh experiments, right-hand side to the LF for pot used in the pre-1994 pot fishery as used in the assessment, i.e., data past 33 cm were excluded. 1-cm wide bins, no plus-group.

Length (cm), lower bound of bin	Proportion
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0
25	0.013699
26	0.022831
27	0.068493
28	0.150685
29	0.182648
30	0.232877
31	0.187215
32	0.141553

Table 3.3: Logbook data (assigned to 2010) length sample distribution for Statistical Areas 025, 027, 030, and whole area. 1-cm wide bins, no plus-group. (Continued on next page.)

Length (cm), lower bound of bin	Statistical Area			
	025	027	030	025+ 027+ 030
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0.000795	0.000181
22	0	0	0	0
23	0	0	0	0.000176
24	0	0	0	0.000176
25	0	0	0.000795	0.000181
26	0.000289	0.001502	0	0.000423
27	0.002891	0	0	0.001756
28	0.004626	0	0	0.00281
29	0.011853	0.001502	0.00159	0.007809
30	0.015322	0.001502	0.006359	0.011002
31	0.022839	0.009009	0.008744	0.017347
32	0.029777	0.024024	0.021463	0.026928
33	0.076034	0.085586	0.065978	0.07529
34	0.082972	0.114114	0.084261	0.088361
35	0.100607	0.121622	0.123211	0.109175
36	0.113328	0.082583	0.114467	0.108488
37	0.091356	0.091592	0.114467	0.096623
38	0.10292	0.076577	0.078696	0.093035
39	0.077768	0.04955	0.074722	0.072404
40	0.052616	0.057057	0.062798	0.055646
41	0.043654	0.034535	0.044515	0.042334
42	0.041631	0.042042	0.033386	0.039807
43	0.022261	0.036036	0.039746	0.0285
44	0.026886	0.043544	0.026232	0.029469
45	0.014166	0.031532	0.022258	0.018861
46	0.012142	0.025526	0.020668	0.016281
47	0.015322	0.016517	0.015898	0.015645
48	0.010408	0.013514	0.010334	0.010898
49	0.00636	0.013514	0.002385	0.00663
50	0.007517	0.009009	0.003975	0.006953
51	0.003758	0.006006	0.007154	0.0049
52	0.005204	0.004505	0.00318	0.004626
53	0.002602	0.001502	0.002385	0.00237
54	0.001156	0.001502	0.002385	0.001492

55	0.000289	0.001502	0	0.000423
56	0.000867	0	0.00159	0.000889
57	0.000289	0	0.003975	0.00108
58	0.000289	0.003003	0.00159	0.001032

Table 3.4: Shed length sample distribution (assigned to 2010 for Statistical Area 025).

Length (cm), lower bound of bin	<u>Proportion</u>		Length (cm), lower bound of bin	<u>Proportion</u>	
	Male	Female		Male	Female
27	0	0	43	0.008195	0.001681
28	0	0	44	0.005884	0.00063
29	0.002101	0.00042	45	0.002942	0.001261
30	0.001471	0.001471	46	0.002101	0
31	0.015339	0.013658	47	0.001471	0
32	0.058416	0.055684	48	0.002101	0
33	0.111158	0.076487	49	0	0
34	0.113469	0.073335	50	0.00021	0
35	0.091826	0.045388	51	0	0
36	0.083841	0.027107	52	0	0
37	0.057155	0.015339	53	0.00021	0
38	0.040555	0.009456	54	0	0
39	0.028367	0.007354	55	0.00021	0
40	0.014709	0.003362	56	0	0
41	0.010927	0.003152	57	0	0
42	0.009876	0.001681	58	0	0

Table 3.5: Statistical Area 025 scaled age sample distributions of the commercial catch that were used in the assessments. The data is truncated at age 3 for modelling purposes. Age 15 is a plus-group.

Age	<u>2018</u>		<u>2019</u>	
	Male	Female	Male	Female
3	0.000113	0.000113	0.000161	0.000161
4	0.000113	0.000113	0.000161	0.000161
5	0.038653	0.000113	0.000161	0.000161
6	0.124204	0.021264	0.082464	0.000161
7	0.080877	0.037513	0.132357	0.000161
8	0.227785	0.132566	0.115831	0.013732
9	0.020334	0.046826	0.277357	0.034168
10	0.055132	0.01954	0.027463	0.009529
11	0.012131	0.031885	0.066926	0.000161
12	0.000113	0.101808	0.053131	0.000161
13	0.000113	0.005715	0.025173	0.038904
14	0.000113	0.013969	0.022882	0.000161
15	0.005352	0.023543	0.000161	0.098154

Table 3.6: Statistical Area 027 scaled age sample distributions of the commercial catch that were used in the assessments. The data are truncated at age 3 for modelling purposes. Age 15 is a plus-group.

Age	2018	
	Male	Female
3	0	0
4	0	0
5	0.017138	0.00863
6	0.06184	0.051379
7	0.055282	0.056634
8	0.117278	0.142595
9	0.095303	0.182353
10	0.040741	0.016876
11	0.048418	0.041096
12	0	0
13	0	0.006698
14	0	0
15	0	0.057739

Table 3.7: Statistical Area 030 scaled age sample distributions of the commercial catch that was used in the assessments. The data are truncated at age 3 for modelling purposes. Age 15 is a plus-group.

Age	2018	
	Male	Female
3	0	0
4	0	0
5	0.043675	0
6	0.046734	0.010438
7	0.07138	0.043964
8	0.143942	0.022866
9	0.05062	0.066038
10	0.080528	0.031383
11	0.020552	0.064433
12	0.012665	0.101965
13	0.003423	0.032399
14	0.003423	0.02823
15	0.001042	0.120302

Table 3.8: Whole area scaled age sample distributions of the commercial catch that were used in the assessments. The data are truncated at age 3 for modelling purposes. Age 15 is a plus-group.

