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The 2023 stock assessment and management procedure evaluation for pāua (*Haliotis iris*) fisheries in PAU 5D

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Management procedures for the pāua (*Haliotis iris*) fishery in quota management area (QMA) PAU 5D have been based on harvest control rules determined by catch-per-unit-effort (CPUE) since 2016. Although the previous stock assessment in 2018 suggested a stock status near the interim management target for pāua, the control rule was aimed at improving biomass levels. The present project updated the stock assessment for PAU 5D and tested control rules to achieve fishery aims of slow rebuilding of catch towards the Total Allowable Commercial Catch.

We fitted the stock assessment to length-composition and CPUE data from the period starting in the 2001–02 fishing year. Length-composition data were standardised using a model-based approach based on measured numbers-at-length, which attempted to derive more accurate characterisation of uncertainty for length compositions for PAU 5D, for which sampling has not been representative.

The CPUE was derived in a number of ways to account for potential differences between Pāua Catch Effort Landing Return (PCELR) and Electronic Reporting System (ERS) data. The latter showed shorter fishing duration for PAU 5D than PCELR-reported effort, and a number of sensitivities, including omitting fishing duration and deriving CPUE as catch-per-day, were attempted.

In contrast to the previous stock assessment, CELR data were omitted from the analysis. This change had a considerable effect on estimated biomass levels, which were markedly lower than biomass levels estimated in the 2018 stock assessment. The current assessment suggested stock levels near the soft limit in the early 2000s and around 2015, with reductions in catch since 2015 leading to a rebuild in biomass. The estimated rebuild in the model was determined by increasing recent CPUE. We tested sensitivities to recent CPUE trends by fitting to model to CPUE with and without fishing duration as the effort measure. None of the sensitivities we tested showed a qualitatively different trend from the trend for the base model. The latter suggested that the stock has been rebuilding and is now as likely as not to be at the interim management target.

The harvest control rule that had been in place in PAU 5D since 2016 was updated to include a lag year on increases and a maximum 5% limit on year-on-year increases. The resulting rule was slightly more conservative (i.e., it led to lower average catch) than the rule implemented in 2016. The updated rule maintained steady harvest rates on average, even under the least productive model assumptions, leading to low short- to medium-term risk if the rule was applied to determine catch. In view of potentially changing ocean conditions influencing growth and recruitment in some areas, it is recommended that the assessment and control rule are reviewed in five years' time to ensure it remains a safe option to manage the fishery.

[1] Dragonfly Data Science, New Zealand.

1. INTRODUCTION

Since the introduction of management procedures in PAU 5D in 2016 (Neubauer 2019, 2021), the pāua (*Haliotis iris*) stock in southern Aotearoa New Zealand (Figure 1) has been managed with harvest-control rules. These rules determine shelving levels under the Total Allowable Commercial Catch (TACC), which sets the upper limit (no shelving). The introduction of harvest control rules led to the adoption of a "rebuilding rule", which was aimed at rebuilding the stock towards derived biomass levels. This aim contrasted with stock assessments that suggested stock levels at or near the interim management target for pāua stocks (40% of unfished spawning biomass; Marsh & Fu 2017, Neubauer & Tremblay-Boyer 2019b).

Stock assessments in the area had relied on relatively sparse growth and length-composition data, with catch-per-unit-effort (CPUE) to determine estimates of stock depletion and biomass trends. Earlier assessments identified the growth data and associated model fits as main sources of uncertainty in the model (Marsh & Fu 2017), whereas recent assessments attempted to address this limitation by introducing a broader, more flexible growth formulation (Neubauer & Tremblay-Boyer 2019b). Nevertheless, sparse length-composition data, and uncertain trends in early CPUE, still remained key sources of uncertainty.

The present study updated the stock assessment, and re-evaluated harvest control rules for PAU 5D. We addressed uncertainty in length-composition data by updating the framework used to derive length-compositions for pāua stock assessments to obtain a useful representation of uncertainty for individual length compositions. In addition, we estimated CPUE trends with a series of assumptions about Electronic Reporting System (ERS) data to account for potential changes in data reporting. Stock assessment models were updated to reflect assumptions made in other QMAs. In addition, a set of updated harvest control rules was examined against the base-case stock assessment and sensitivities to assessment assumptions.

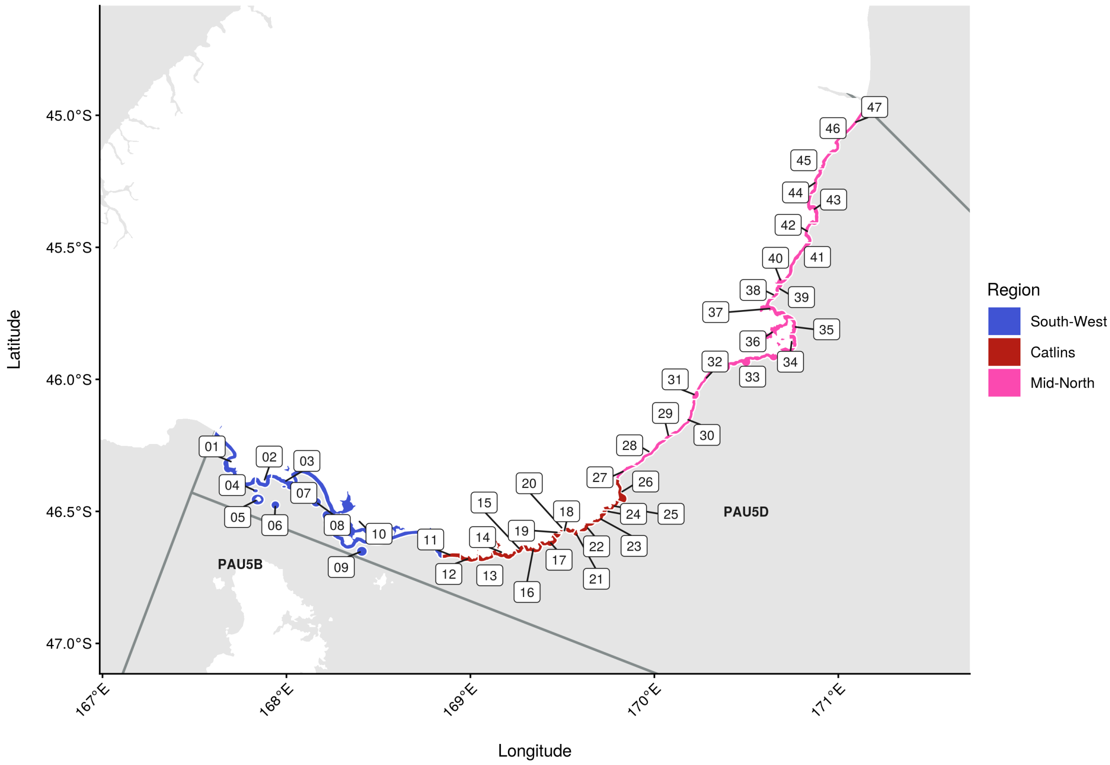

Figure 1: Pāua quota management area (QMA) PAU 5D (Otago and Southland), including key spatial divisions. Catch reporting was initially at a lower spatial resolution of large statistical areas (not shown), and subsequently changed (in 2002) to fine-spatial scale pāua statistical areas shown here (coloured).

2. METHODS

2.1 Inputs

Inputs for the PAU 5D stock assessment model consisted of data of commercial catch, CPUE data from (Paua) Catch Effort Landing Return ((P)CELR) forms and the Electronic Reporting System (ERS), and length-frequency data from commercial sampling (CSLF). Catch assumptions for recreational, customary, and illegal take were agreed by the Shellfish Working Group (SFWG), and considered known. Only limited biological data (i.e., growth data) are available for PAU 5D, and these data are not considered representative of the fished areas (Neubauer & Tremblay-Boyer 2019a); only distributions derived from meta-analyses were used in models for PAU 5D.

All data sources were compiled and prepared through the Kahawai Collective reporting system, which implements reproducible and standardised prepared fisheries datasets for further analyses. Documentation for the Kahawai system is currently being developed (Middleton in prep.). For pāua in the current assessment, data preparation within the Kahawai database was minimal, consisting only of consistency assessments as part of database builds. Any substantial data preparation or analyses that were performed for individual analyses of datasets are detailed below.

2.1.1 Commercial catch

Commercial catch was assumed to be known without error in the assessment model and, therefore, had to be reconstructed for the assessment period (1965 to 2022). Data sources for early catch included early reports on commercial pāua catch (Murray & Akroyd 1984), the Fisheries Statistical Unit (FSU) database (1984–1988), and catch effort data supplied by Fisheries New Zealand (Table 1, Figure 2).

Table 1: Sources of pāua catch data for quota management area PAU 5D, by period. FSU, Fisheries Statistical Unit; (P)CELR, (Paua) Catch Effort Landing Return; ERS, Electronic Reporting System.

Period	Source
1965–1973	Linear increase from 1 t to 1974 value.
1974–1983	Murray & Akroyd (1984) as cited by Schiel (1989).
1984–1988	FSU database.
1989	Interpolated.
1990–2019	Estimated catch from (P)CELR.
2020–2022	Estimated catch from ERS.

Commercial catch for PAU 5D cannot be reconstructed with precision prior to the introduction of intermediate fine-scale statistical areas in 1996 and Pāua Catch Effort Landing Return (PCELR) forms in 2002. Prior reporting on non-pāua-specific CELR forms was at the level of large-scale statistical areas. The area with the majority of catch at the time, Statistical Areas 025 and 030, straddled PAU 5A and PAU 5B, and PAU 5D. The majority of catch is considered to have been from areas in South Fiordland (PAU 5A) and Stewart Island (PAU 5B). For all data prior to 2002, it was assumed here that 25% of catch reported from Statistical Area 025 were from PAU 5D. Similarly, it was assumed that 7% of landings from Statistical Area 030 were from PAU 5D before 1996. This assumption was consistent with previous assessments (Marsh & Fu 2017), and the SFWG considered that it is unlikely that more accurate estimates could be derived for the early catch splits for areas shared between the PAU 5 QMAs. Since 1996, catches can be attributed to current QMAs based on intermediate finer-scale statistical areas (Figure 3).

For the early part (1974–1983) of the catch history, the commercial catch reconstruction used data from Murray & Akroyd (1984); the FSU data were considered unreliable. From 1990 onwards, estimated catch data from CELR forms were used. Catch in 1989 was interpolated between 1988 and 1990 (Table 1).

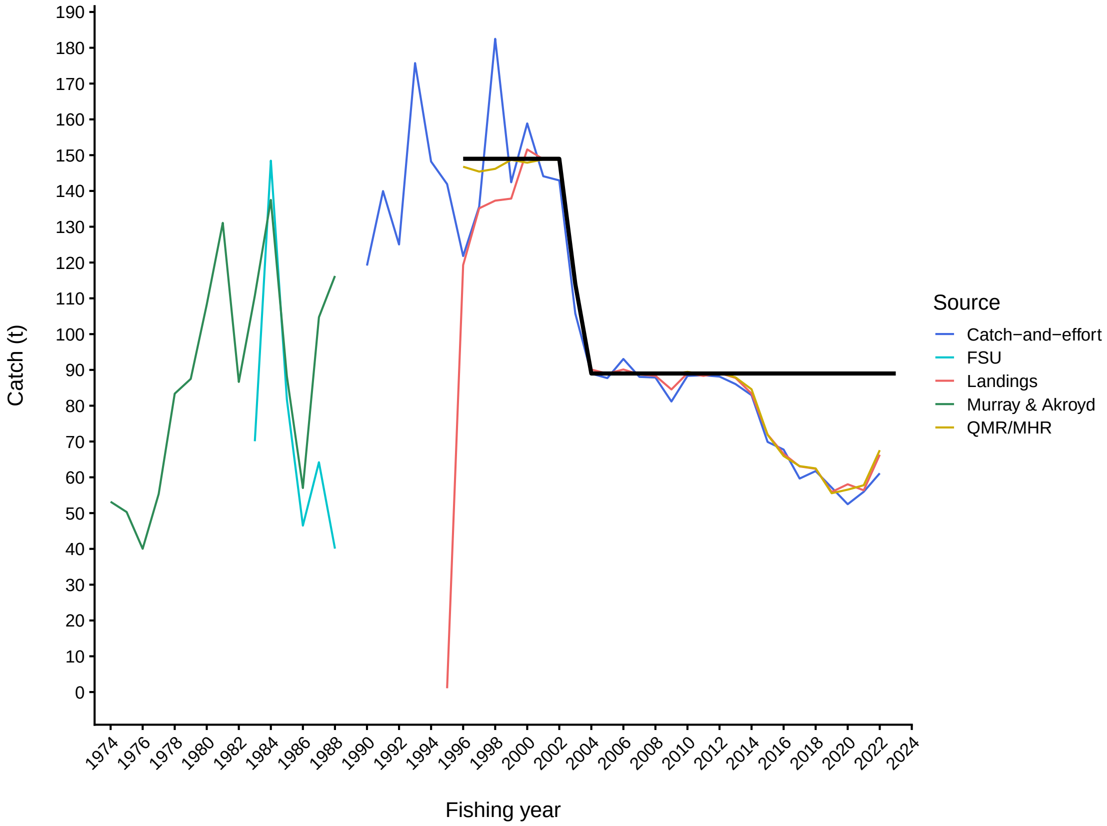

Figure 2: Commercial catch history for pāua quota management area (QMA) PAU 5D from 1974 to 2022. Catch to 1986 was reconstructed from data reported by Murray & Akroyd (1984; green line). Data from the Fisheries Statistical Unit (FSU) database (teal line) were not used in the present assessment due to unrealistically low catches in later years. Catch-effort data from 1989 was supplied by Fisheries New Zealand (catch-and-effort, blue line), alongside QMR/MHR (quota/monthly harvest return; yellow) and reported landings (red line). The total allowable commercial catch (TACC) since introduction of the quota management system system is shown in black.

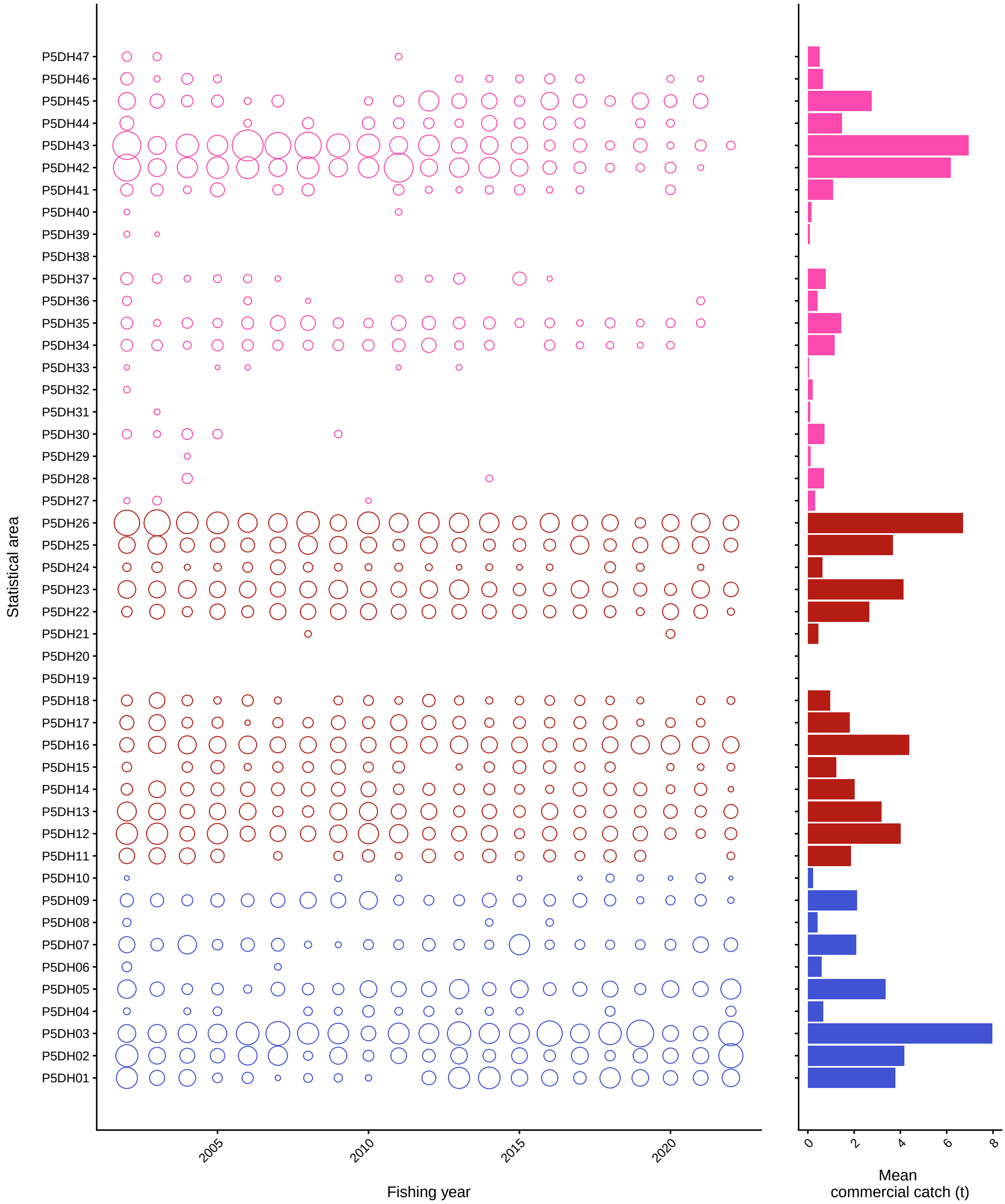

Figure 3: Relative trend in pāua catch (kg) over time by pāua statistical areas in quota management area PAU 5D for the period from 2002 to 2022, with total catch over the same time period (right-hand side). Spatial areas within PAU 5D are colour-coded (blue: south-west; red: Catlins; pink: mid-north).

2.1.2 Recreational, customary, and illegal catch

Two estimates from the national panel surveys provided some limited information about recreational pāua fishing in the area. The survey estimated that about 22 t of pāua were taken by recreational fishers in the entire area of PAU 5D for 2011–12 (Wynne-Jones et al. 2014). In 2017–18, the national panel survey was repeated and the estimated recreational catch was near 20 t (Wynne-Jones et al. 2019). Nevertheless, the SFWG considered that most of this catch may be from areas that are closed to commercial fishing (e.g., on Otago Peninsula). For this reason, the SFWG decided to assume a linear increase in recreational take from 1 t in 1974 to 10 t in 2005, with stable catch since then.

There is no comprehensive information available on customary take in recent years. Owing to this lack, the SFWG agreed to assume that customary catch has been constant at 2 t since 1974. For the illegal catch component, the SFWG agreed to assume a constant illegal catch of 10 t per year since 1974.

Based on the different catch components, estimates of the total catch by area (Figure 4) were used in the spatial assessment attempts, compared with total catch estimates for the overall QMA derived as the sum of individual area estimates (Figure 5).