Age	Male	Female
3	0	0
4	0	0
5	0.031492	0.010865
6	0.088868	0.035873
7	0.082622	0.054564
8	0.153783	0.120131
9	0.055427	0.092934
10	0.046181	0.029603
11	0.021803	0.039537
12	0.004199	0.051573
13	0.000669	0.009965
14	0.002394	0.010645
15	0.00176	0.055111

Table 3.9: Scaled length sample distributions of the recreational catch for 2009–10 used in the assessments. The same LF was applied to each sub-area assessed. Length bins were 1-cm wide and there was no plus-group.

Length (cm), lower bound of bin	Proportion	Length (cm), lower bound of bin	Proportion
13	0.009846	36	0.077094
14	0.001532	37	0.0634
15	0.008314	38	0.088041
16	0.007727	39	0.049778
17	0.003717	40	0.070687
18	0.009047	41	0.022917
19	0.003064	42	0.031802
20	0.009713	43	0.016692
21	0.001386	44	0.009927
22	0.014361	45	0.005543
23	0.004744	46	0.011737
24	0.012976	47	0.003504
25	0.019559	48	0.005102
26	0.023261	49	0
27	0.016919	50	0
28	0.0267	51	0
29	0.023928	52	0
30	0.060393	53	0
31	0.036237	54	0
32	0.035731	55	0
33	0.067683	56	0
34	0.07409	57	0

Pot mesh experiment, 2015

Pot 1 (pre-2018 standard pot) was a 50–52 mm galvanised mesh (3' 6" x 3' 6") and Pot 2 (proposed new pot) had 54-56 mm stainless steel mesh (3' 6" x 4'). These pots were set simultaneously 19 times at a total of six sites across four statistical areas (Table 3.10).

Table 3.10: Data design of the 2015 pot mesh experiments conducted by G. Carbines (pers. comm.).

Statistical Area	Number of			
	Sites	Sets	Pots	Blue cod
025	2	9	3	496
027	1	3	3	56
029	1	3	3	102
030	2	4	3	81
Total	6	19	51	735

The experiment was reviewed by the SINSWG in November 2015 and the notes of the meeting (M. Griffiths, Fisheries New Zealand, pers. comm.) found that:

1. “Limitations of the experimental design precluded meaningful comparison of size composition by statistical area, or area related differences in selectivity. The data did, nevertheless, enable a comparison of the relative selectivity of the three pot types.
2. Proportions of undersize (< 33cm TL) blue cod retained by the pots were: 11% for Pot 1, 2% for Pot 2, and 50% for Pot 3. Apart from retaining a larger proportion of undersized fish, Pot 3 also allowed a substantial portion of larger fish to pass through the escape gaps.
3. Almost all commercially caught undersized blue cod retained by pots are dead on return to the water.”

Table 3.11: LHS length sample distribution from Pot 2 in the 2015 pot mesh experiments as used in the assessment. Data from 38 cm onwards were excluded.

Length bin lower limit (1 cm wide)	Proportion
29	0.012
30	0.016
31	0.028
32	0.024
33	0.113
34	0.140
35	0.272
36	0.227
37	0.168

APPENDIX 4: MCMC DIAGNOSTICS

Full MCMC diagnostics are presented for all parameters in the Statistical Area 025 assessment because this was the area that had about half of the total catch and the most data, and which was used to develop the base case run and to investigate sensitivities. For the sake of brevity, the other Statistical Areas have been reported for only the main parameters, B_0 and B_{2019} , but similar results for the other parameters occurred as in the Statistical Area 025 assessment.

The parameter codes (as generated automatically from Casal2) and their descriptions are shown in Table 4.1.

Table 4.1: Parameter codes used in this appendix and their descriptions. YCS are shown in the section 3.2.

Code	Parameter class	Parameter
process.Recruitment..b0		B_0 , virgin biomass
selectivity.potSurveySel_male..a50	Pot survey selectivity, male	Age at 50% selection
selectivity.potSurveySel_male..ato95		Extra time from 50% to 95% selection
selectivity.potSurveySel_female..a50	Pot survey selectivity, female	Age at 50% selection
selectivity.potSurveySel_female..ato95		Extra time from 50% to 95% selection
time_varying.potFsel.L50..values.1900.	Pot fishery selectivity, 1900–1993	Length at 50% selection
time_varying.potFsel.Lto95..values.1900.	Note, the 1993 comes from the start year of the next time block minus 1 year	Extra length to go from 50% to 95% selection
time_varying.potFsel.L50..values.1994.	Pot fishery selectivity, 1994–2017	Length at 50% selection
time_varying.potFsel.Lto95..values.1994.		Extra length to go from 50% to 95% selection
time_varying.potFsel.L50..values.2018.	Pot fishery selectivity, 2017–2018	Length at 50% selection
time_varying.potFsel.Lto95..values.2018.		Extra length to go from 50% to 95% selection
selectivity.recFsel..L50	Recreational selectivity	Length at 50% selection
selectivity.recFsel..Lto95		Extra length to go from 50% to 95% selection

Table 4.2: Statistical Area 025 MCMC parameter estimates: median, 95% confidence level, and CV.