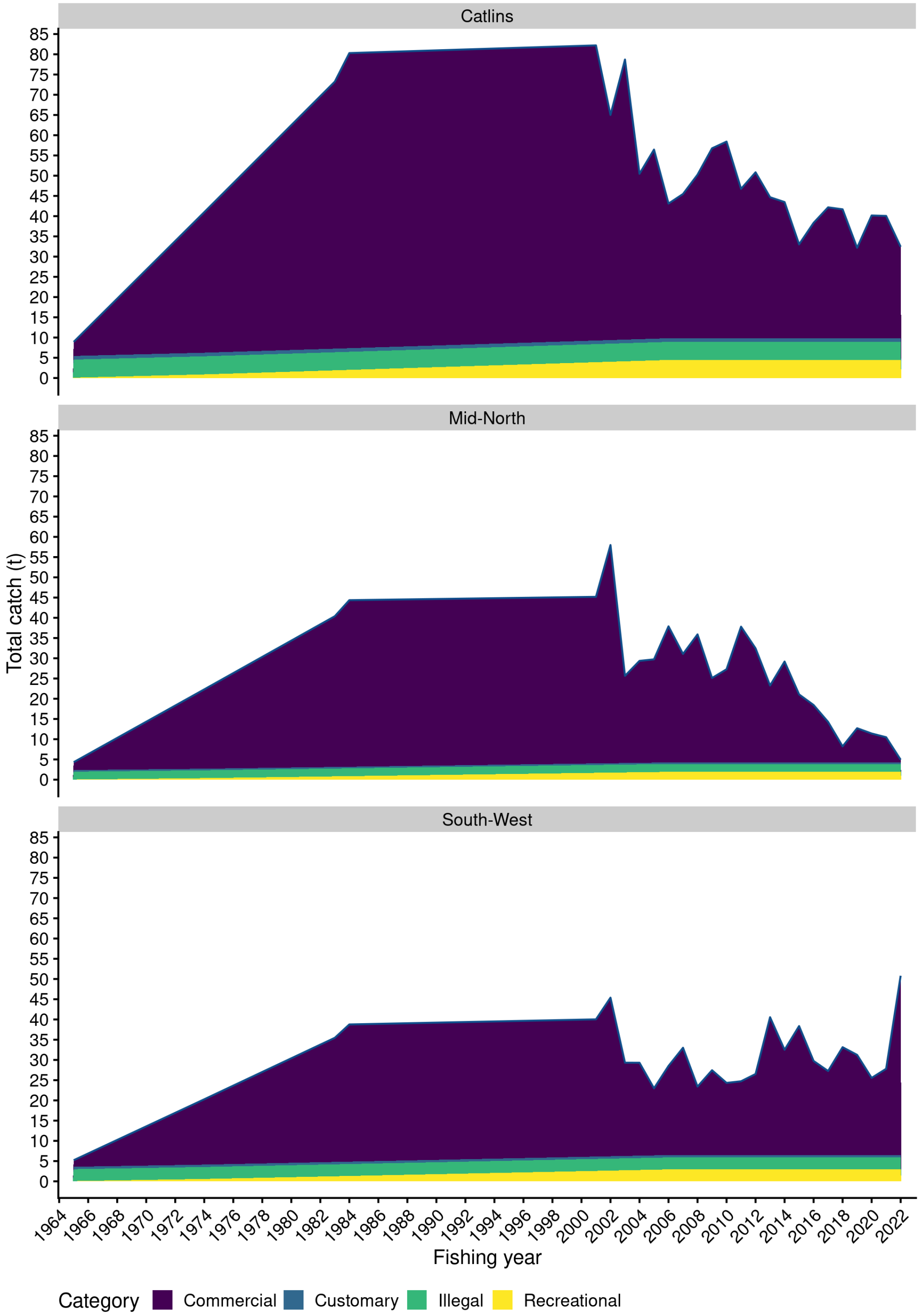

Figure 4: Estimated total pāua catch history for quota management area (QMA) PAU 5D from 1974 to 2022 by fishery component and reporting area. Fishery categories were commercial customary, illegal, and recreational catch. Commercial catch was reconstructed up to 1995, when the QMA was created, and based on landing records thereafter.

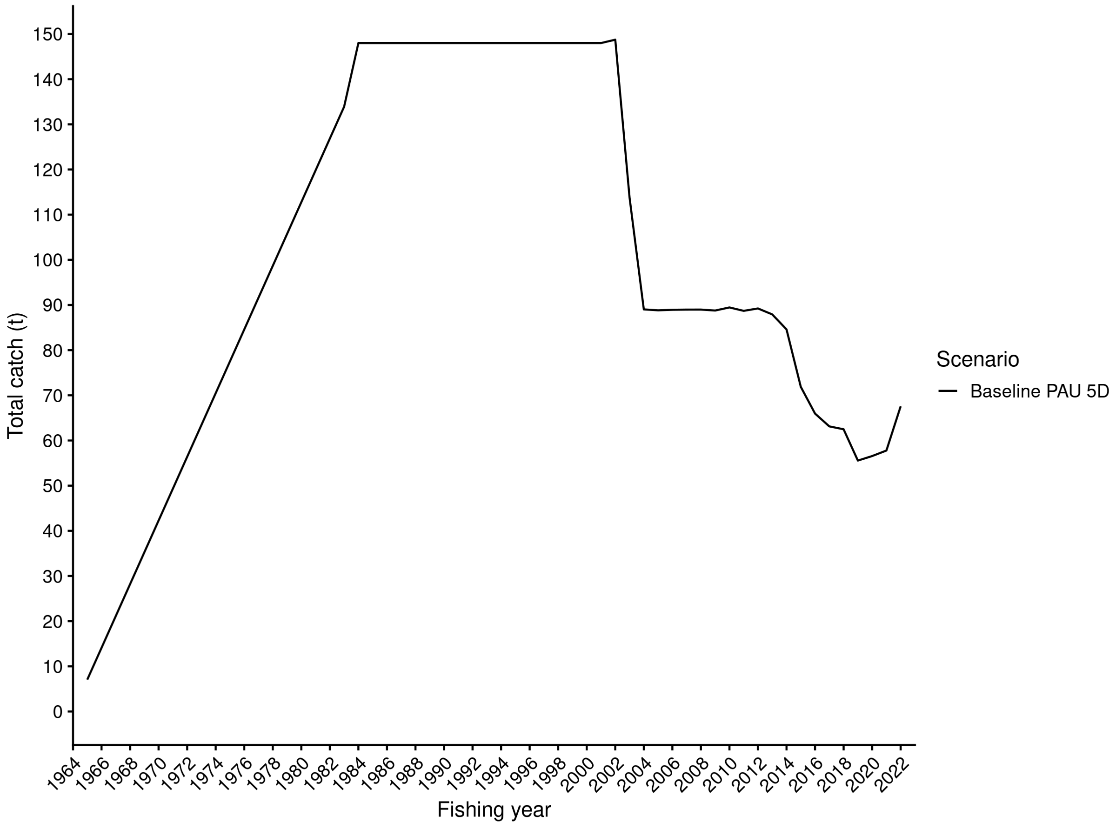

Figure 5: Total pāua catch history used in the single-area stock assessment for quota management area PAU 5D from 1974 to 2022 as the sum of all catch components (commercial, customary, recreational, illegal).

2.1.3 Catch-per-unit-effort (CPUE)

The present assessment only considered PCELR (2002 to 2019) and ERS data (2020 to 2022). Although data from the CELR forms were used in previous assessments (CELR data were used up to 2018), these data have been rejected as being too unreliable as a proxy for trends of relative abundance in pāua QMAs. Poor reporting, considerable changes in the fishing fleet, and operational changes (increases in fishing power) are likely to have led to an unknown degree of hyper-stability in these time series. In addition, the spatial resolution in pre-PCELR data is insufficient to partition the CPUE from Statistical Areas 025 and 030 to present-day QMAs, and does not allow partitioning of trends by industry management zones. These reporting deficits had largely disappeared, and the fishing fleet had stabilised by the time PCELR reporting was introduced in 2002. Therefore, CPUE based on PCELR has been considered a more robust indicator of abundance since the early 2000s.

Data preparation procedures for PCELR data generally followed established protocols detailed by Fu et al. (2017) (see details of the data preparation in Table 2). Data preparation steps are summarised as follows:

1. Use only events with “diving” as method.
2. Remove items with missing fields needed for standardisation.
3. Remove clients who have not been active for extended periods of time (2 years), and divers with less than 2 years experience.
4. Retain only events with less than four recorded divers, and a recorded fishing duration of $\leq$10 h, as well as CPUE between 10 and 500 kg/h.

For recent electronic reporting (ERS) data, the same procedure was followed (Table 3).

Table 2: Data preparation steps and number of records removed for data from Paua Catch Effort Landing Return (PCELR) forms by year and in total (as record numbers retained and percentage retained). FIN, fisher (client) identification number; CPUE, catch-per-unit-effort.

Data preparation	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total	Retained (%)
All	1252	979	763	675	591	572	547	439	487	450	532	586	564	530	412	391	310	235	10 315	100.00
Missing fields	1252	979	763	675	591	572	547	439	487	450	532	586	564	530	412	391	310	235	10 315	100.00
FIN years ≥2	1250	977	762	675	591	572	547	439	487	450	532	586	564	530	412	391	305	235	10 305	99.90
Diver years ≥2	1038	860	663	633	544	539	498	413	451	434	492	567	545	491	372	365	285	217	9 407	91.20
No. of divers ≤4	1038	860	663	633	544	539	498	413	451	434	492	567	545	491	372	365	285	217	9 407	91.20
Fishing duration ≤10h	1038	860	663	633	544	539	498	413	451	434	492	567	545	491	372	365	285	217	9 407	91.20
10kg/h ≤CPUE ≤500kg/h	997	800	623	616	538	529	490	401	450	431	486	550	529	464	349	351	284	215	9 103	88.25

Table 3: Data preparation steps and number of records removed for data from Electronic Reporting System (ERS) reports by year and in total (as number and percentage of records retained). FIN, fisher (client) identification number; CPUE, catch-per-unit-effort.

Data preparation	2020	2021	2022	Total	Retained (%)
All	249	312	288	849	100.00
FIN years ≥2	249	312	287	848	99.90
Diver years ≥2	201	304	270	775	91.2
No. of divers ≤4	201	304	270	775	91.2
Fishing duration ≤10h	201	304	270	775	91.2
10kg/h ≤CPUE ≤500kg/h	195	300	267	762	89.7

Alternative data preparation procedures for ERS data (Neubauer 2023a) were employed to correct for potential misreporting in ERS data or differences relative to data reported on PCELR forms. These potential changes were found to be more likely for PAU 5D data (Figure 6). For the present analysis, we used a series of subsets derived from that analysis, namely:

1. The full dataset under standard data preparation procedures,
2. data subset of clients for which reporting was at least as likely as not (50%) to be consistent between PCELR and ERS reported effort,
3. data subset of clients for which reporting was highly likely (95%) to be consistent between PCELR and ERS reported effort,
4. and data without fishing duration, using catch-per-day.

For the data subset of clients for which reporting was highly likely (95%) to be consistent between PCELR and ERS reported effort, only few records (17%) were retained for analysis. As a result, the fourth option (no fishing duration) was retained to provide a greater contrast between analyses, reflecting uncertainty about the impact of ERS on PAU 5D effort reporting and resulting CPUE.

The PCELR and ERS data from 2002 were combined to derive standardised, fishery-dependent indices of abundance based on the four data subsets. The CPUE standardisation was carried out using Bayesian Generalised Linear Mixed Models (GLMM) which partitioned variation among fixed (spatial areas) and random variables. The CPUE was defined as the log of daily catch. Variables in the model were fishing year, estimated fishing effort, client (Annual Catch Entitlement (ACE) holder) identification number, spatial stratum, small-scale statistical area, and diver identification.

For the base dataset, the fit of the log-normal CPUE index model was considered reasonable (Figure 7), with an index that was relatively similar to the raw data. Standardised CPUE in all areas suggested increases in recent years (Figure 8), with the most notable increase in the South-west area. Client and diver identification numbers had the strongest standardising effects for recent CPUE (Figure 9). The diver identification had a standardising effect (Figure 10), mainly for 2019 and 2020 when fewer inexperienced divers were active, leading to up to 10% higher unstandardised CPUE. A larger proportion of effort was carried out by more efficient crews in recent years, leading to an increasingly positive influence on CPUE (Figure 11). In combination, these adjustments reduced standardised CPUE relative to raw CPUE in recent years.

The same analysis was conducted for subsets of CPUE data described above. The resulting indices were generally similar to the base index. The main difference was from the model without fishing duration, which showed either flat or declining trends in the most recent years, relative to all other indices, which were generally higher over the last three years (Figure 12).

The CPUE and estimated observation error (σ_{OBS}) were used as direct inputs to the attempted stock assessment model without further modifications, as process error is estimated within the model based on relative weights for CPUE and commercial sampling length-frequency (CSLF) data.

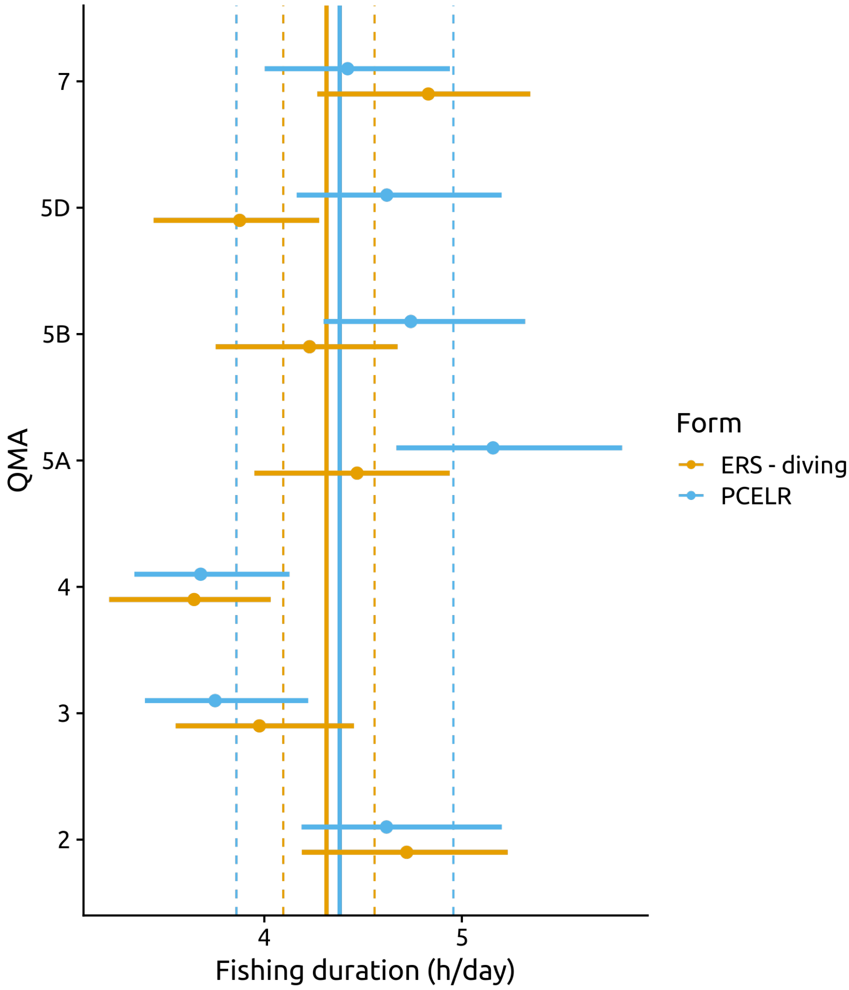

Figure 6: Estimated mean fishing duration by day per quota management area (QMA) reported via electronic reporting system (ERS) and on paper-based Pāua Catch Effort Landing Return (PCELR) forms. Vertical solid lines show estimates of the global mean duration under ERS and PCELR reporting, with their uncertainty (95% confidence interval) indicated with dashed vertical lines (reproduced from Neubauer (2023a)).

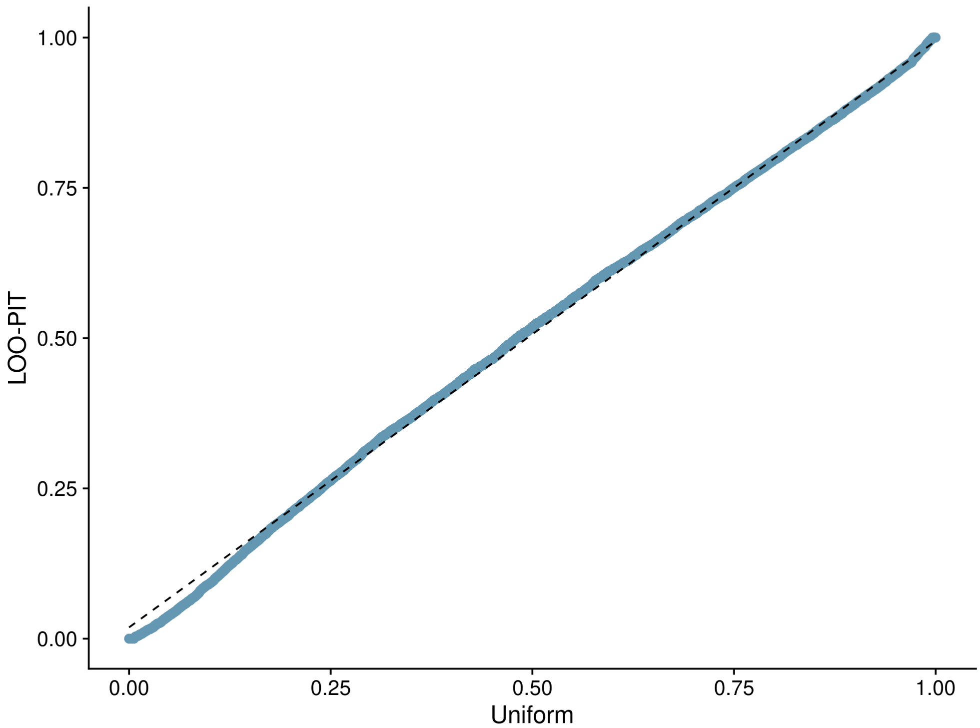

Figure 7: Fit of the log-normal generalised linear mixed model used for catch-per-unit-effort (CPUE) index standardisation. The quantile-quantile plot compares the PIT (Probability Integral Transform) of the leave-one-out (LOO) posterior predictive distribution to the theoretically expected uniform distribution.

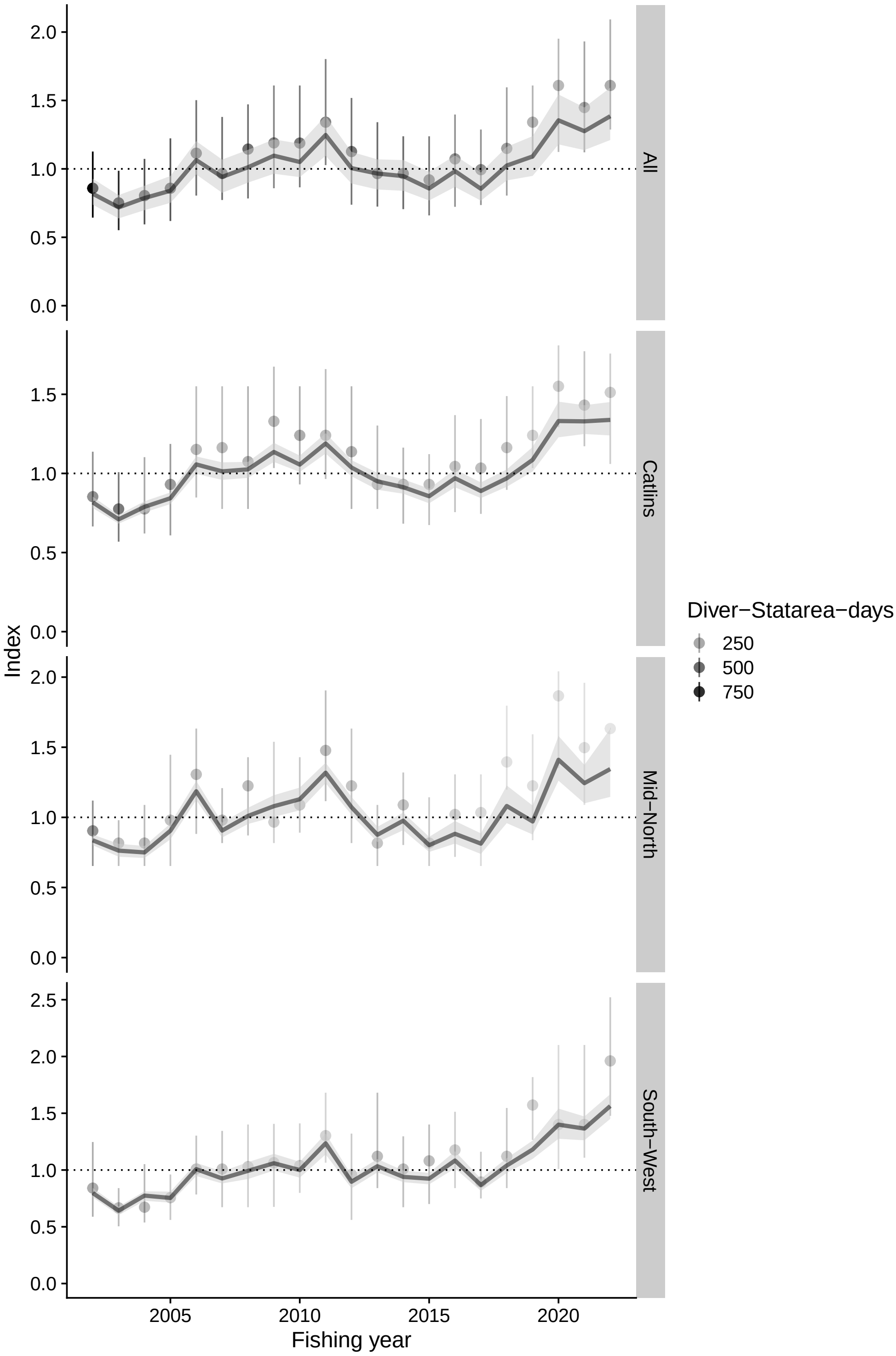

Figure 8: Standardised catch-per-unit-effort (CPUE) using a generalised linear mixed model with area-year interaction; showing CPUE by area. Black line and confidence interval show estimated CPUE index and 95% posterior quantiles, with data mean and inter-quartile range shown as points and error bars, respectively.