Name	Median	<u>95% Confidence interval</u>		CV (%)
process.Recruitment..b0	10670	10186	11258	3
selectivity.potSurveySel_male..a50	2.35	1.09	3.18	27
selectivity.potSurveySel_male..ato95	1.49	0.22	4.24	63
selectivity.potSurveySel_female..a50	2.82	1.3	3.57	23
selectivity.potSurveySel_female..ato95	2.25	0.32	4.74	52
time_varying.potFsel.L50..values.1900.	29.89	26.41	40.95	12
time_varying.potFsel.L50..values.1994.	36.27	34.63	38.44	3
time_varying.potFsel.L50..values.2018.	33.57	31.14	36.14	4
time_varying.potFsel.Lto95..values.1900.	4.46	0.66	13.99	72
time_varying.potFsel.Lto95..values.1994.	3.71	1.15	6.3	36
time_varying.potFsel.Lto95..values.2018.	2.38	0.61	7.87	68
selectivity.recFsel..L50	41.09	34.79	44.78	7
selectivity.recFsel..Lto95	16.05	12.19	19.55	12

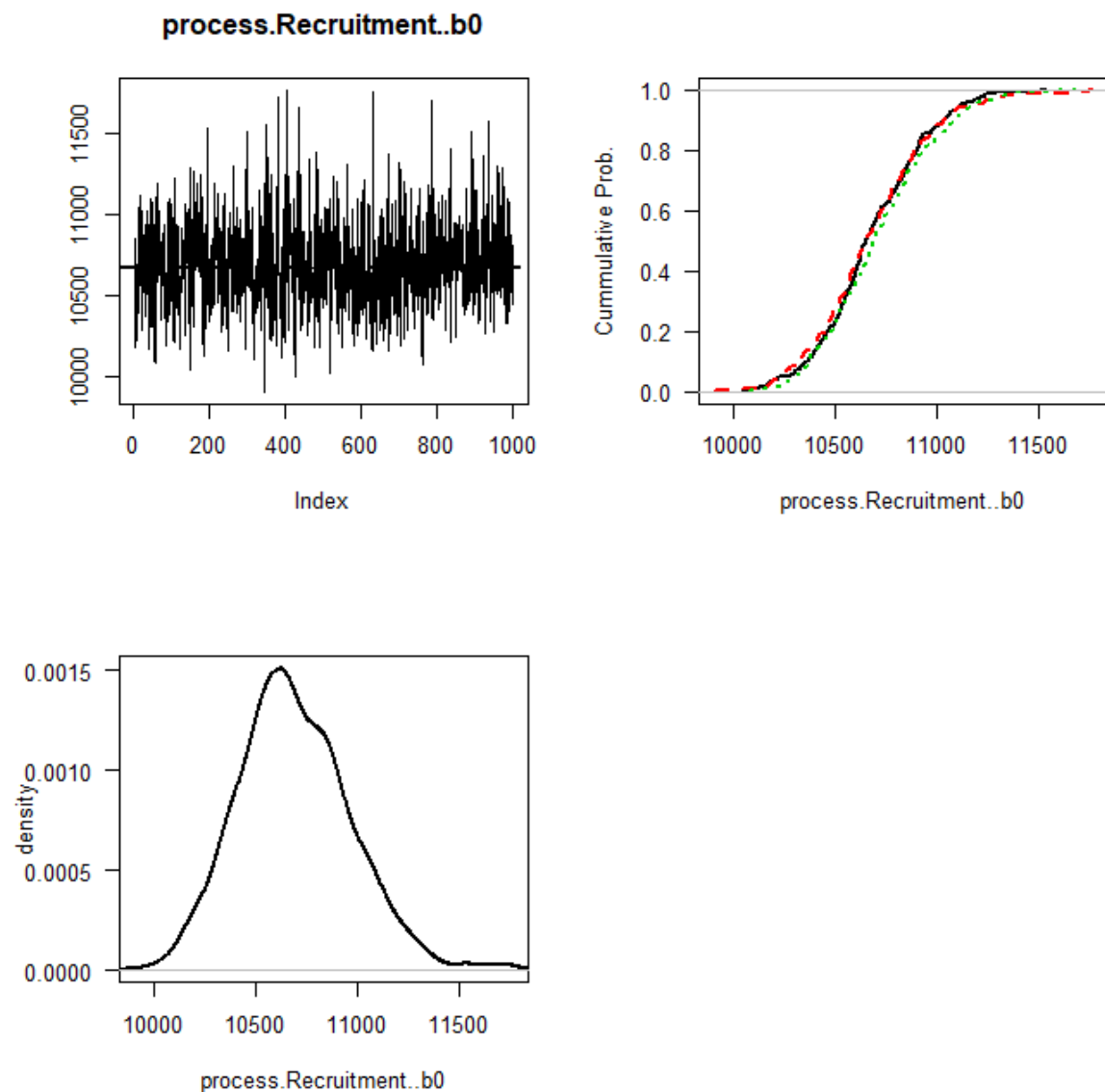


Figure 4.1: Statistical Area 025 virgin biomass, B_0 , from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution (MPD estimate ~ 10 500 t).