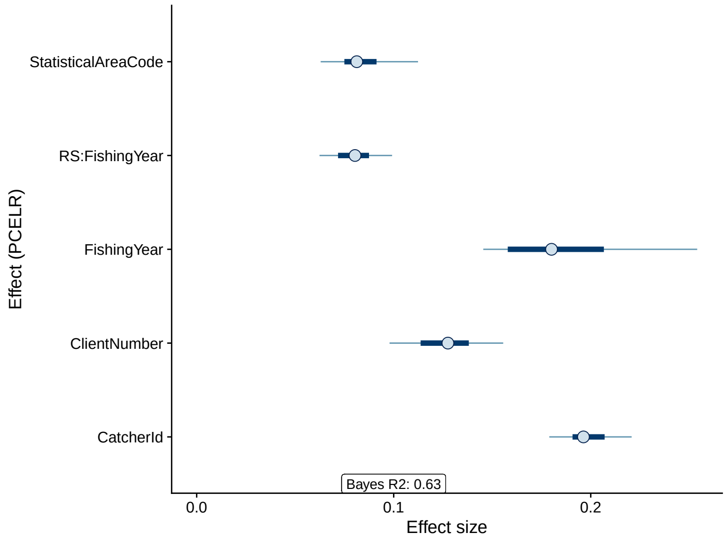

Figure 9: Effect size as variance explained for variables included in the random effects standardisation model. PCELR, Paua Catch Effort Landing Return.

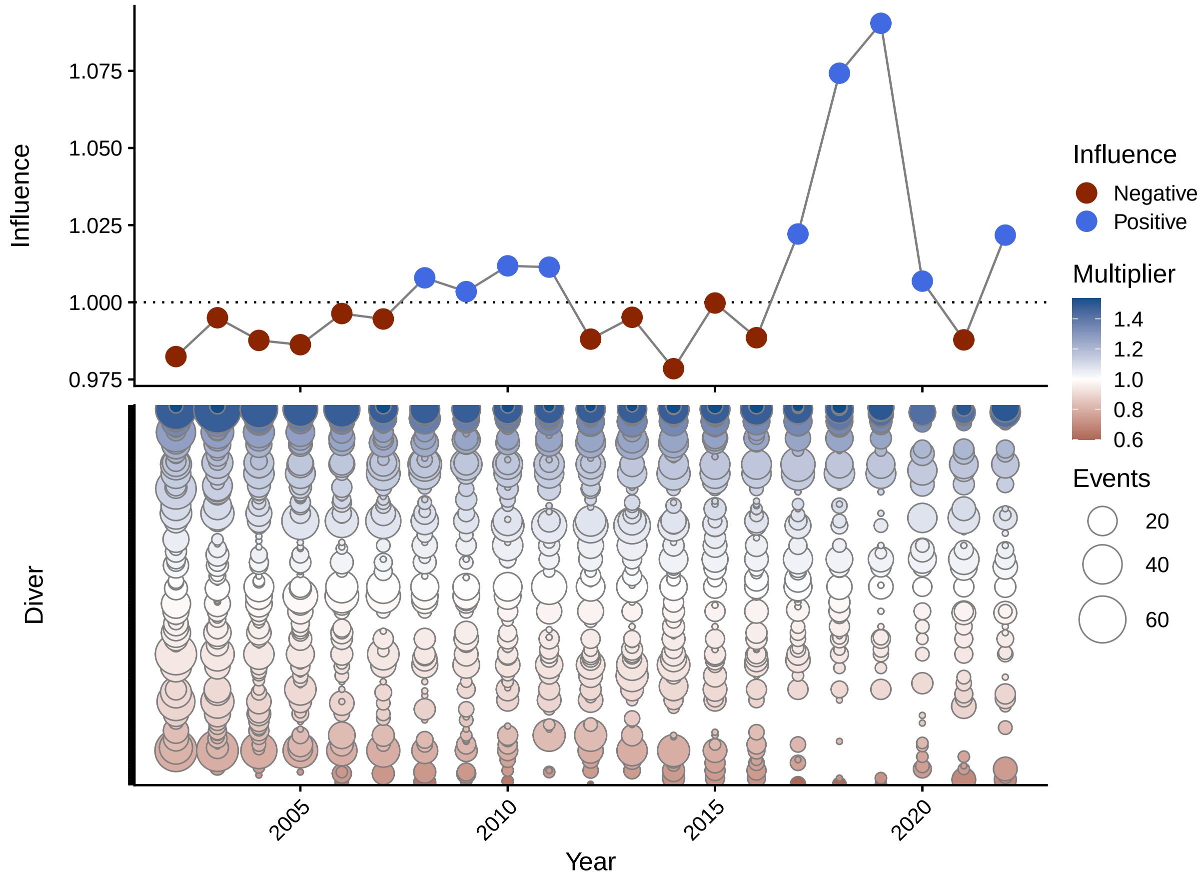

Figure 10: Influence plots for diver random effects, showing the effect on raw catch-per-unit-effort (CPUE; top graph) of applying estimated effect sizes (bottom graph) from the factor levels encountered each fishing year. A positive (>1) influence for a given time period means that the unstandardised index was increased due to the relative distribution of the covariate.

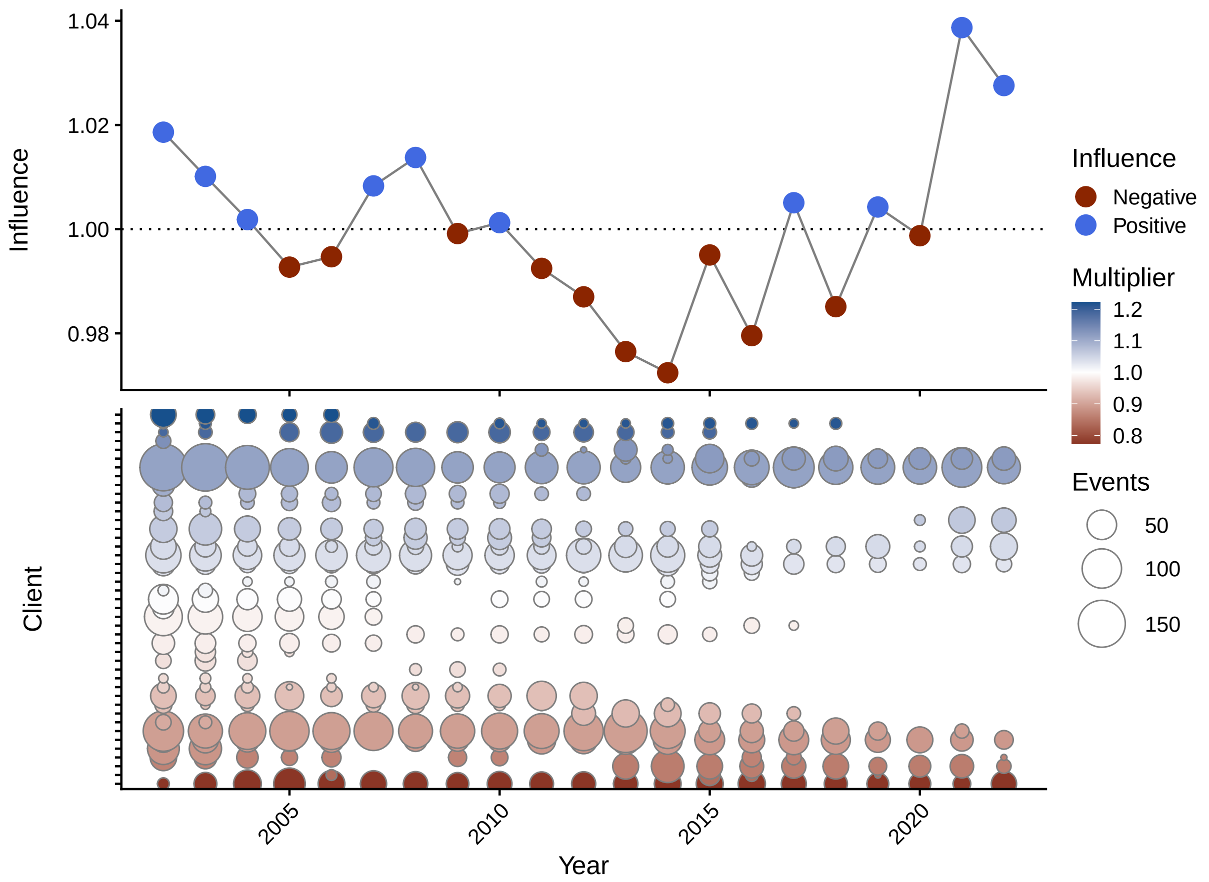

Figure 11: Influence plots for client number (FIN) effect, showing the effect on raw catch-per-unit-effort (CPUE; top graph) of applying estimated effect sizes (bottom graph) from the factor levels encountered each fishing year. A positive (>1) influence for a given time period means that the unstandardised index was increased due to the relative distribution of the covariate.

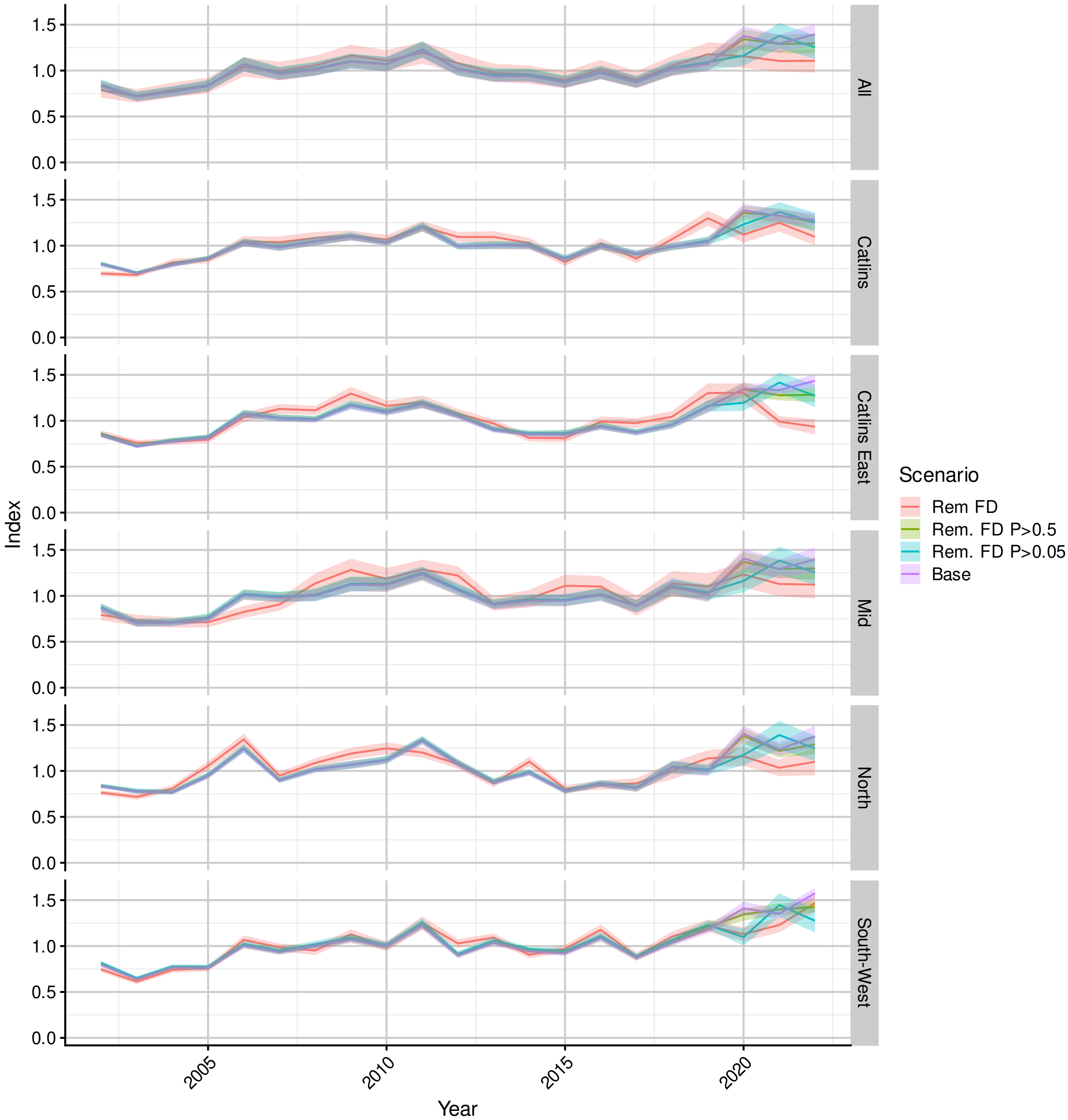

Figure 12: Standardised CPUE indices with 95% confidence intervals (solid line and ribbon) for the combined PCELR and ERS time-series. Base uses all available CPUE data (after grooming procedures were applied), REM FD removed fishing duration from the analysis, and REM FD P>0.5 and P>0.05 removed clients unless reporting was as likely as not (0.5) and highly likely (0.05) to have remained the same.

2.1.4 Commercial catch sampling length-frequency (CSLF) data

Length-composition data have been regularly sampled at factories in PAU 5D since early 2000s; however, until recently, the spatio-temporal representativeness of the sampling has been relatively poor (Figure 13). As a result, a model-based approach for length compositions for pāua stocks was originally developed for this area to account for this lack of representative sampling.

The present modelling used a standardisation model for composition data. The model is similar to the model developed by Neubauer (2020), and used in previous assessments, but it included a marked improvement in that it fits to measured numbers-at-length rather than proportions. The procedure adjusts the length-frequency samples based on spatial and temporal variability. This adjustment is similar to adjustments in CPUE applied during the standardisation of CPUE, and adjusts the estimated length-frequency of removals. This procedure has the advantage that reasonably smooth length-frequency distributions (i.e., filtering out variance from highly multi-modal length-frequency distributions that result from low sample numbers) for sparsely sampled strata can be extracted, even if individual samples in those strata are unlikely to provide a reliable estimate of the length frequencies. Random effects formulations ensure the sharing of information across strata.

The updated formulation was an extension of the multinomial GLM, which was developed for estimating length frequencies of rock lobster removals (D. Webber, unpublished analysis). The extension here was achieved by factorising the multinomial distribution into independent Poisson distributions for total measurements (N_s) in sample s, and a second Poisson distribution with mean $\lambda_{i,s}$ over draws $n_{i,s}$ for the number of pāua in length category i in sample s. Length proportions π can then be recovered by setting $\pi_i = \lambda_i / \sum_j(\lambda_j)$. This setting allows the formulation as a straightforward Poisson GLM, using the total counts as an offset term. This model can be implemented in *brms* and efficiently run via:

```
bf(n_i,s ~ (1|Lcat:Area:Year/site_code) +
        (1|Lcat:Area/site_code) +
        (1|Lcat) +
        offset(log(N_s))).
```

The length-composition standardisation model converged well (Figure 14) and provided a good fit to the data (Figure 15). Estimates for standard deviation parameters suggested that annual differences in the composition of removed pāua were seen at regional and statistical-area scales (Figure 16), while static differences between statistical areas within regions were larger than differences between regions. Standardised length compositions often reflected samples, but uncertainty captured the lack of representativeness of sampling in some years (e.g., 2006–07 in the Catlins; Figure 17).

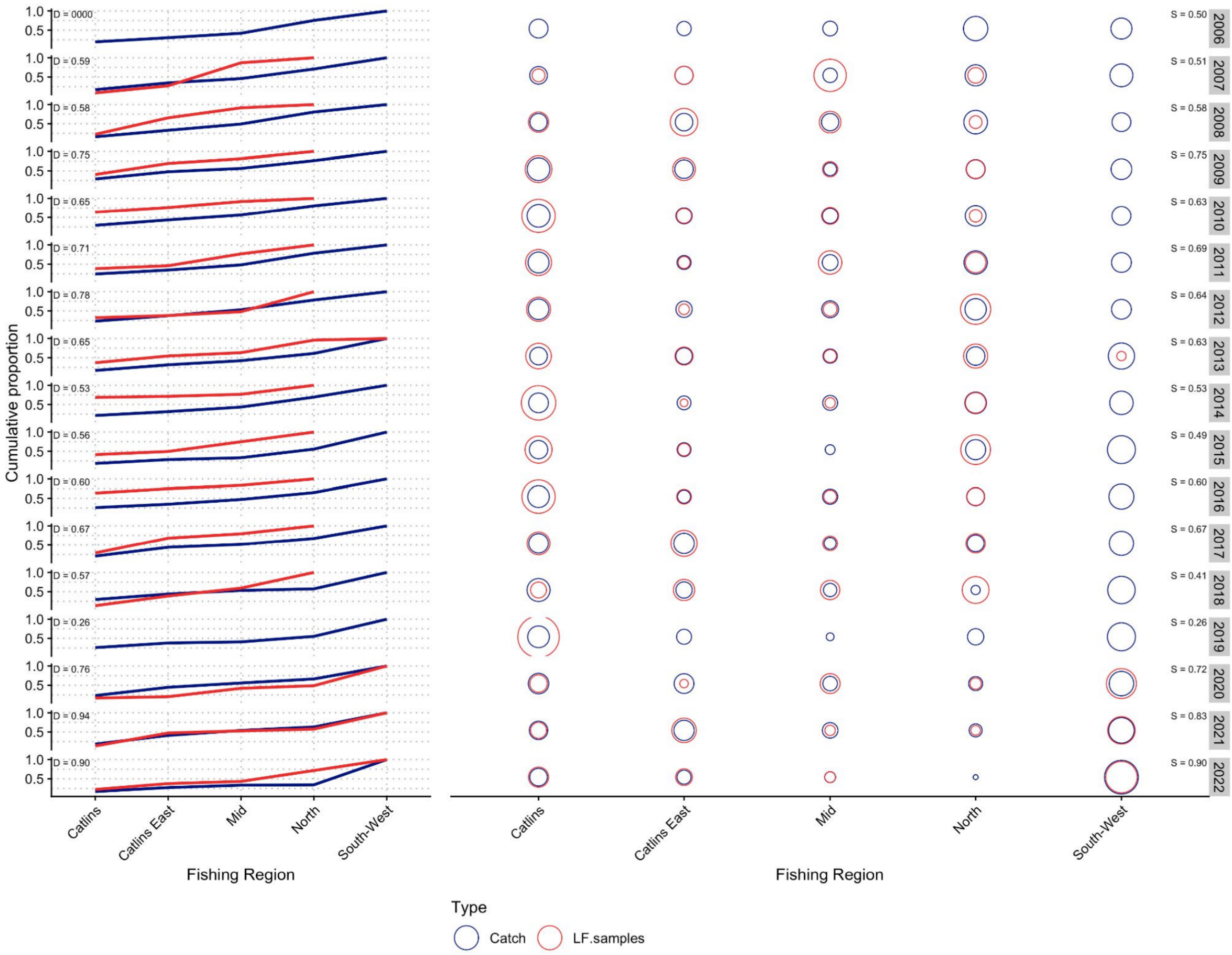

Figure 13: Representativeness of catch sampling by year, area, and overall. The left panel compares cumulative proportions (kg of pāua) of catch and from sampling by year and area, whereas circles on the right panel show the alignment between catch and sampling in each sub-area and year. The Manhattan distance (S) and Kolmogorov distance (D) are two measures of compositional discrepancy, with a value of 1 indicating perfect alignment, and lower values suggesting less representativeness.

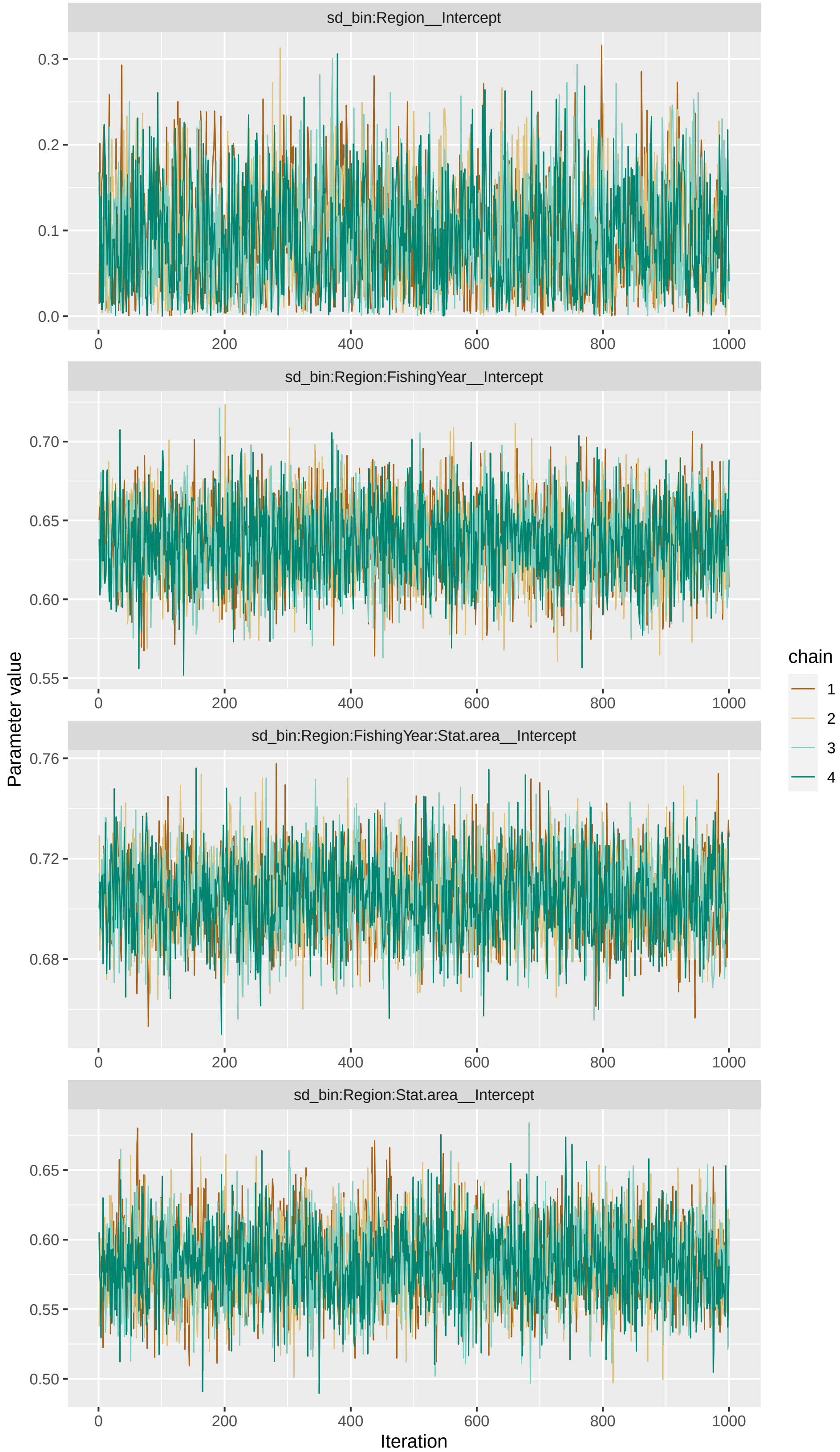

Figure 14: Length-composition standardisation model Markov Chain Monte Carlo trace-plots for key parameters.

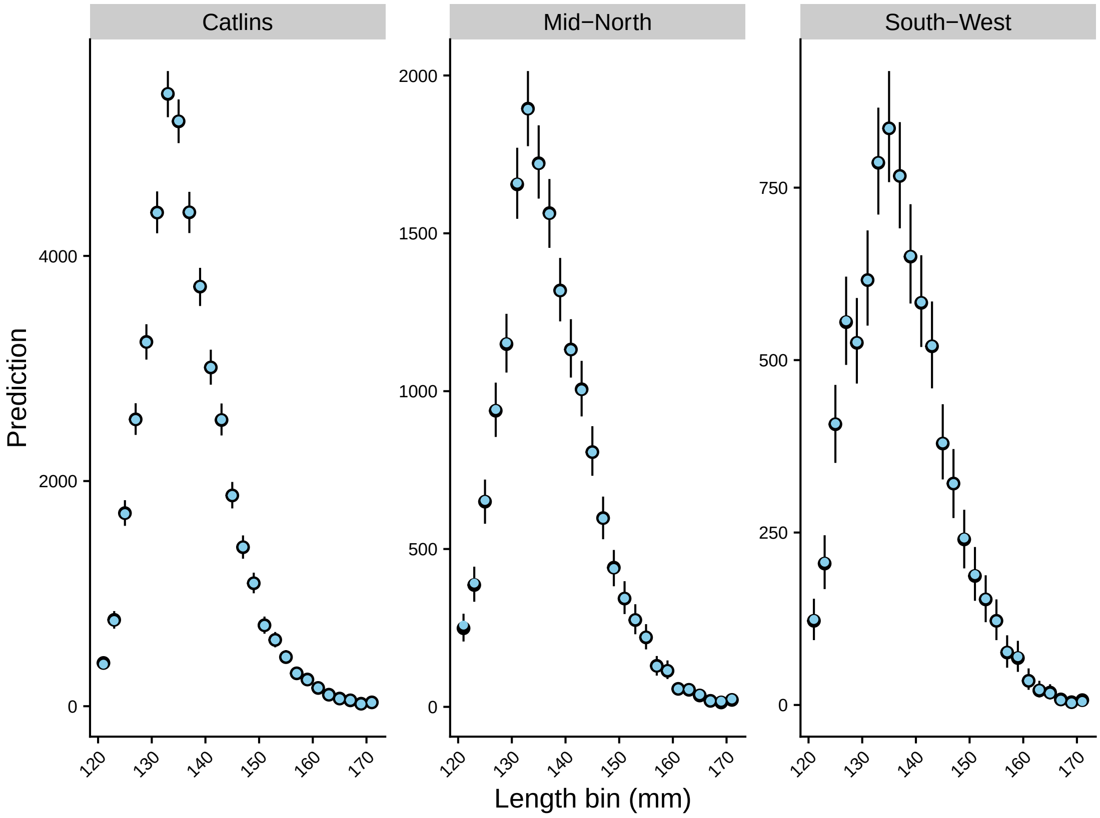

Figure 15: Length-composition standardisation model fit (black posterior median and 95% prediction interval) to the observed numbers in each model length bin, by region.

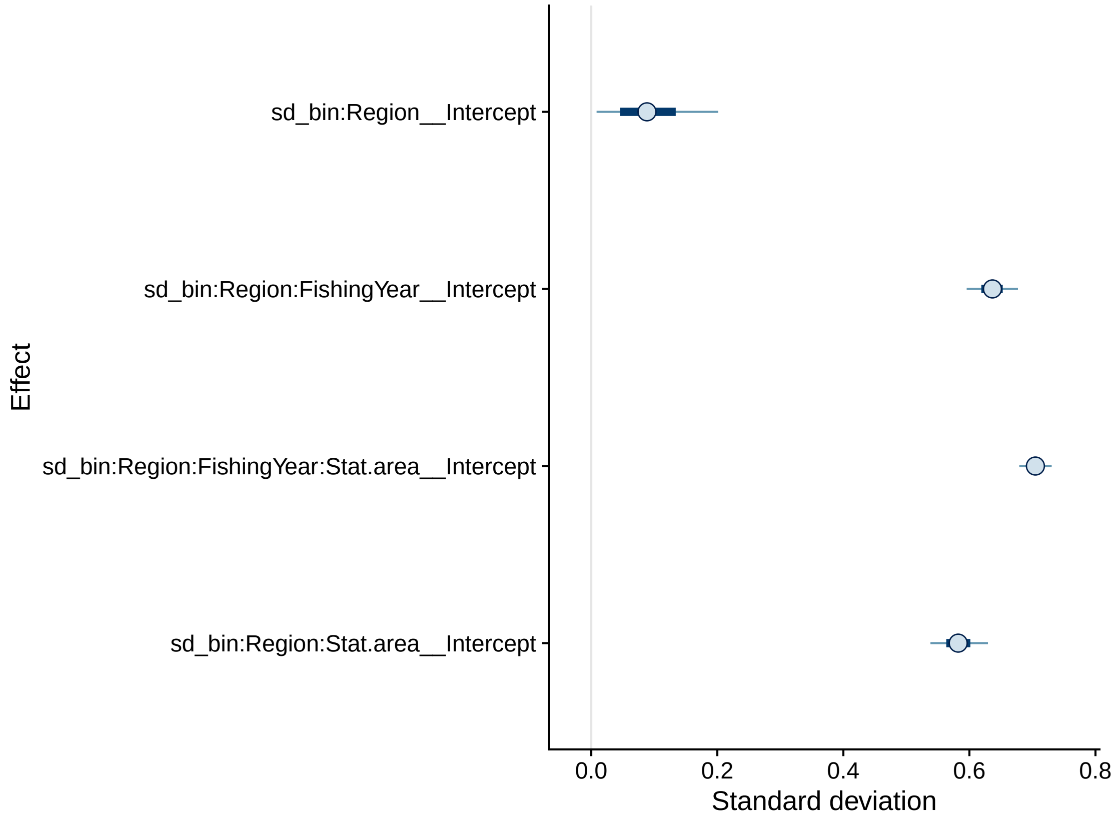

Figure 16: Length-composition standardisation model estimates (posterior median and 95% confidence interval) for standard deviation parameters associated with standardising effects.

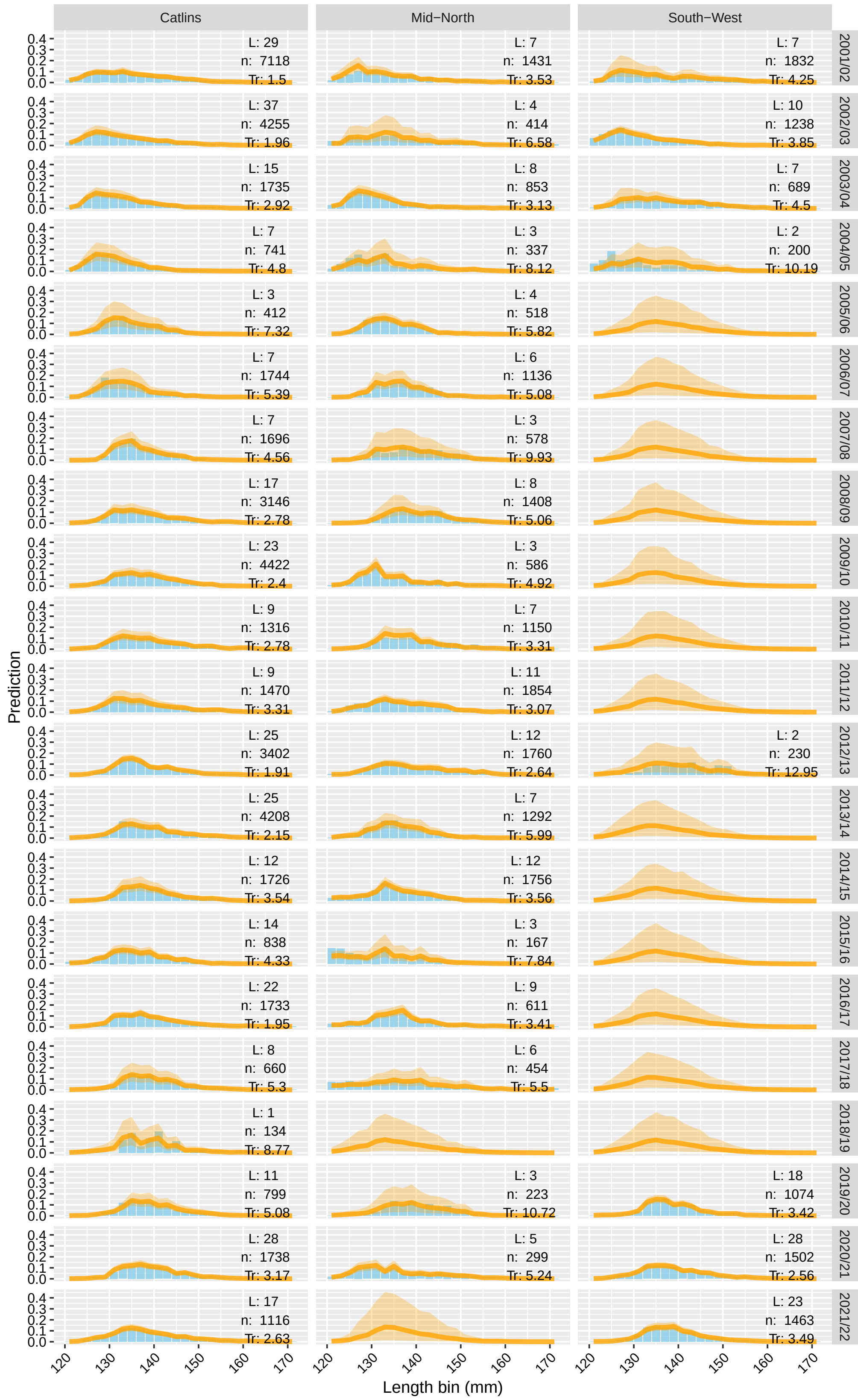

Figure 17: Sampled length compositions (blue histogram) and catch-scaled standardisation model estimates (orange posterior median and 95% confidence interval) by area and year. L: number of landings; n: number of pāua sampled, tr: trace of the covariance matrix for estimated compositions (i.e., sum of standard deviations).

2.1.5 Growth and maturation

Following previous assessments since 2018, data from individual growth tagging sites in PAU 5D were not fitted. Previous assessments used relatively arbitrary fixed assumptions about growth based on growth in other QMAs.

Recent developments in pāua growth models suggest that flexible growth models based on energy balance equations (e.g., Ohnishi et al. 2012) can describe observed growth and maturation differences across pāua QMAs (Neubauer & Tremblay-Boyer 2019a).

Similar to other recent stock assessments, an informed prior was used for the present models, which was derived from a meta-analysis of pāua growth. It allowed the model to adjust growth in accordance with other sources of information (priors on mortality M, CSLF, and CPUE input)(see priors for mean growth and growth standard deviation in Figure 18). At each length l, a proportion $z(l)$ of the population grows according to a log-normal growth prior, and a proportion $(1-z(l))$ of pāua is located in areas with no growth at length l (i.e., stunted growth at length l; Figures 18 and 19). Maturation was estimated simultaneously with growth in the meta-analysis, but was not found to be linked to growth in the meta-analysis based on available data (Figure 20).

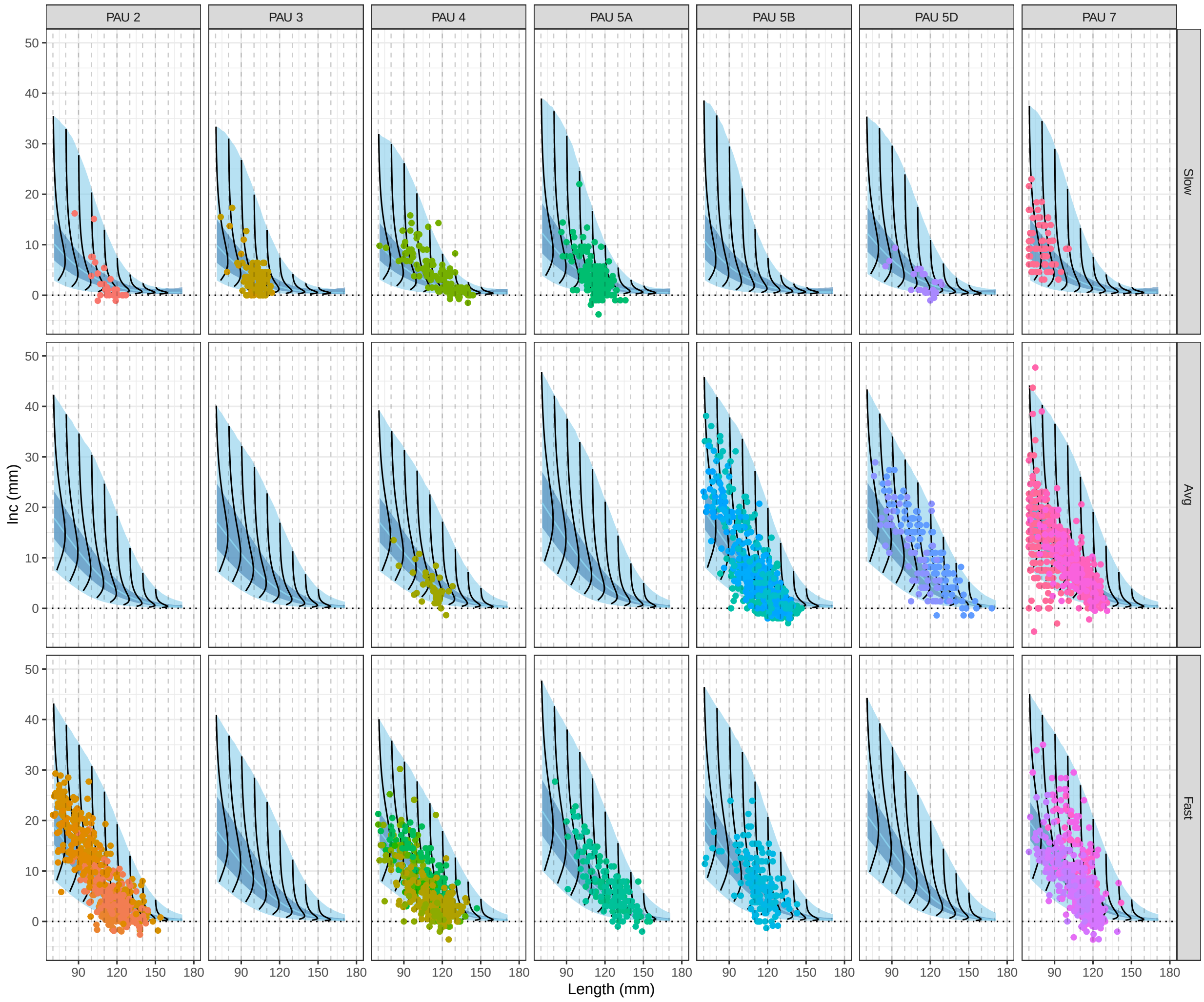

Figure 18: Priors derived from a meta-analysis of growth and maturity of pāua, based on model-fitting to all tag-increment and maturity data across quota management areas (QMAs). Shown is the joint prior for positive growth increments at size l by QMA and growth stratum. Dark blue shading shows uncertainty about mean growth; light blue line indicates posterior median for mean growth; light blue area shows the posterior median for the population standard deviation applied to mean growth; black lines indicate the implied distribution of growth at the median of the prior.