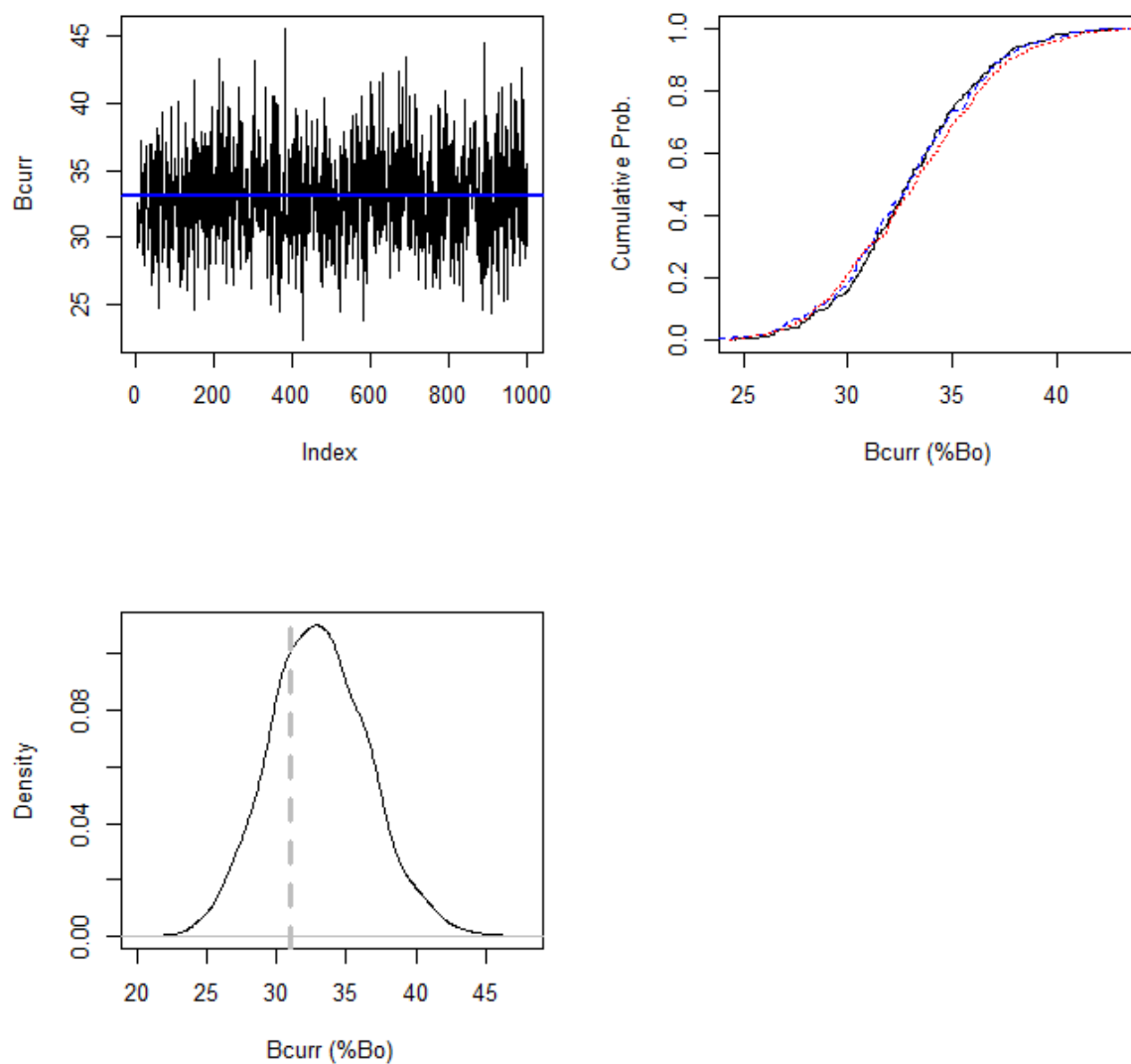


Figure 4.2: Statistical Area 025 B_{2019} , from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution (dotted vertical line, MPD estimate).

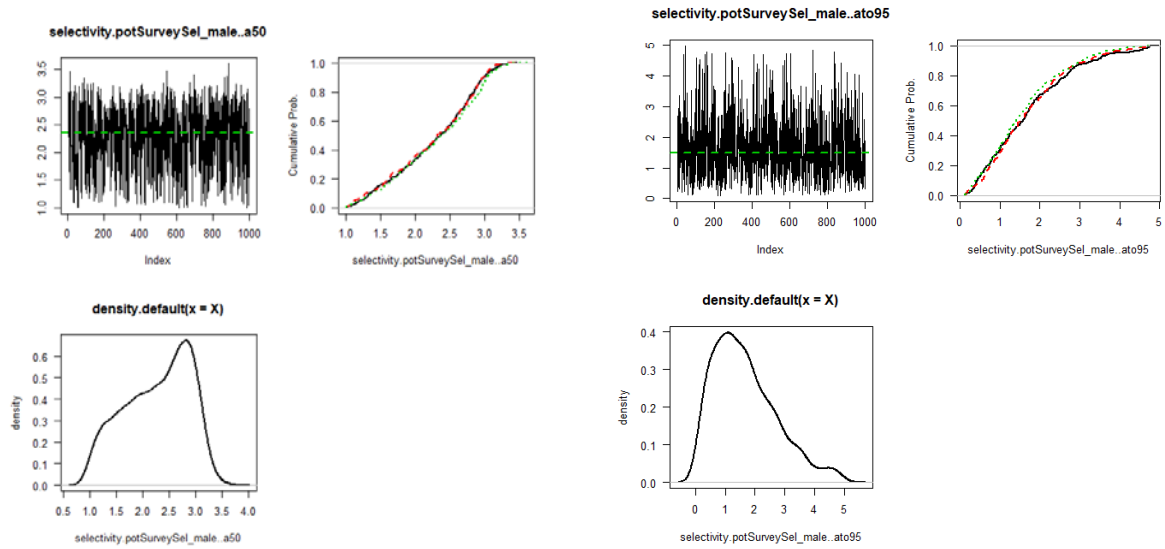


Figure 4.3: Statistical Area 025 pot survey male selectivity; left panel A_{50} , right panel A_{95} . In each panel, from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution (MPD estimate ~ 10 500 t).

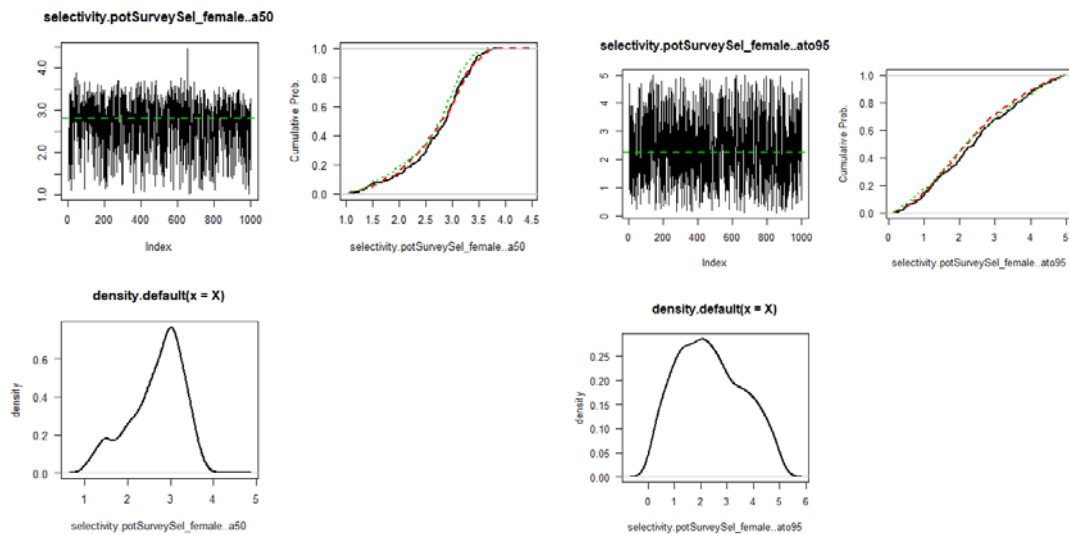


Figure 4.4: Statistical Area 025 pot survey female selectivity; left panel A_{50} , right panel A_{95} . In each panel, from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution.

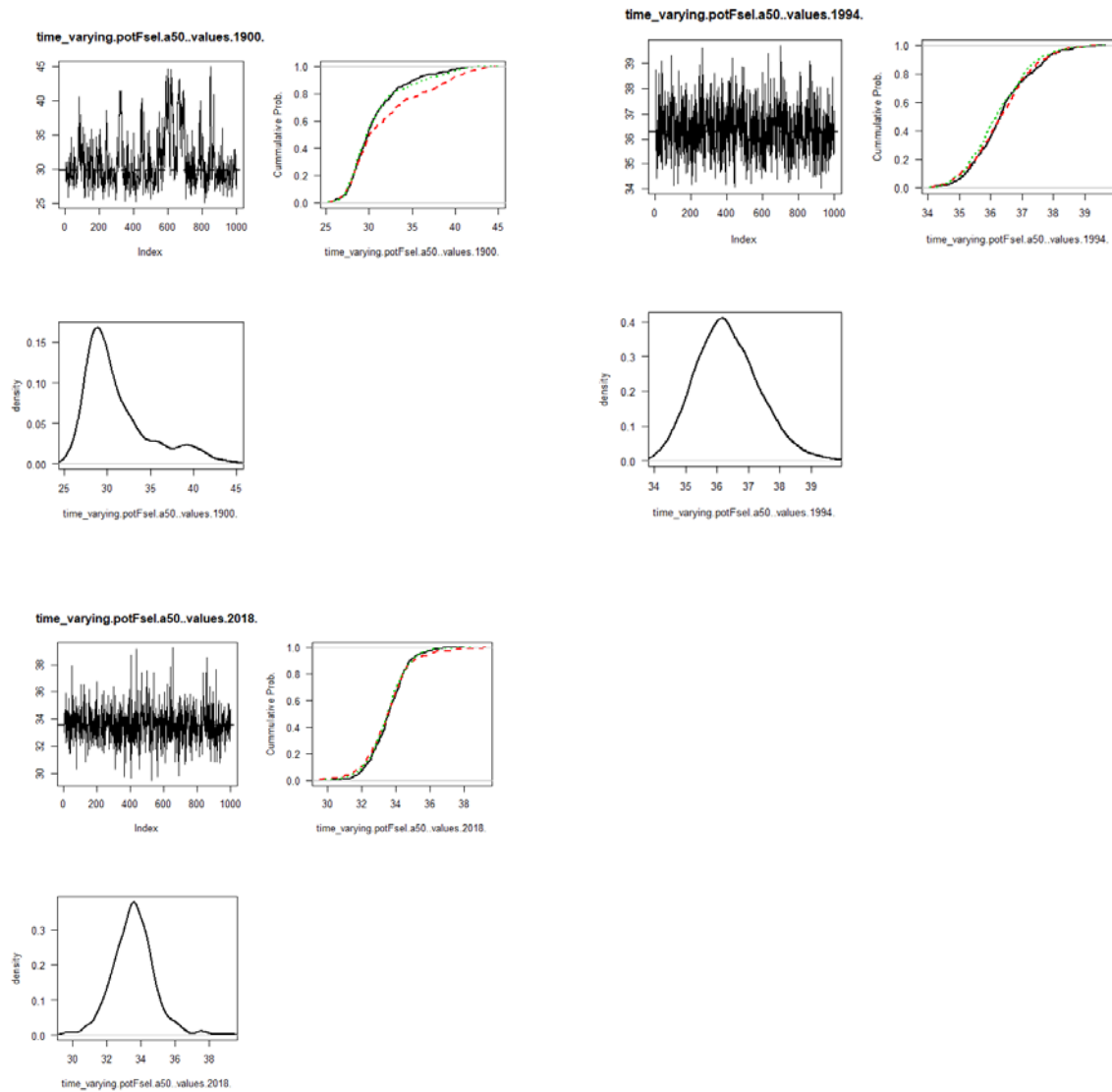


Figure 4.5: Statistical Area 025 pot fishery A_{50} for selectivity by time blocks; start years for time blocks are: 1900, 1994, 2018. Top left panel, 1900–1983; top right panel, 1983–2017; lower left panel, 2018–2019. In each panel, from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution.