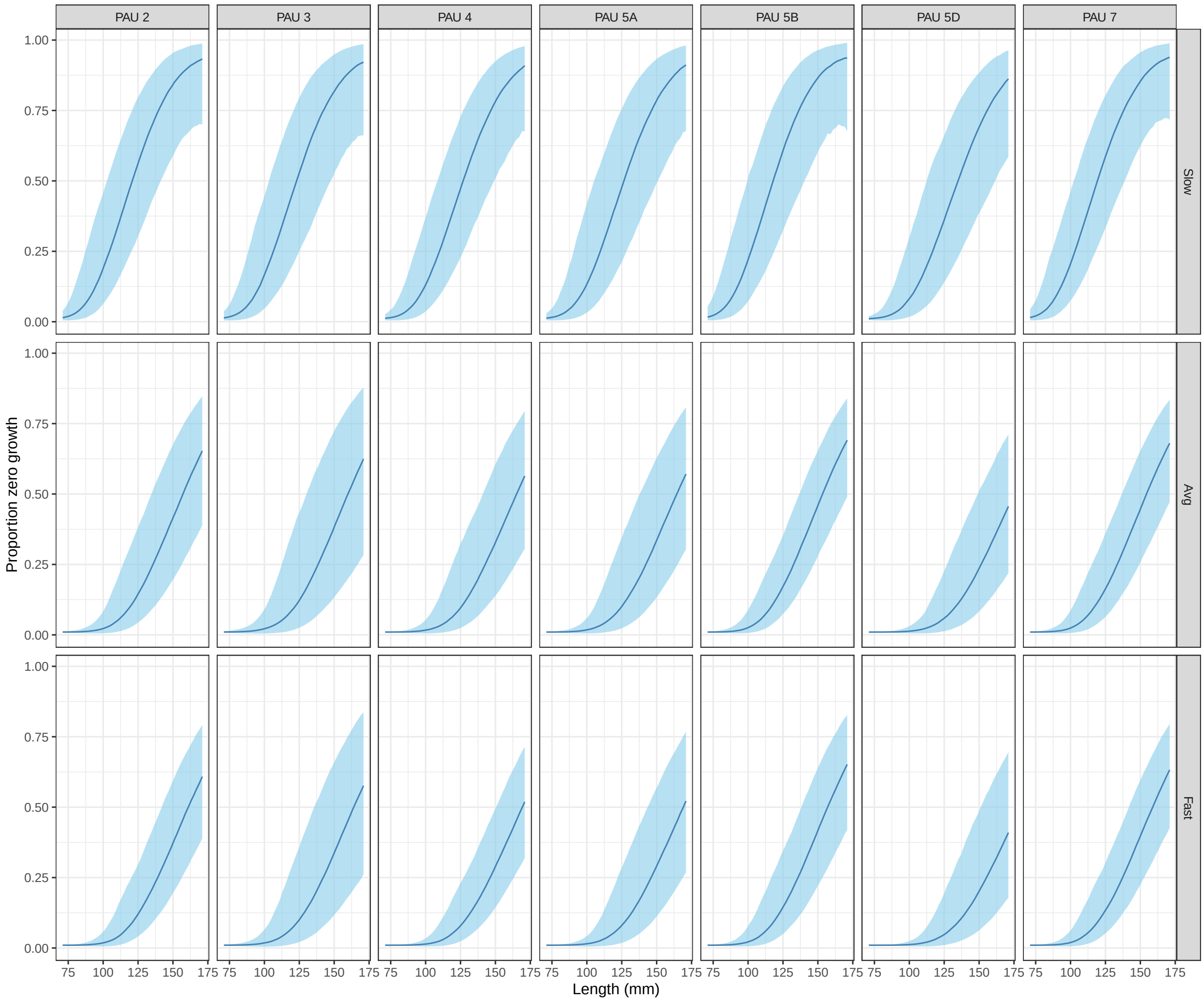

Figure 19: Priors derived from a meta-analysis of growth and maturity of pāua, based on model-fitting to all tag-increment and maturity data across quota management areas (QMAs). Shown is the expected proportion of local populations not growing at size l by QMA and growth stratum.

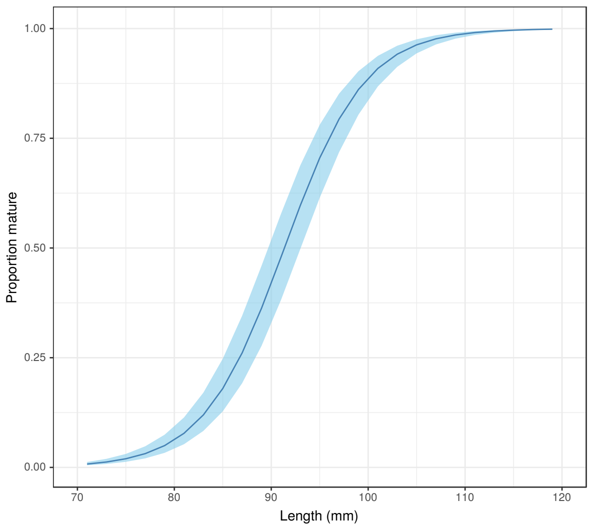

Figure 20: Priors derived from a meta-analysis of growth and maturity of pāua, based on model-fitting to all tag-increment and maturity data across quota management areas. Shown is the population level maturity.

2.2 Assessment model

2.2.1 Model specification

The main pāua population dynamics are described by Breen et al. (2003), but some changes were recently implemented following recommendations by an international expert review panel for the stock assessment (Butterworth et al. 2015). Detailed equations for the most recent version of the population dynamics model are described by Neubauer & Tremblay-Boyer (2019b).

2.2.2 Prior distributions

The CPUE process error was estimated in the model using a half-normal prior distribution (N^0), with prior standard deviation $\tau_{PE_{CPUE}}$:

$$\mathrm{PE_{CPUE}} \sim \mathrm{N}^0(\tau_{\mathrm{PE_{CPUE}}}).$$

Similarly, the CSLF process error was estimated in the model using a half-normal prior distribution, with prior standard deviation $\tau_{\mathrm{PE_{CSLF}}}$.

Recruitment deviations (R_{dev}), equilibrium recruitment (R_0), natural mortality (M, when estimated), catchability ($\log(q)$), length at 50% selectivity (D_{50}), and 95% selectivity offset (D_{95}) were assigned log-normal priors, parameterised in terms of mean and standard deviation (sd; on the log-scale), with the sample mean for R_{dev} forced to one.

Steepness h was estimated in this iteration of the assessment model and was assigned a beta distribution prior with parameters a and b, with $a = 1$ and $b = 1$ the default prior (see Table 4 for other default priors).

The initial data weighting started with a set of weights that provided reasonable fits for both CPUE and CSLF data in the spatial stock assessment model for pāua and the stock assessment for PAU 5D (Neubauer & Tremblay-Boyer 2019b, Neubauer 2020). These weights were then varied to assess the effect of weighting of CSLF and CPUE data on model outcomes.

2.2.3 Technical model details

The model was initialised using equilibrium conditions calculated from the theoretical numbers-at-length in the absence of fishing. All Markov chain Monte Carlo algorithms (MCMCs) were run using the no-u-turn-sampler (NUTS) implemented in Stan (Stan Development Team 2018). The Stan language is more efficient

Table 4: Default priors used in the pāua stock assessment model (LN=Lognormal, N^0=half-normal), with prior mean and standard deviation (SD) shown on the log-scale (log) and on the positive scale (pos; CPUE, catch-per-unit-effort; CSLF, catch sampling length frequency).

Parameter	Symbol	Prior	Mean (log)	SD (log)	Mean (pos)	SD (pos)
Equilibrium recruitment	R_0	LN	13	10	fixed: 1	1.19×10^{49}
Recruitment deviations	R_{dev}	LN	0	0.4	1.08	0.45
Natural mortality	M	LN	log(0.1)	0.2	0.12	0.02
Length at 50% selectivity	D_{50}	LN	log(125)	0.05	123.15	6.16
95% selectivity offset	D_{95}	LN	log(5)	0.5	5.67	3.02
CPUE process error	$\mathrm{PE_{CPUE}}$	$\mathrm{N}^0(0.05)$		0.04	0.03	
CSLF process error	$\mathrm{PE_{CSLF}}$	$\mathrm{N}^0(1)$		0.80	0.6	

than conventional Metropolis Hastings or Gibbs sampling for MCMC, and also provides diagnostics that can signal biased MCMC transitions (divergences) and potential bias in estimated quantities from these transitions. All MCMC chains were, therefore, monitored for divergent transitions to ensure that MCMCs were not biased. Initial models were run with four independent chains for the MCMC, and 500 iterations were kept after discarding the initial 500 iterations. For the simulations and sensitivities, 500 samples were drawn from the conditioned model.

2.3 Stock assessment runs

2.3.1 Step-wise model updates

To illustrate updates to the previous model for PAU 5D, we started with comparable datasets, with an updated model version that was previously used for the 2022 stock assessment in PAU 7 (Neubauer 2023b). The model was set up according to the 2018 stock assessment (including CELR data), and was updated with new data, before subsequent changes were introduced. The resulting suite of models was a follows:

1. Model version PAU 7 2022.
2. Update data to 2019.
3. Update data to 2020.
4. Update data to 2021.
5. Update data to 2022.
6. Omit CELR data: CPUE data between 1990 and 2001 were not fitted to in this model.
7. No estimated recruitment prior to observing composition data: this change was introduced in 2019 and was, therefore, added to the present list.
8. Time-varying selectivity: this feature was first trialled in PAU 5A in 2019, and estimates the $L50$ parameter of logistic selectivity as a random effect that can vary by year; it has a mean given by the prevalent minimum harvest size (MHS). The MHS was here taken to be 125 mm shell length for years prior to 2013, and 130 mm shell length since 2013, according to MHSs detailed in fishery annual operating plans. Time-varying selectivity acknowledges that not all areas are fished every year, and that the relative harvest from areas of varying MHS can lead to different realised selectivity curves across years.
9. CPUE weight was reduced relative to weights used in the 2018 assessment, since, in combination with time-varying selectivity, the model over-fitted CPUE, leading to spurious patterns in selectivity.

2.3.2 2023 base-case model

The 2023 base case estimated natural mortality (M) from a prior based on estimates from PAU 5B and PAU 7 (see Neubauer 2019), unfished recruitment (using a vague prior), and time-varying selectivity. Although spatial models across three regions (South-west, Catlins, and Mid-north) were initially trialled alongside single-area models, length-composition data from the South-west area were too sparse and led to unstable models. For this reason, only single-area models were retained for further analysis. Recruitment deviates were estimated between 1996 (five years prior to length-composition data becoming available) and 2017. All other recruitment deviations were set to 1, and recent (post-2017) deviates were re-sampled from the last 10 years of estimated recruitment deviates for projections.

The model fitted to length compositions estimated from the Poisson-factorised multinomial model, and joint PCELR/ERS time series of CPUE.

2.3.3 Key sensitivities for the 2023 model

A series of sensitivities were trialled to examine the robustness of the assessment model to key assumptions about productivity and data inputs:

1. Fixed natural mortality at 0.10 and 0.16 to examine stock dynamics at the lower and upper bounds of the posterior distribution for natural mortality.
2. Model without time-varying selectivity.
3. Hyper-stability in CPUE, using a curvature parameter (power of CPUE) of 0.75.
4. CPUE without fishing duration, to examine the possibility of biased CPUE from ERS data, and the potential for a smaller recent increase in CPUE.

2.4 Management procedure evaluation: Updating the existing control rule

Management procedures from 2016 (Figure 21) were updated using two new meta-rules:

1. Lag-year on increases: catch can only be increased if two successive increases are observed. The same is not true for declines, the latter trigger immediate reductions in catch if the rule suggests as much.
2. A maximum of 5% on increases.

Management procedures were tested against the base-case model and sensitivities. In addition to projecting with the most recent 10 years of estimated recruitments, an alternative scenario was chosen that re-sampled from the last 15 years of estimated recruitments. This choice provided a scenario with slightly lower average recruitment than the base case with resampling from the last 10 years. Updates to the previously-employed harvest control rule were introduced in a step-wise manner to visualise the impact of individual changes for risk, future biomass, and expected catch under each option.

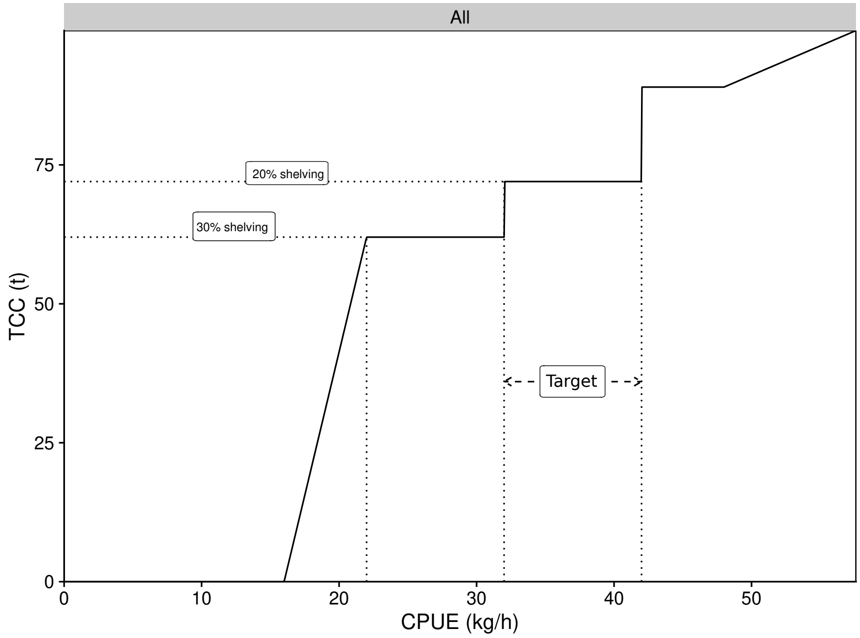

Figure 21: Harvest control rule for pāua quota management area PAU 5D as employed since 2016. CPUE, catch-per-unit-effort; TCC, Total Commercial Catch. (Note that additional settings introduced in 2023 are "meta-rules", which alter the timing and magnitude of increases depending on a previous year's value and cannot, therefore, be graphed.)

3. RESULTS

3.1 Stock assessment runs

3.1.1 Step-wise model updates

A key decision in the present assessment was to omit CELR CPUE data, in line with recent stock assessments. The CELR CPUE was flat, and although the assessment model was able to fit the data (Figure 22), it led to higher estimated natural mortality (M ca. 0.15; Figure 23) and slower estimated growth (Figure 24) than for models without the corresponding dataset. These estimates were not altered by the addition of new data, and led to lower estimated unfished biomass (Figure 25) and higher stock status (Figure 26) as less of the unfished population was available to the fishery (Figure 27).

When CELR was omitted, the stock trajectory for relative spawning stock biomass was markedly lower (Figure 26), with all scenarios at or close to the soft limit in the early 2000s, and again around 2015–16. The assumption of time-varying selectivity led to a slightly higher estimated stock status, while omitting the CPUE weight relative to the 2018 stock assessment led to slightly lower status.

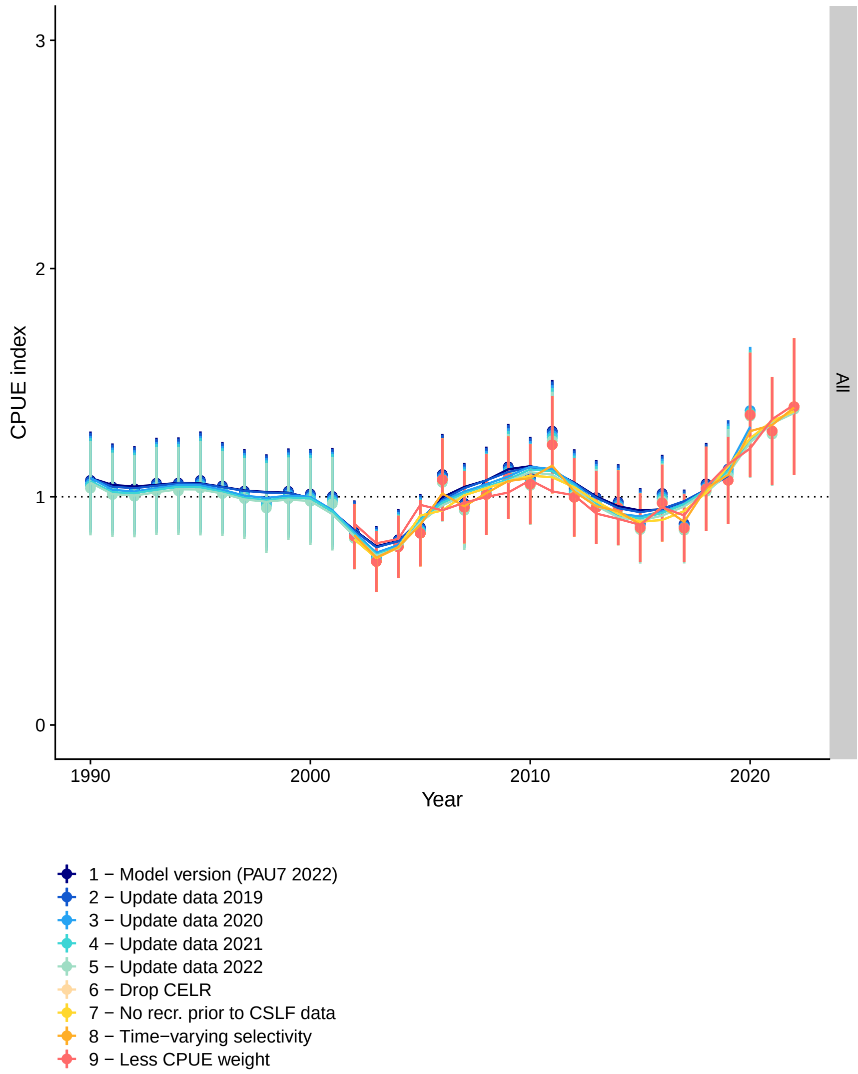

Figure 22: Comparison of posterior median predicted catch-per-unit-effort (CPUE) in stepwise updates of assessment assumptions from previous assumptions used for the 2018 stock assessment to the set-up assumptions used for quota management area PAU 5D.

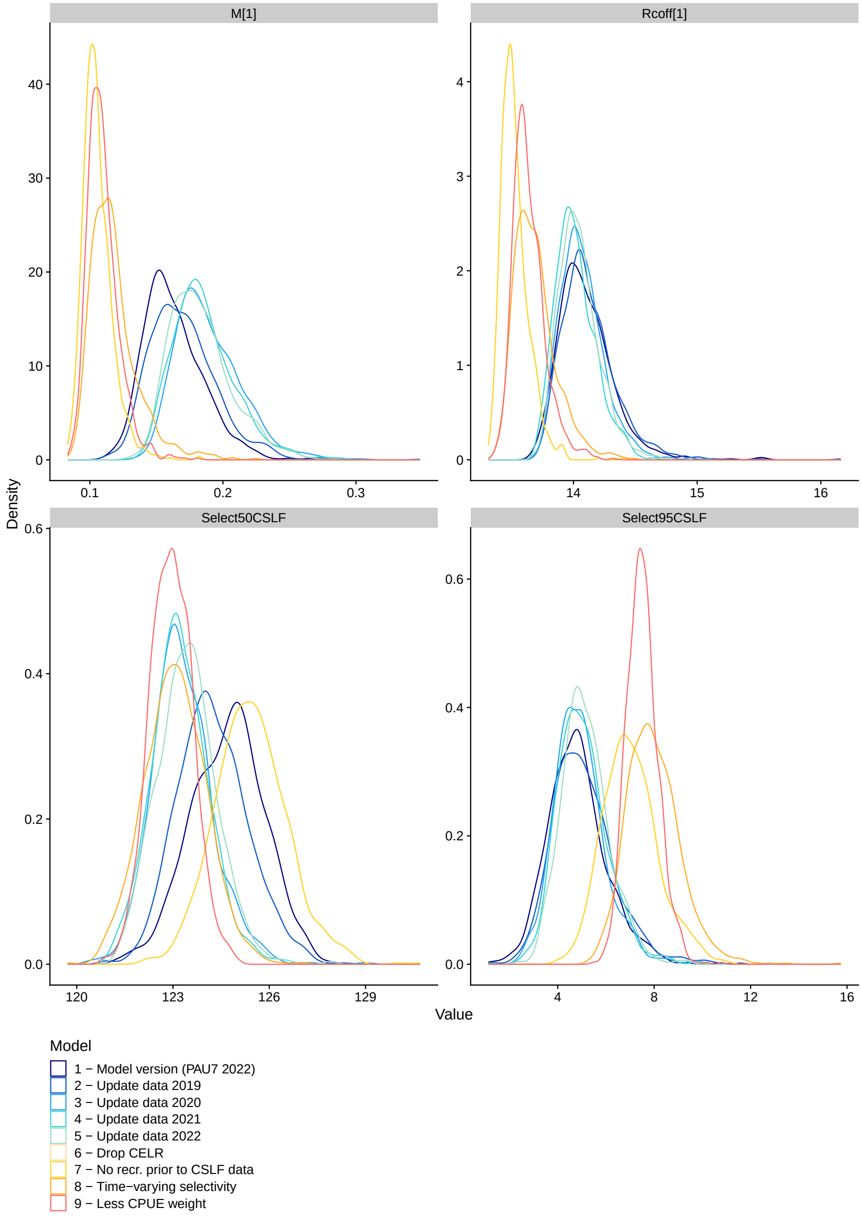

Figure 23: Comparison of posterior densities for parameters in stepwise updates of assessment assumptions from previous assumptions used for the 2018 stock assessment to the set-up assumptions used for quota management area PAU 5D.