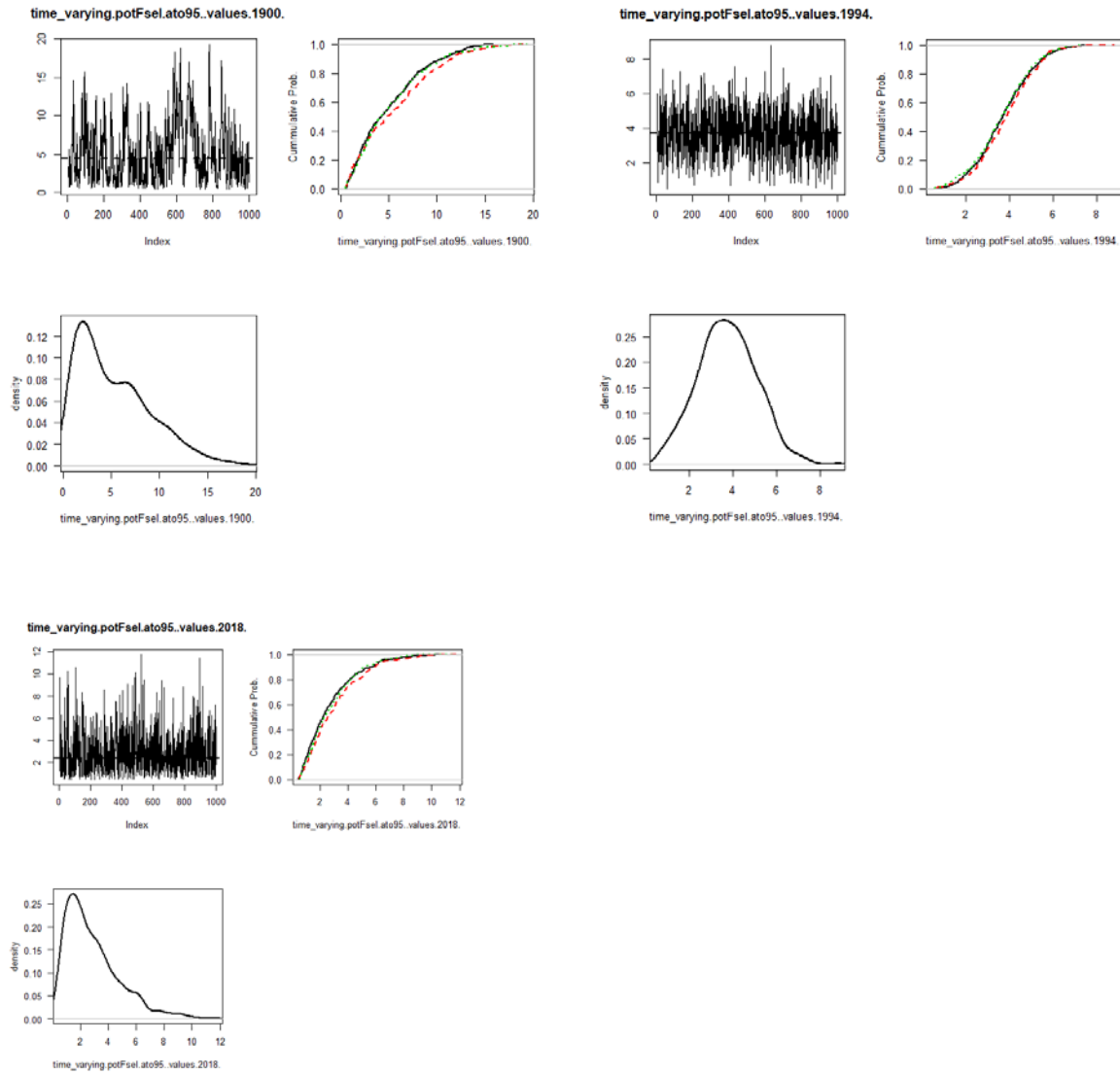


Figure 4.6: Statistical Area 025 pot fishery A_{to95} for selectivity by time blocks; start years for time blocks are: 1900, 1994, 2018. Top left panel, 1900–1983; top right panel, 1983–2017; lower left panel, 2018–2019. In each panel, from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution.

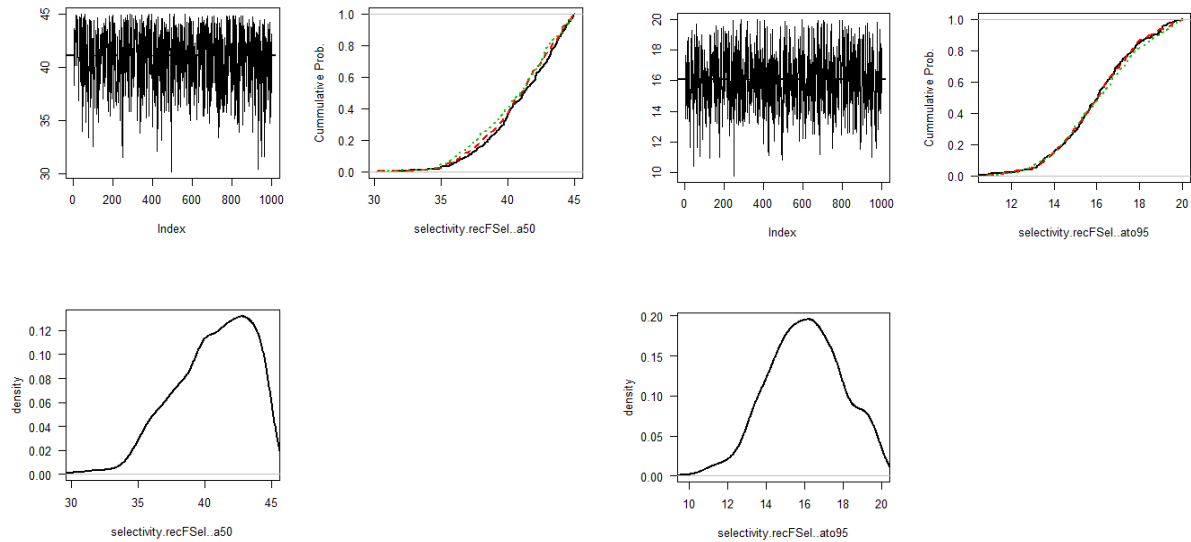


Figure 4.7: Statistical Area 025 recreational selectivity: left panel L_{50} parameter, right panel, L_{to95} . In each panel, from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution. [Note: the script that generated the plots used the L_{50} and L_{to95} parameters, not the age parameters given on the x-axis labels.]

Table 4.3: Statistical Area 027 MCMC parameter estimates: median, 95% confidence level, and CV.

Name	Median	<u>95% credible interval</u>		CV (%)
process.Recruitment..b0	4599	4128	5494	8
time_varying.potFsel.L50..values.1900.	29.23	25.65	43.13	14
time_varying.potFsel.L50..values.1994.	35.38	34	37.97	3
time_varying.potFsel.L50..values.2018.	30.58	27.19	32.44	4
time_varying.potFsel.Lto95..values.1900.	3.99	0.65	16.12	82
time_varying.potFsel.Lto95..values.1994.	1.87	0.56	5.7	63
time_varying.potFsel.Lto95..values.2018.	1.66	0.54	5.49	66
selectivity.recFsel..L50	33.45	26.73	41.85	12
selectivity.recFsel..Lto95	16.12	10.38	19.74	16

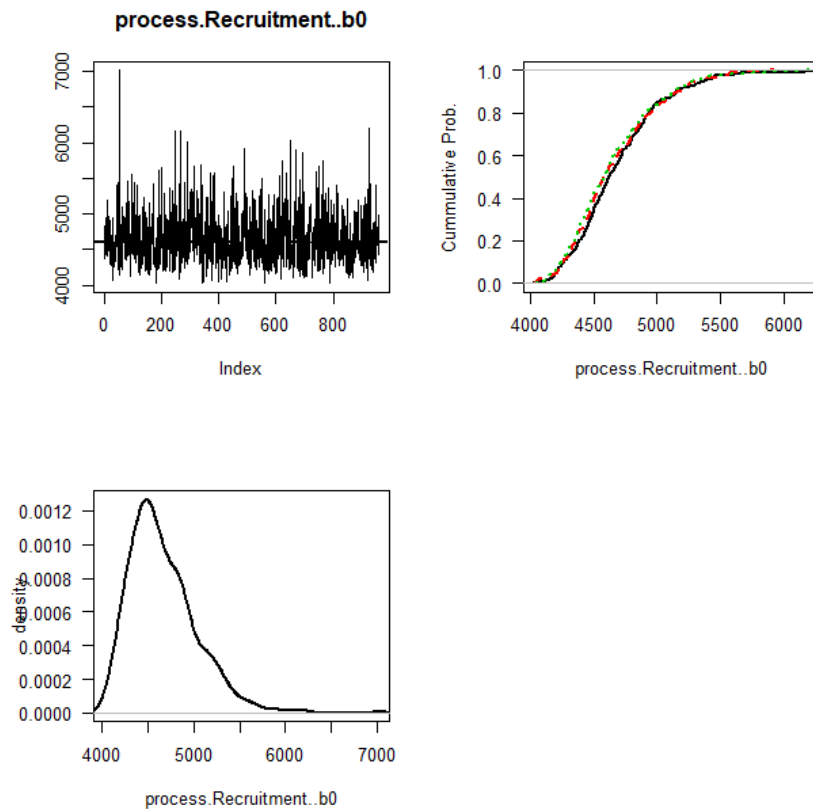


Figure 4.8: Statistical Area 027 virgin biomass, B_0 , from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution (MPD estimate ~ 4400 t).

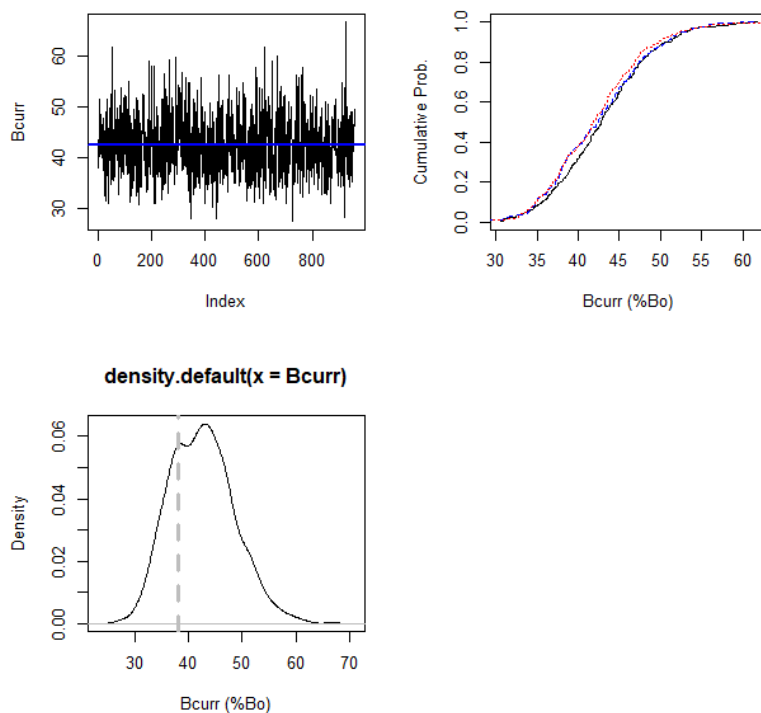


Figure 4.9: Statistical Area 027 B_{2019} , from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution (dotted vertical line, MPD estimate).