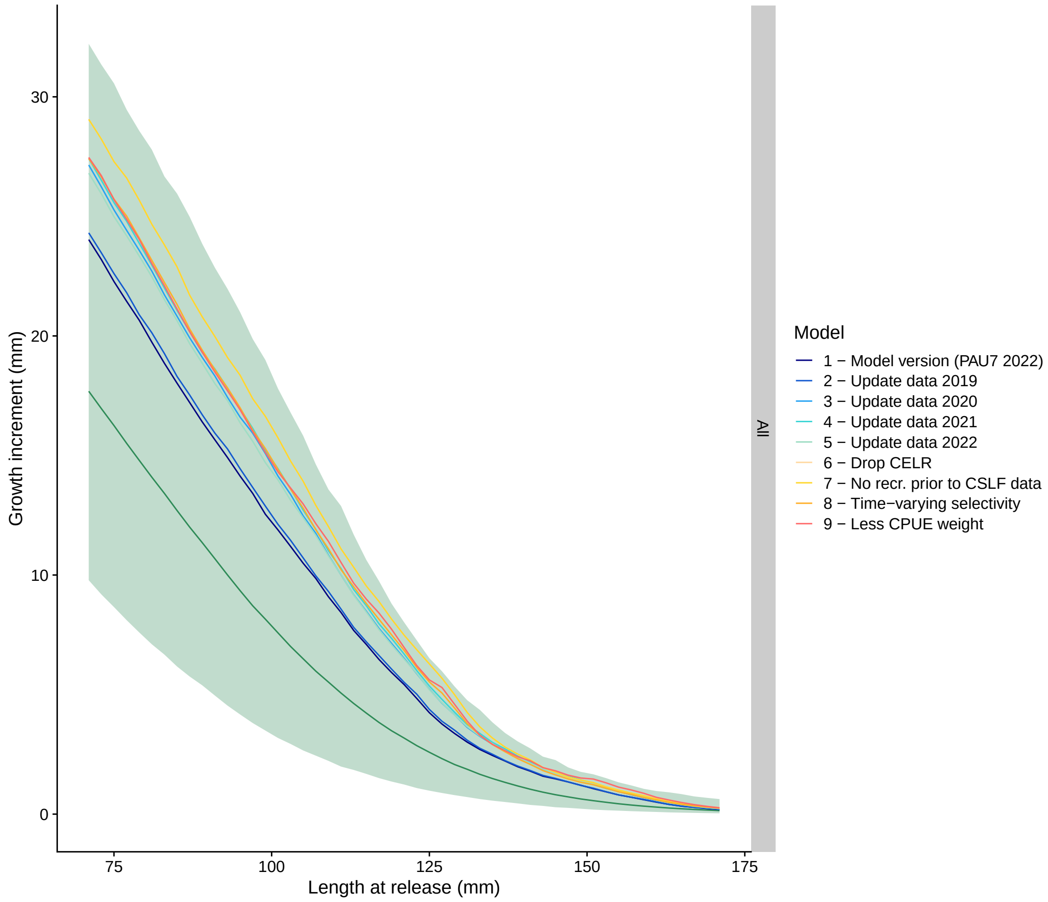

Figure 24: Comparison of prior and posterior growth in stepwise updates of assessment assumptions from previous assumptions used for the 2018 stock assessment to the set-up assumptions used for quota management area PAU 5D. Prior for population mean growth (prior mean, green line; 95% prior interval, green shading), and posterior mean growth (light blue, posterior median and 95% posterior interval).

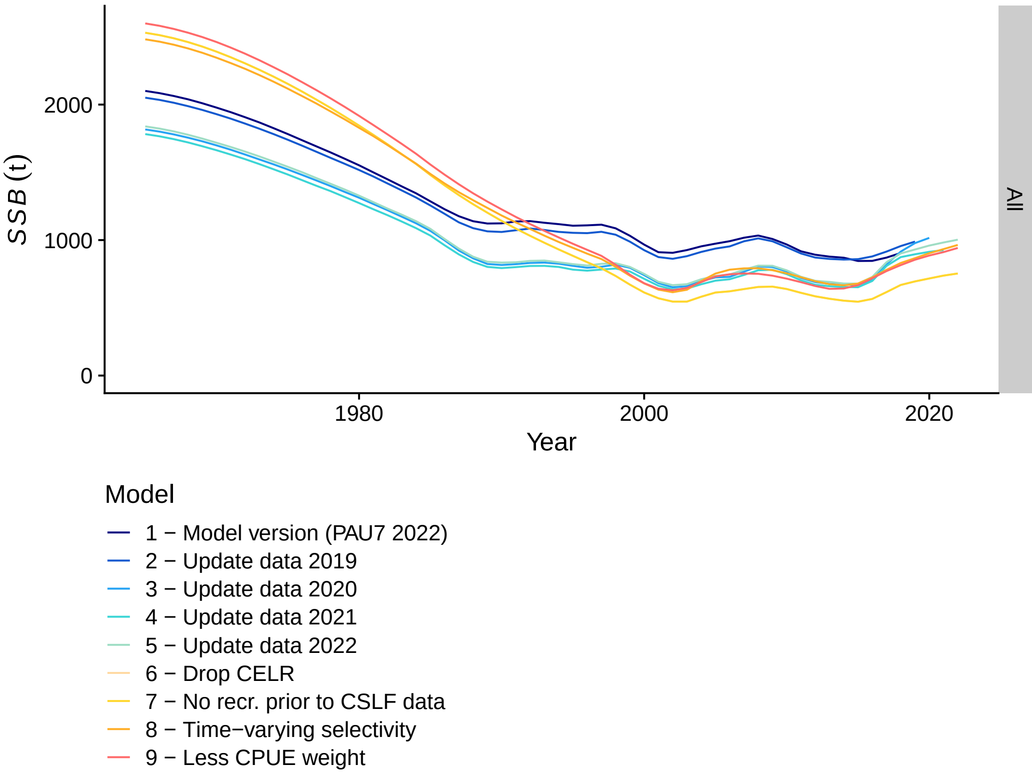

Figure 25: Comparison of posterior median predicted spawning stock biomass (SSB) trend in stepwise updates of assessment assumptions from previous assumptions used for the 2018 stock assessment to the set-up assumptions used for quota management area PAU 5D.

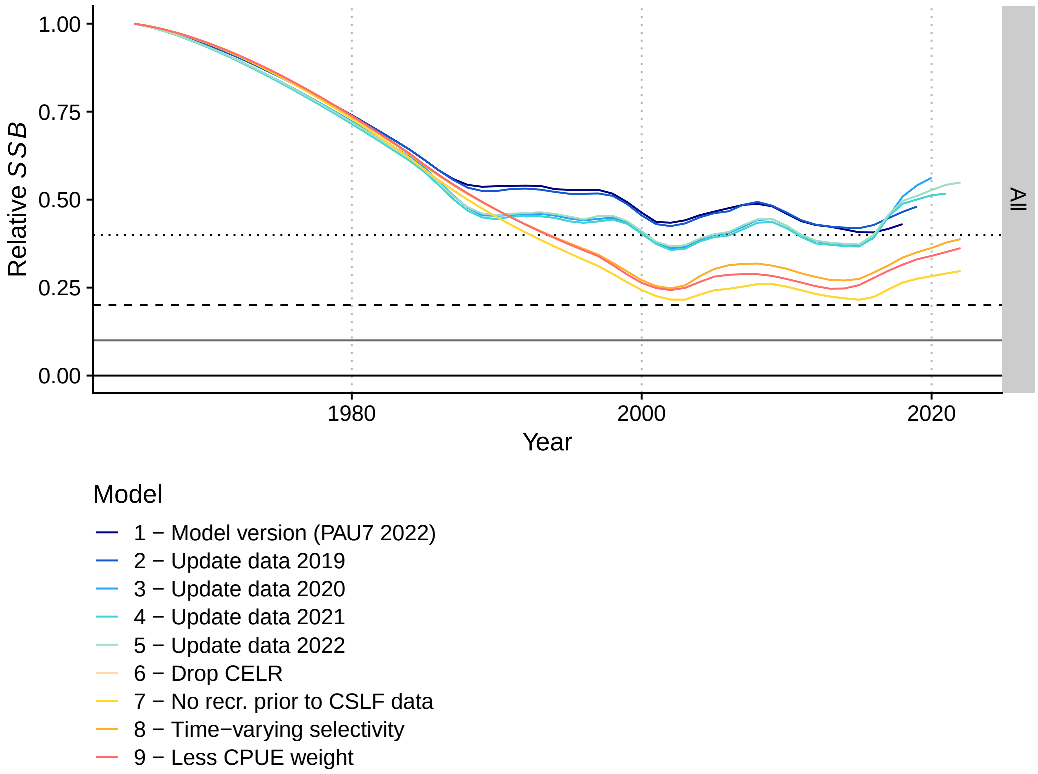

Figure 26: Comparison of posterior median predicted relative spawning stock biomass (SSB) trend in stepwise updates of assessment assumptions from previous assumptions used for the 2018 stock assessment to the set-up assumptions used for quota management area PAU 5D.

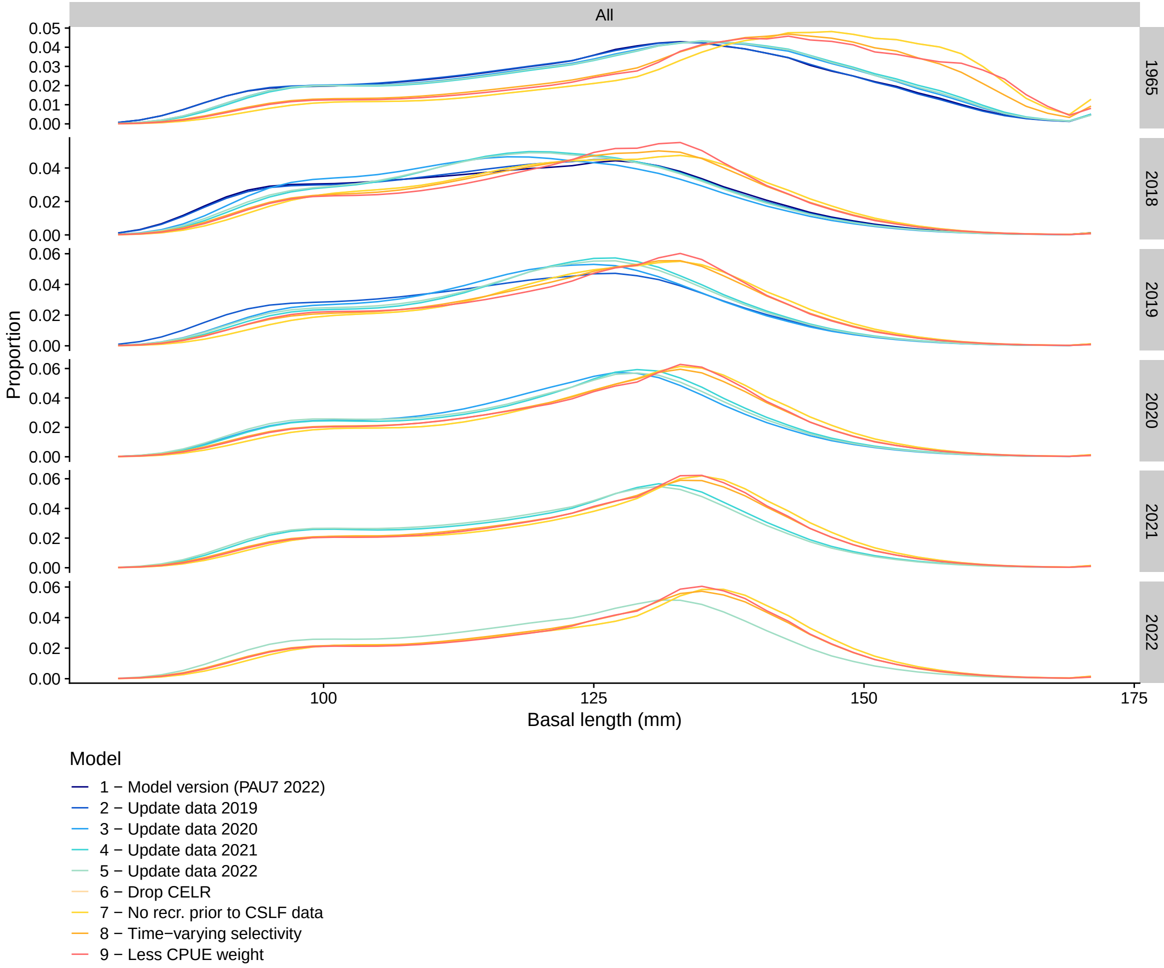

Figure 27: Comparison of posterior mean proportions-at-length for the unfished population (1965) and recent years in stepwise updates of assessment assumptions from previous assumptions used for the 2018 stock assessment to the set-up assumptions used for quota management area PAU 5D.

3.1.2 2023 base-case model

The base-case model (Appendix A, Figures A-1 to A-14) showed a good fit to both CPUE (Figures A-3 and A-4) and LF data (Figure A-5). Selectivity was estimated to be split into two broad periods before 2013, when the MHS was raised, and post 2013 (Figure A-7). The period post 2013 was marked by greater variability in annual selectivity, with a size at 50% vulnerability near 130 mm shell length in recent years.

The model used only minor fluctuations in recruitment to explain biomass trends ((Figure A-9). Biomass was estimated to have declined markedly from the beginning of the fishery in the 1960s to the early 2000s (Figure A-10), when it was estimated to have been near the soft limit. Catch reductions and associated reduced exploitation rates (Figure A-13) at that time led to a temporary rebuild, which was followed by a furthe r recruitment-driven decline until 2015 to biomass levels in the early 2000s. Shelving and implementation of management procedures led to further reductions in the exploitation rate, and a subsequent rebuild since 2016, to levels near the interim target, with the stock being about as likely as not to be at (interim) target levels.

3.1.3 Key sensitivities for the 2023 model

Only the model with high fixed natural mortality led to substantially different estimates of stock size and status (Appendix B; Figures B-1 to B-10). Models with CPUE without fishing duration had lower recent CPUE (Figure B-2), but did not lead to markedly different estimates of recent status (Figure B-10). Similarly, assuming hyper-stability in CPUE did not affect estimates in ways made the conclusions of the base model dubious. Models without time-varying selectivity, and low fixed M led to slightly lower stock status, but were considered less likely to reflect the fishery (for selectivity) and uncertainties (for M) than the base model.

3.2 Management procedure evaluation: Updated control rule

The two main changes introduced for the updated control rule (a lag year on increases, and maximum five percent annual increases) led to only minor differences from the previously active rule (Appendix C, Figures C-1 to C-5). Notably, the slower increase in catch (Figure C-4) for the new rule led to a slightly higher short-term re-build and CPUE (Figure C-3). Over a longer period, the updated rule led to a slight reduction in risk, at the expense of a long-term reduction of approximately 6 t of catch (Table C-1), and higher long-term CPUE.

None of the tested rules appeared to run up against risk thresholds in the short or long term, although uncertainty about the long-term recruitment patterns resulted in notably higher risk towards the end of the 20 year projection horizon (Appendix D, Figures D-1–D-5). The realised catch and CPUE under the updated control rule suggested a long-term catch close to, but largely below, the TACC of 89 t (Figure 28). Due to the asymmetric nature of the rule, the simulations were often associated with the second plateau, because any small increases were followed by subsequent reductions back to the corresponding point on the control rule.

Only the most unproductive models (fixed M at 0.1) increased the long-term risk above thresholds (Appendix E, Figures E-1 to E-5). In contrast, short-term risks remained low, despite models leading to markedly different long-term predictions in biomass status. Regardless of the relative level of biomass, the control rules largely maintained biomass at these levels (on average; Figure E-1), at stable exploitation rates (Figure E-5), with lower long-term catch (Table E-1).

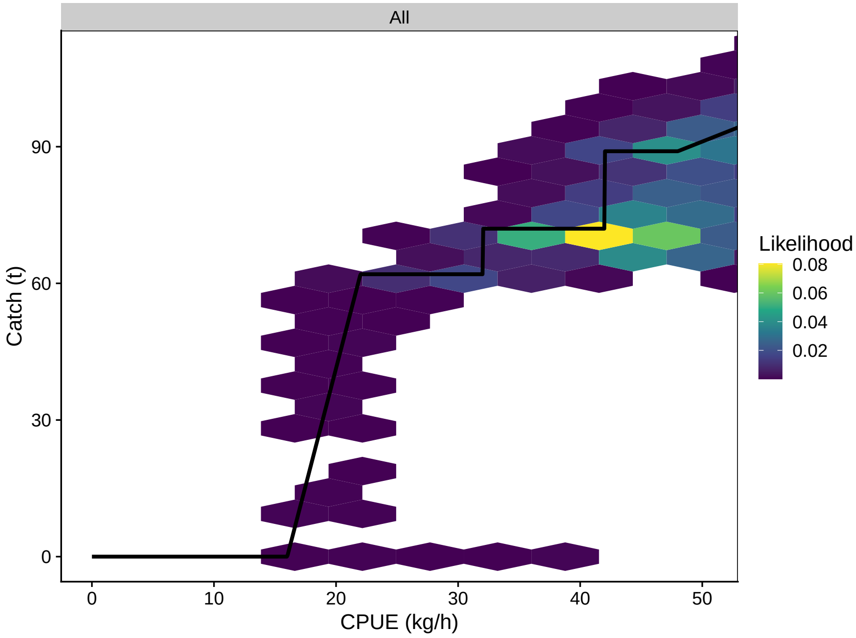

Figure 28: Realisations from the management procedure evaluation shown as binned densities for combinations of catch and catch-per-unit-effort (CPUE). Due to the "meta-rules" introducing a lag in increases and a maximum rate of increase, the realisations mostly fell to the right of the rule itself, which in turn only determined decreases in catch.

4. DISCUSSION

The present assessment presented a shift for PAU 5D, with a notably lower estimate of stock status over the recent exploitation history than was produced by the previous assessment (Neubauer & Tremblay-Boyer 2019c). This change was demonstrably due to the omission of CELR CPUE from the model. The resulting model aligned more closely with diver observations around 2016, when harvest control rules were first established in the QMA. At the time, increased shelving was brought about by the application of the control rules, with an aim to rebuild the fishery from a perceived low point. The previous assessment did not reflect this observation, whereas the present assessment closely corresponded with diver observations.

The CELR CPUE suggested a relatively stable biomass for a relatively long period (until the late 1990s), leading the model to estimate that a larger proportion of the fishery was inaccessible to fishing. Although the latter may be the case, in other QMAs CELR CPUE has been questioned and omitted from stock assessments (e.g., Neubauer 2022) as it is likely hyper-stable during a period of significant technological progress in the fishery. In addition, its non-alignment with present data fishery strata makes it difficult to use in areas that were subdivided from larger QMAs, and which are split over multiple CELR statistical areas, such as the QMAs PAU 5 and PAU 3 .

Recent CPUE has increased markedly since the 35% shelving was put place in 2016, suggesting that the fishery has responded well to the reduction in catch. Nevertheless, some doubts remain about the value of recent CPUE. Since the introduction of ERS, fishing duration values reported from all PAU 5 areas have decreased considerably, leading to potential positive bias in CPUE. Nevertheless, CPUE without fishing duration largely corresponded with standard CPUE up to recent years, and models run with the alternative CPUE did not alter the model-estimated recent rebuild. Furthermore, the rebuild was already evident in the last years of PCELR-recorded catch and effort, suggesting that the fishery had rebounded from a low level in about 2015–16.

Another change that was introduced for the present assessment was time-varying selectivity. The formulation of time-varying selectivity acknowledges that not all areas are fished every year, and that the relative harvest from areas of varying MHS can lead to different realised selectivity curves across years. As expected, the period post 2013 was marked by greater variability in annual selectivity given the variability in MHS in space and time, coupled with variable spatial harvest patterns year-on-year. The outcome of this procedure was to lift the model slightly from lower stock status estimates, although the effect was minor relative to the effect of omitting CELR data from the model.

The management procedure, determined by a CPUE-based harvest control rule, has been in place in PAU 5D since 2016. It has contributed to shelving decisions that have likely contributed to recent rebuilding in the fishery. The procedure was updated with additional mechanisms that avoid large increases in harvest in favour of small, steady increase, using a maximum rate of increase of 5% per year. Furthermore, the update included the imposition of a lag year on increases, meaning catches will only be increased if a sustained increase in biomass has been observed. Because the procedure only applies at levels below or at the current TACC, the rules provide a shelving framework that supports steady exploitation rates and low medium-term risk even under conservative assumptions. Nevertheless, given impacts of environmental stressors, such as marine heatwaves, these risk levels should not be considered as absolute, because they apply to a relatively steady state. In this context, a responsive and conservative control rule, such as the rule applied here, will mitigate short-term effects of stressors, provided they are detectable in CPUE.

5. BROADER OUTCOMES

5.1 Building capacity and capability in the fisheries research sector

This project has contributed to the professional development of early-career scientists in fisheries, in particular to develop an understanding of the stock assessment process, and to apply stock assessment models based on Bayesian approaches to New Zealand fisheries. The project was part of Dragonfly's wider initiative to build capacity in this research sector. This initiative is focused on supporting graduate researchers to develop analytical skills that are directly relevant to fisheries science in New Zealand.

In addition to supporting the development of analytical skills, the training of staff at Dragonfly Data Science is focused on our commitment to reproducible research. Relevant training includes processes and practices in open-source data science and fisheries tools that are transferable to related disciplines. New employees are actively trained in these methods to ensure they adhere to high standards of analysis and reproducibility while extending their skillset. This training also ensures that junior staff play a significant role in science projects at all steps, from data preparation to reporting. This involvement allows graduate researchers to up-skill over time, and become project leads as they progress.

Dragonfly Data Science's commitment to reproducible research principles is also evident in our partnership with other research providers forming the Kahawai Collective. The Kahawai Collective is a non-profit organisation promoting reproducible fisheries analyses and reporting, and all reporting for the present project was conducted using the Kahawai reporting frameworks.

5.2 Commitment to zero waste and sustainable practices

Dragonfly are committed to sustainability in our office and work activities, through active application of our sustainability policy. The policy includes waste reduction through recycling and composting (via Kaicycle, https://kaicycle.org.nz/), the lowering of energy consumption (through efficient installations and appliances in a recent office upgrade), and favouring public transport over private vehicles. Staff mainly commute by bike, public transport, or by walking, and bike storage is provided within the office. To avoid non-essential long-distance travel, we enable video conferencing and online meetings.

Our sustainability efforts include a reduction of paper use in the office, by working with documents digitally, and the use of electronic files and electronic archiving. Similarly, we use electronic methods for office systems such as project management and accounting.

Our focus on sustainability also extends to other organisations, and we favour local suppliers and manufacturers where possible; e.g., for food, furniture and other office supplies. Considerations for purchasing are not solely focused on cost, but include environmental and social aspects and (e.g., fair-trade coffee, certified-organic beverages). We review our suppliers to ensure that they are working towards sustainable outcomes.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Breen, P.A.; Kim, S.W.; Andrew, N.L. (2003). A length-based Bayesian stock assessment model for the New Zealand abalone *Haliotis iris*. *Marine and Freshwater Research 54 (5)*: 619–634.

Butterworth, D.S.; Haddon, M.; Haist, V.; Helidoniotis, F. (2015). Report on the New Zealand paua stock assessment model; 2015. *New Zealand Fisheries Science Review 2015/4*. 31 p.

Fu, D.; McKenzie, A.; Marsh, C. (2017). Summary of input data for the 2016 PAU 5D stock assessment. *New Zealand Fisheries Assessment Report 2017/32*. 79 p.

Marsh, C.; Fu, D. (2017). The 2016 stock assessment of paua (*Haliotis iris*) for PAU 5D. *New Zealand Fisheries Assessment Report 2017/33*. 48 p.

Middleton, D.A.J. (in prep.). The Kahawai database.

Murray, T.; Akroyd, J.M. (1984). The New Zealand paua fishery: an update of biological considerations to be reconciled with management goals. Fisheries Research Centre Internal Report No. 5. Unpublished report held by National Institute of Water and Atmospheric Research, Wellington. 34 p.

Neubauer, P. (2019). Development and evaluation of management procedures in pāua quota management areas 5A, 5B and 5D. *New Zealand Fisheries Assessment Report 2019/37*. 63 p.

Neubauer, P. (2020). Development and application of a spatial stock assessment model for pāua (*Haliotis iris*). *New Zealand Fisheries Assessment Report 2020/30*. 42 p.

Neubauer, P. (2021). Pāua management procedure: review of current state and prospects for wider application. *New Zealand Fisheries Assessment Report 2021/03*. 13 p.

Neubauer, P. (2022). The 2021 stock assessment of pāua (*Haliotis iris*) for PAU 2. *New Zealand Fisheries Assessment Report 2022/35*. 108 p.

Neubauer, P. (2023a). Quantifying effects of reporting changes for pāua (*Haliotis iris*) catch-per-unit-effort. *New Zealand Fisheries Assessment Report 2023/18*. 19 p.

Neubauer, P. (2023b). The 2022 stock assessment of pāua (*Haliotis iris*) for PAU 7. *New Zealand Fisheries Assessment Report 2023/17*. 46 p.

Neubauer, P.; Tremblay-Boyer, L. (2019a). Input data for the 2018 stock assessment of pāua (*Haliotis iris*) for PAU 5D. *New Zealand Fisheries Assessment Report 2019/38*. 40 p.

Neubauer, P.; Tremblay-Boyer, L. (2019b). The 2018 stock assessment of pāua (*Haliotis iris*) for PAU 5D. *New Zealand Fisheries Assessment Report 2019/39*. 58 p.

Neubauer, P.; Tremblay-Boyer, L. (2019c). The 2018 stock assessment of pāua (*Haliotis iris*) for PAU 5D. *New Zealand Fisheries Assessment Report 2019/39*. 94 p.

Ohnishi, S.; Yamakawa, T.; Okamura, H.; Akamine, T. (2012). A note on the von Bertalanffy growth function concerning the allocation of surplus energy to reproduction. *Fishery Bulletin 110 (2)*: 223–229.

Schiel, D.R. (1989). Paua fishery assessment 1989. Unpublished New Zealand Fisheries Assessment Research Document 89/9 (held by NIWA, Wellington).

Stan Development Team. (2018). RStan: the R interface to Stan. R package version 2.17.3. http://mc-stan.org/.

Wynne-Jones, J.; Gray, A.; Heinemann, A.; Hill, L.; Walton, L. (2019). National panel survey of marine recreational fishers 2017–18. *New Zealand Fisheries Assessment Report 2019/24*. 104 p.

Wynne-Jones, J.; Gray, A.; Hill, L.; Heinemann, A. (2014). National panel survey of marine recreational fishers 2011–12: harvest estimates. *New Zealand Fisheries Assessment Report 2014/67*. 139 p.

APPENDIX A: BASE CASE ASSESSMENT

A.1 Markov Chain Monte Carlo and posteriors

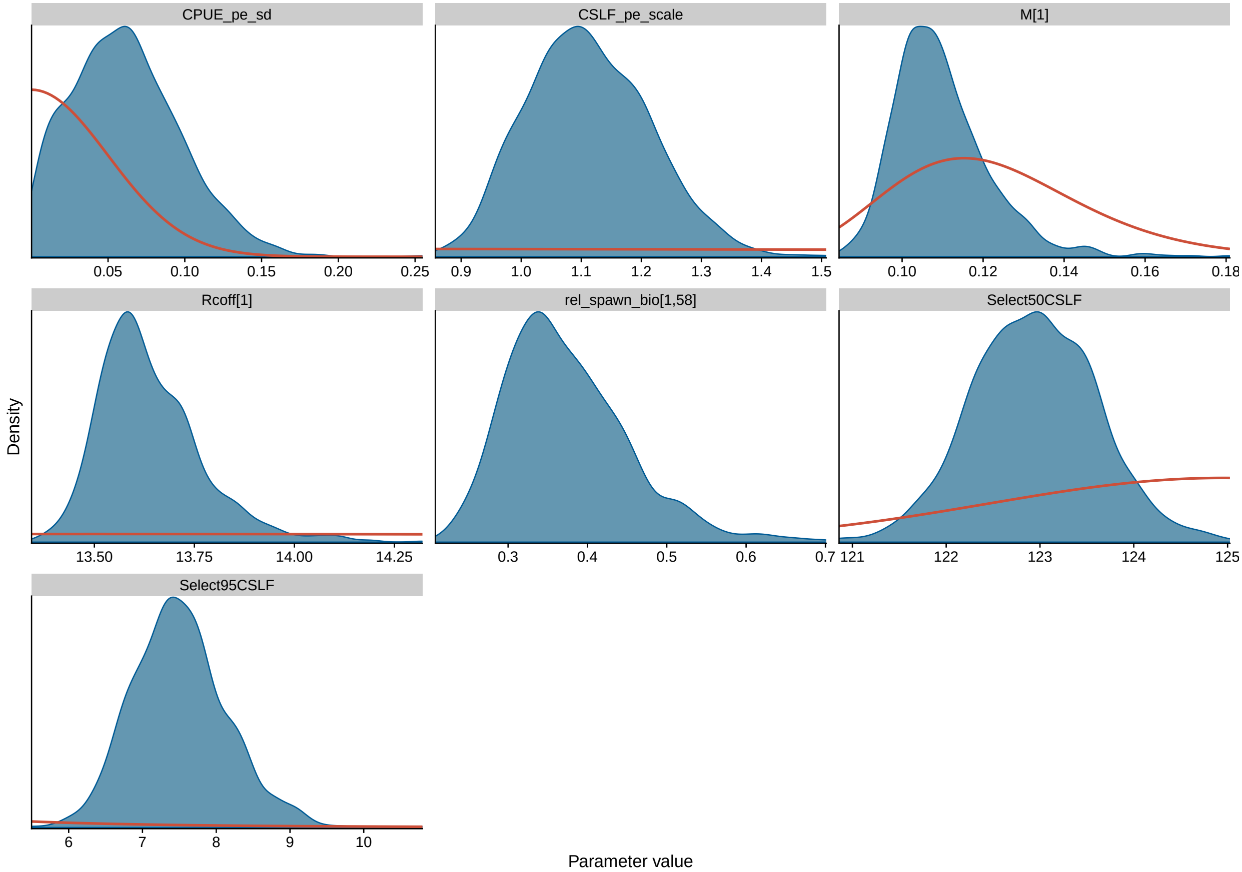

Figure A-1: Marginal posterior densities of key model parameters for the base-case stock assessment model for quota management area PAU 5D, with prior densities indicated in red.

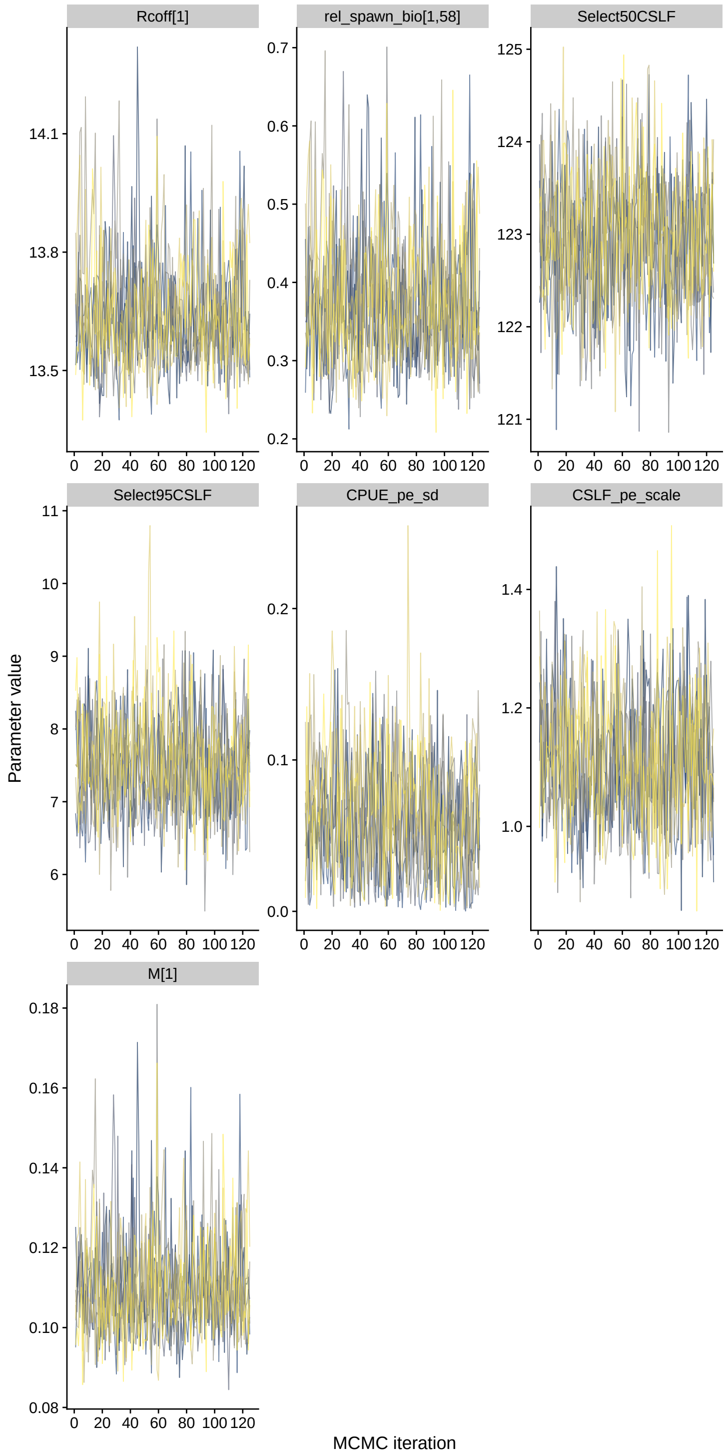

Figure A-2: Traces of Markov Chain Monte Carlo estimation for the marginal posterior distribution of key model parameters for the base-case stock assessment model for quota management area PAU 5D.

Table A-1: Posterior quantities for key parameters in the base-case stock assessment model for quota management area PAU 5D. Logarithm of unfished recruitment, $log(R_0)$; size at which 50% of individuals are selected, D_{50}; size at which 95% of individuals are selected, D_{95}; the exploitation rate (U) leading to 40% of unfished SSB; natural mortality, M, process error, PE; stock status (relative spawning stock biomass (SSB))

Parameter	Posterior percentile				
	2.5%	25%	50%	75%	97.5%
log(R_0)	13.44	13.55	13.62	13.71	13.96
D_{50}	121.67	122.48	122.94	123.39	124.24
D_{95}	6.36	7.07	7.47	7.88	8.91
$U_{40\%\mathrm{SSB}_0}$	0.02	0.09	0.12	0.18	0.38
M	0.09	0.10	0.11	0.12	0.14
$\mathrm{PE}_{\mathrm{CPUE}}$	0.00	0.04	0.06	0.08	0.14
$\mathrm{PE}_{\mathrm{CSLF}}$	0.94	1.04	1.11	1.18	1.32
relative SSB_{2022}	0.25	0.32	0.36	0.42	0.55

A.2 Catch-per-unit-effort

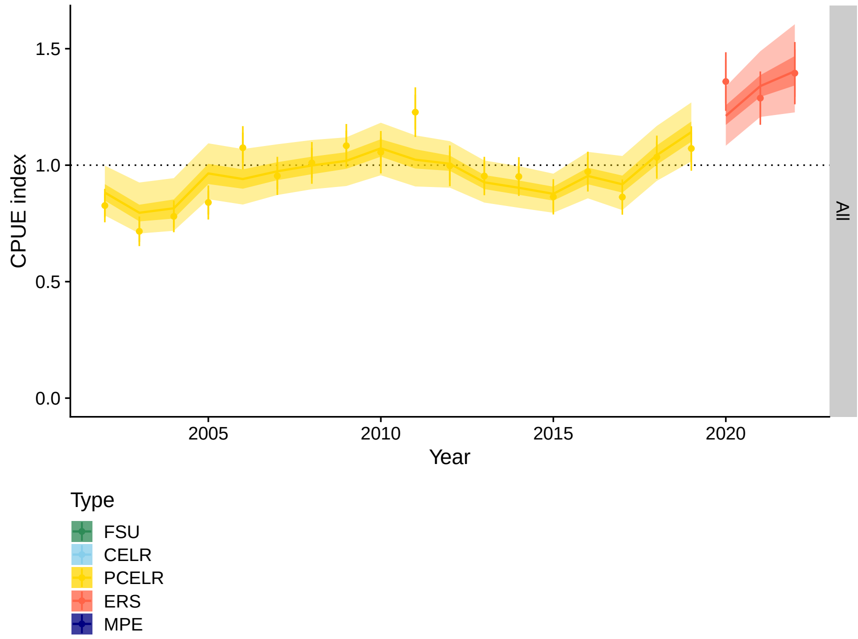

Figure A-3: Comparison of posterior median (line) and 95% confidence (shaded ribbon) predicted catch-per-unit-effort (CPUE) with estimated CPUE index and observation error for the base-case stock assessment model for quota management area PAU 5D (points and error bars; PCELR data from Paua Catch Effort Landing Return forms; ERS data from Electric Reporting Systems).

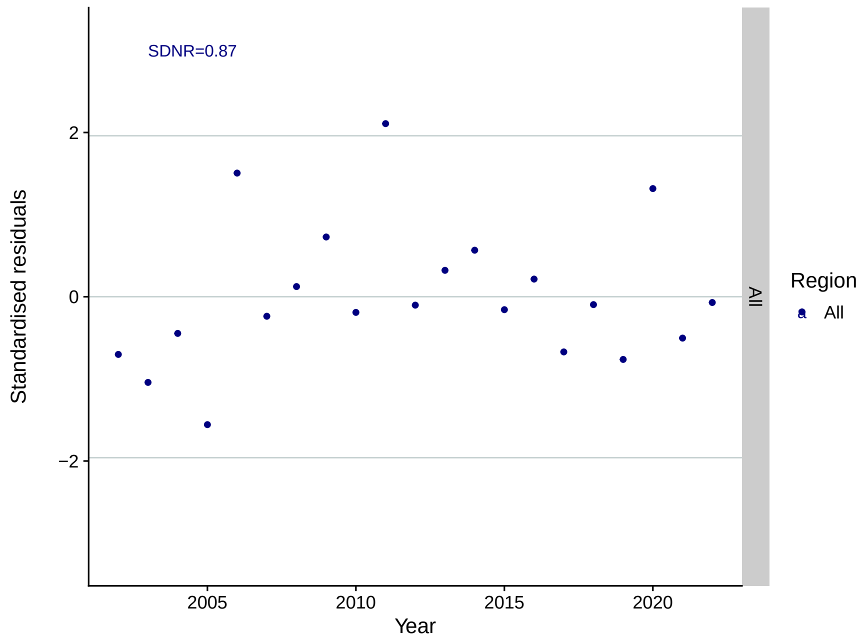

Figure A-4: Standardised residuals at the posterior median of predicted catch-per-unit-effort for the base-case stock assessment model for quota management area PAU 5D.

A.3 Length frequency

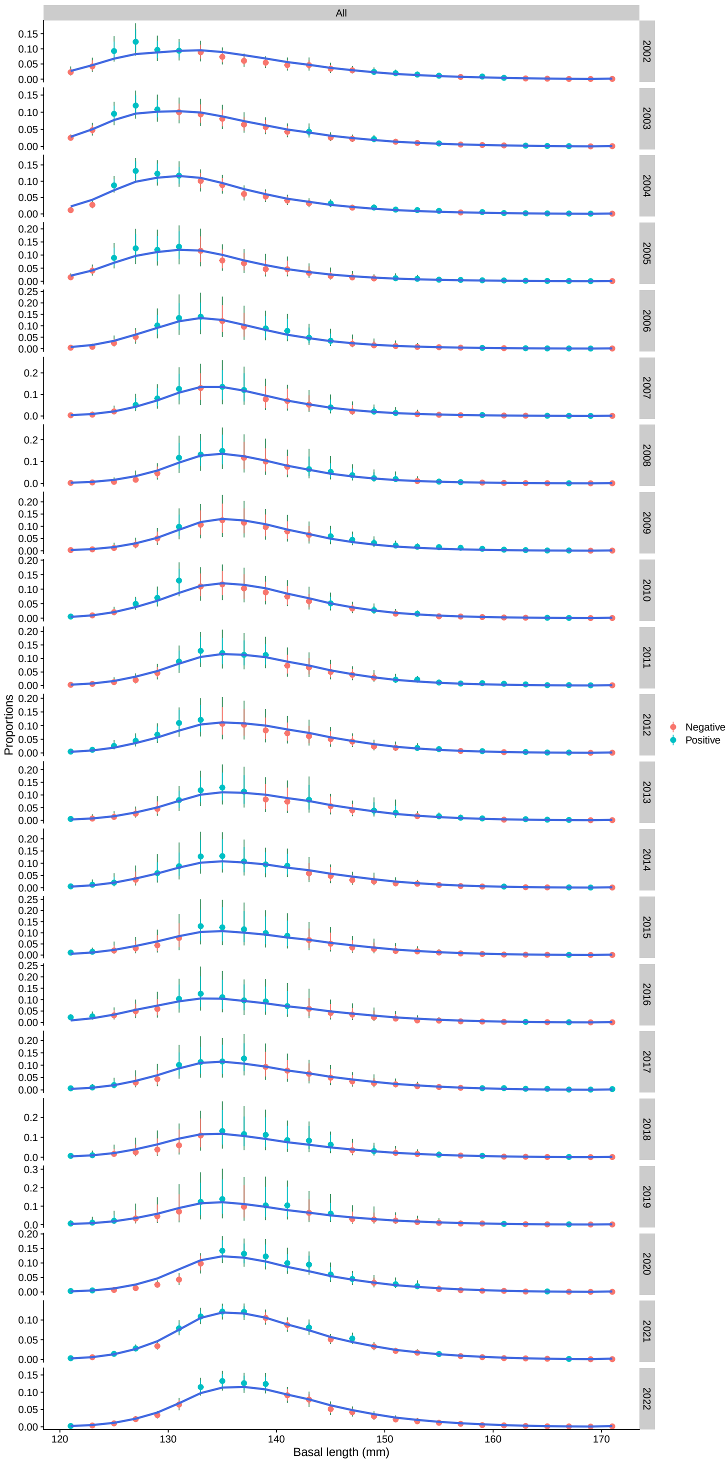

Figure A-5: Comparison of posterior mean predicted catch sampling length frequency (CSLF) with estimated CSLF proportions and observation error for the base-case stock assessment model for quota management area PAU 5D. Length classes with positive residuals in blue, with negative residuals in red.