Table 4.4: Statistical Area 030 MCMC parameter estimates: median, 95% confidence level, and CV.

Name	Median	<u>95% Credible interval</u>		CV (%)
process.Recruitment..b0	4403	4099	4935	5
time_varying.potFsel.L50..values.1900.	29.89	26.41	40.95	12
time_varying.potFsel.L50..values.1994.	28.79	25.33	41.72	14
time_varying.potFsel.L50..values.2018.	36.45	34.74	38.89	3
time_varying.potFsel.Lto95..values.1900.	33.78	31.31	36.01	4
time_varying.potFsel.Lto95..values.1994.	3.8	0.67	14.63	77
time_varying.potFsel.Lto95..values.2018.	3.19	0.73	6.29	45
selectivity.recFsel..L50	2.23	0.61	7.12	69
selectivity.recFsel..Lto95	36.27	29.99	44.04	10

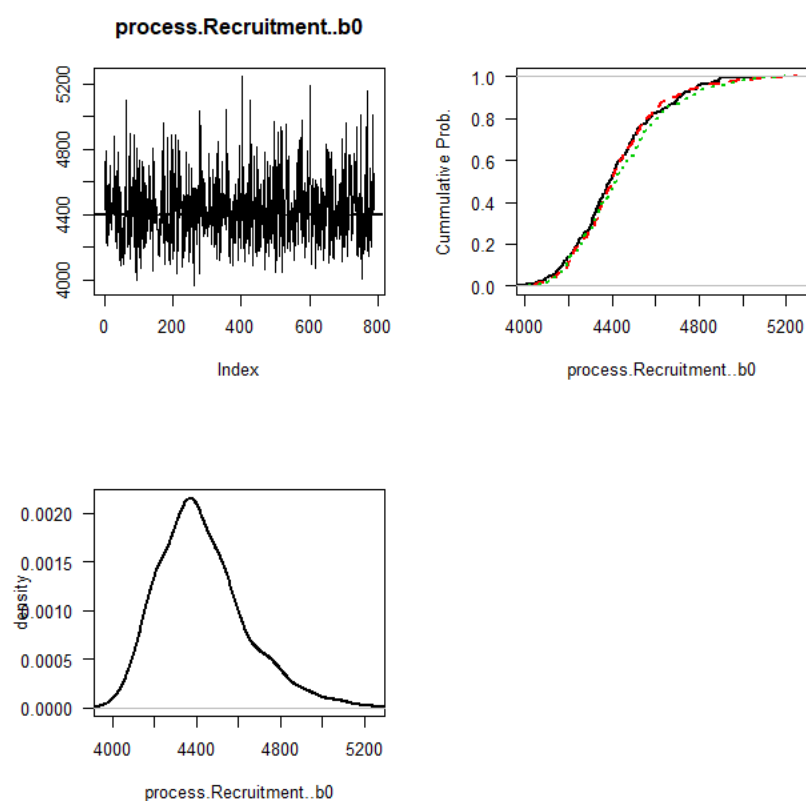


Figure 4.10: Statistical Area 030 virgin biomass, B_0 , from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution (MPD estimate ~ 10 500 t).

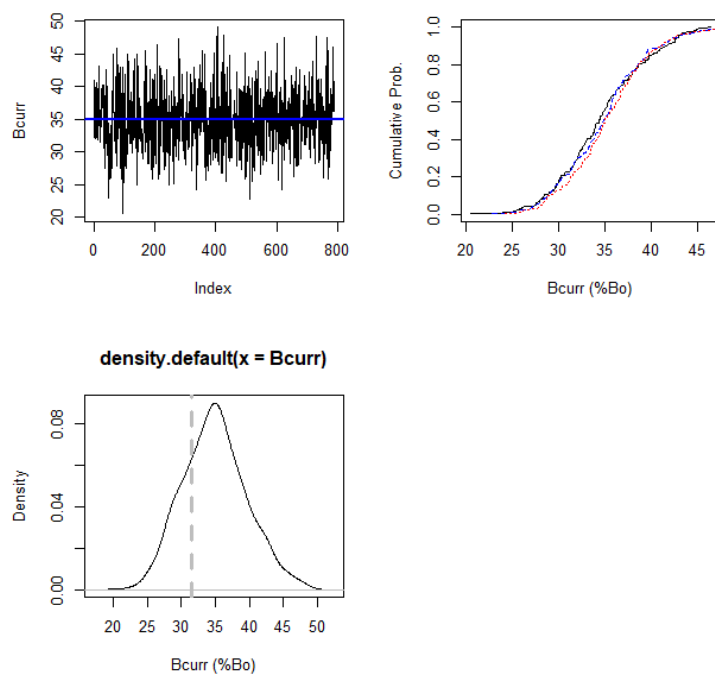


Figure 4.11: Statistical Area 030 B_{2019} , from top clockwise: MCMC trace, cumulative distribution from each 3rd of the chain, posterior distribution (MPD estimate ~ 4200 t).