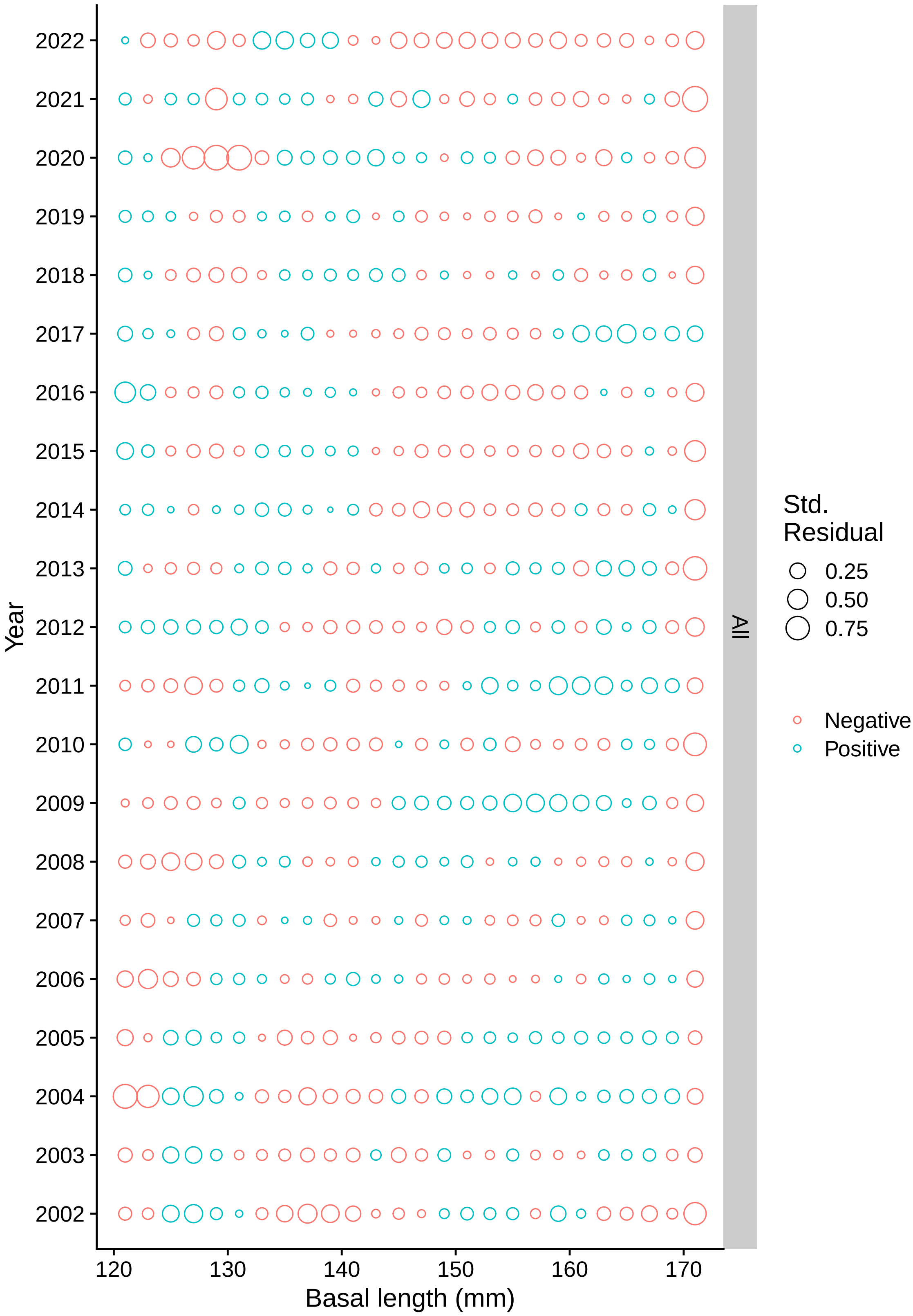

Figure A-6: Catch sampling length frequency model residuals for the base-case stock assessment model for quota management area PAU 5D. Length classes with positive residuals in blue, with negative residuals in red.

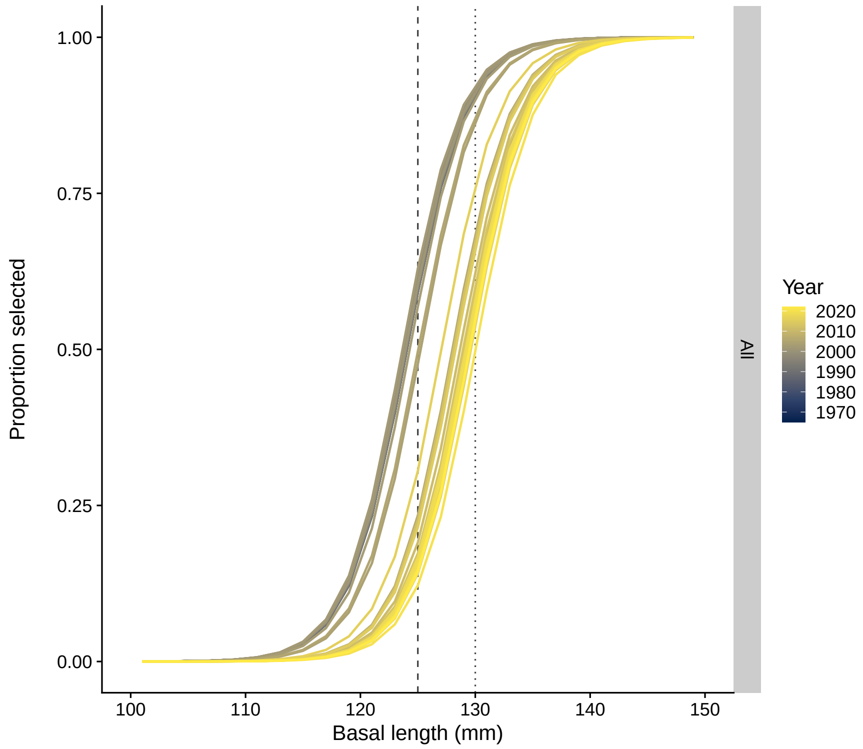

Figure A-7: Estimated selectivity (posterior mean) for pāua for the base-case stock assessment model for quota management area PAU 5D.

A.4 Growth

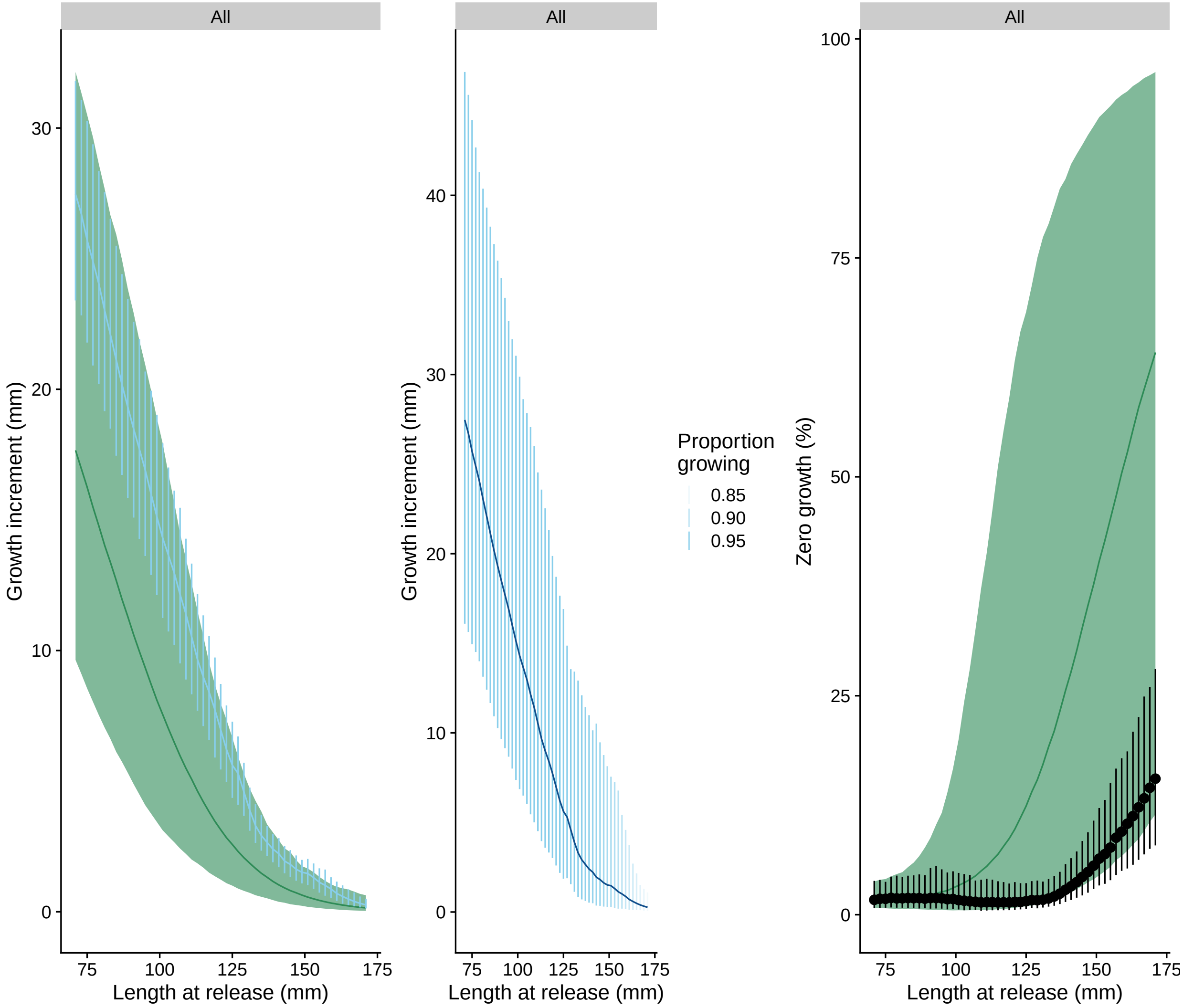

Figure A-8: Pāua growth for the base-case stock assessment model for quota management area PAU 5D. Left: Posterior mean growth (population mean (dark blue line) and standard deviation of the estimate (light blue ribbon)), relative to the prior (dark green); middle: estimated population standard deviation (posterior median; light blue) relative to estimated population mean (blue line); right: estimated proportion of pāua stock not growing at each length (black points and 95% confidence interval) relative to the prior (green) for the base-case stock assessment model for quota management area PAU 5D.

A.5 Recruitment and biomass trends

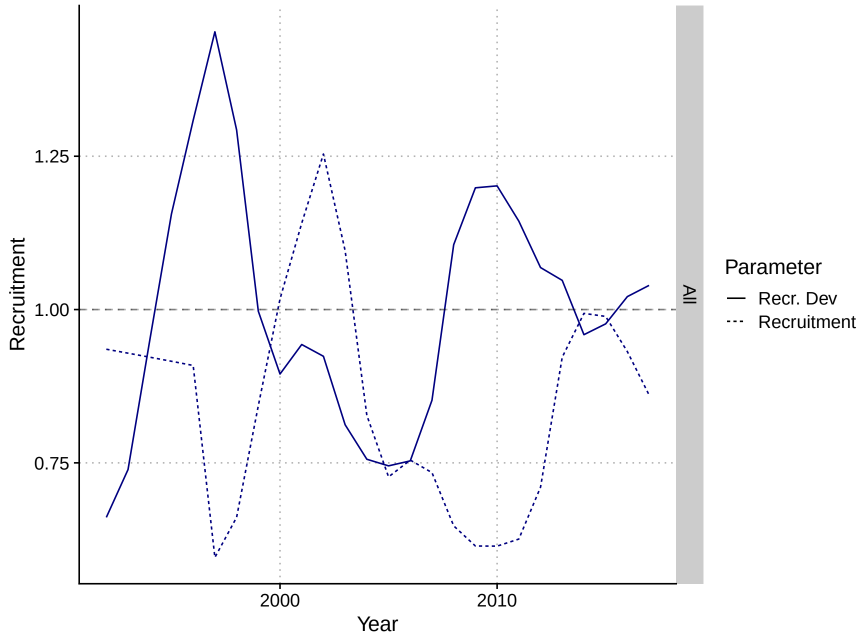

Figure A-9: Posterior mean recruitment for pāua for the base-case stock assessment model for quota management area PAU 5D (R_{dev}, recruitment deviation).

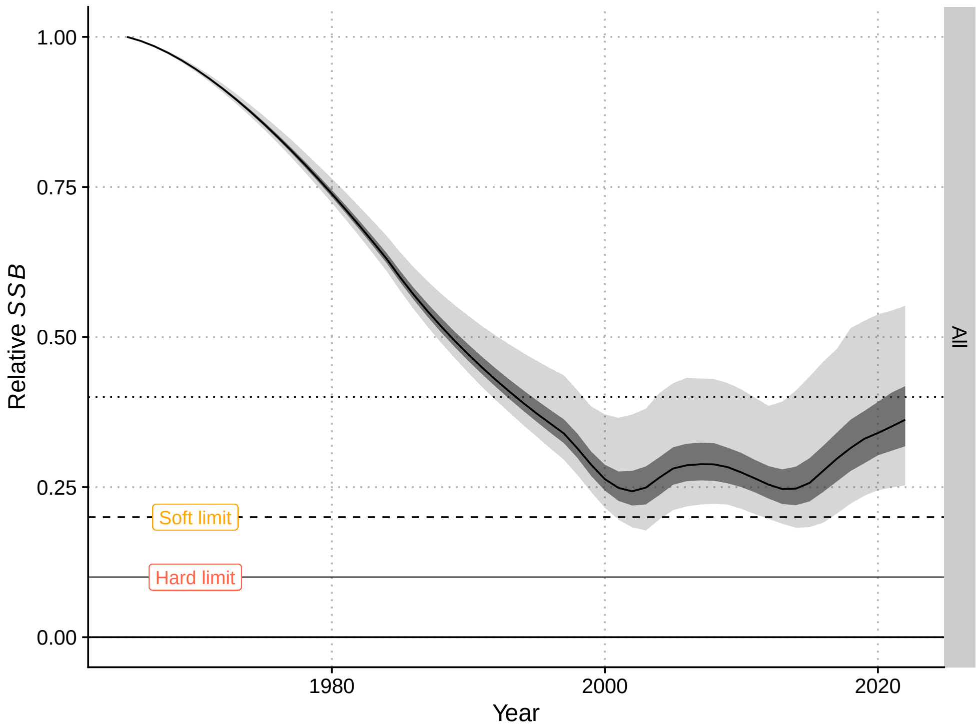

Figure A-10: Estimated relative spawning stock biomass (*SSB*) trend for pāua for the base-case stock assessment model for quota management area PAU 5D (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

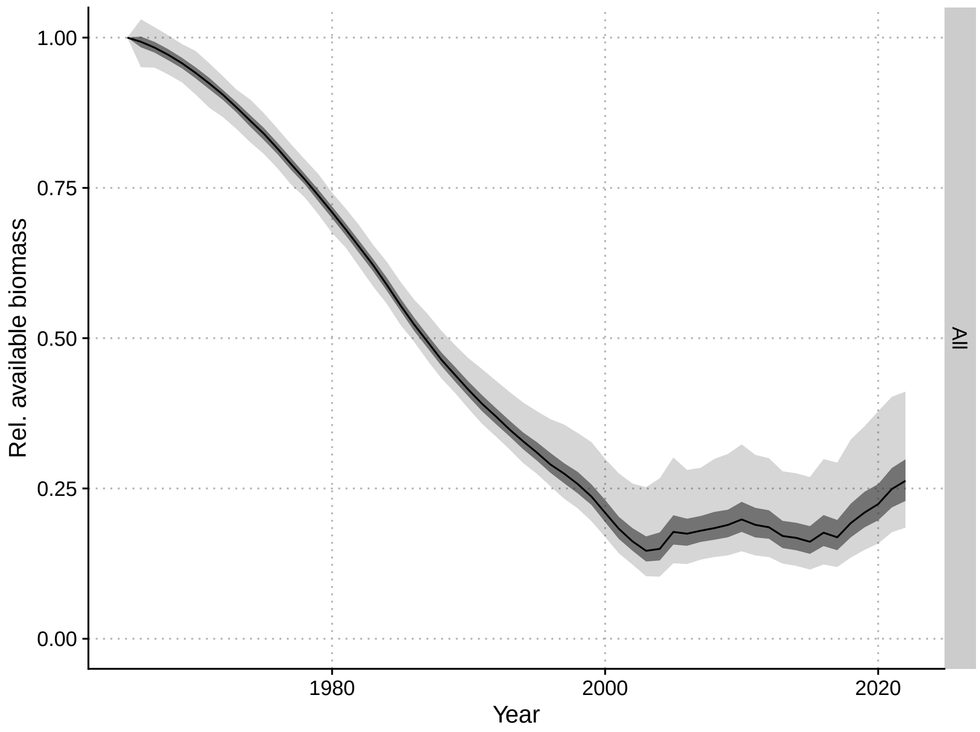

Figure A-11: Estimated relative available biomass trend for pāua for the base-case stock assessment model for quota management area PAU 5D (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

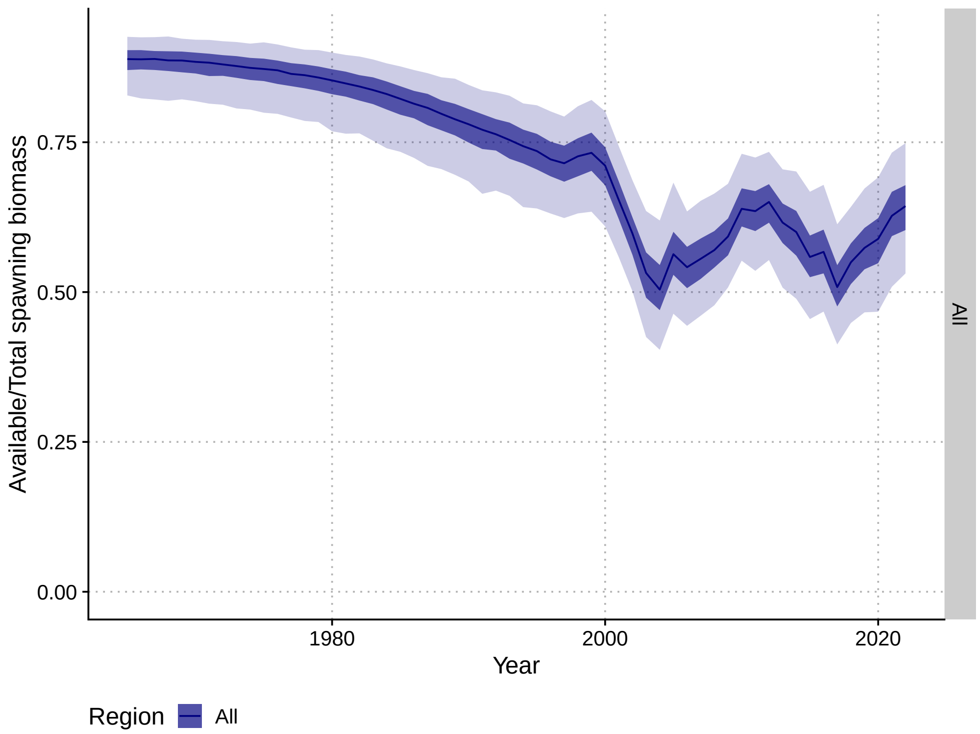

Figure A-12: Estimated relative available pāua biomass (relative to spawning stock) for the base-case stock assessment model for quota management area PAU 5D (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

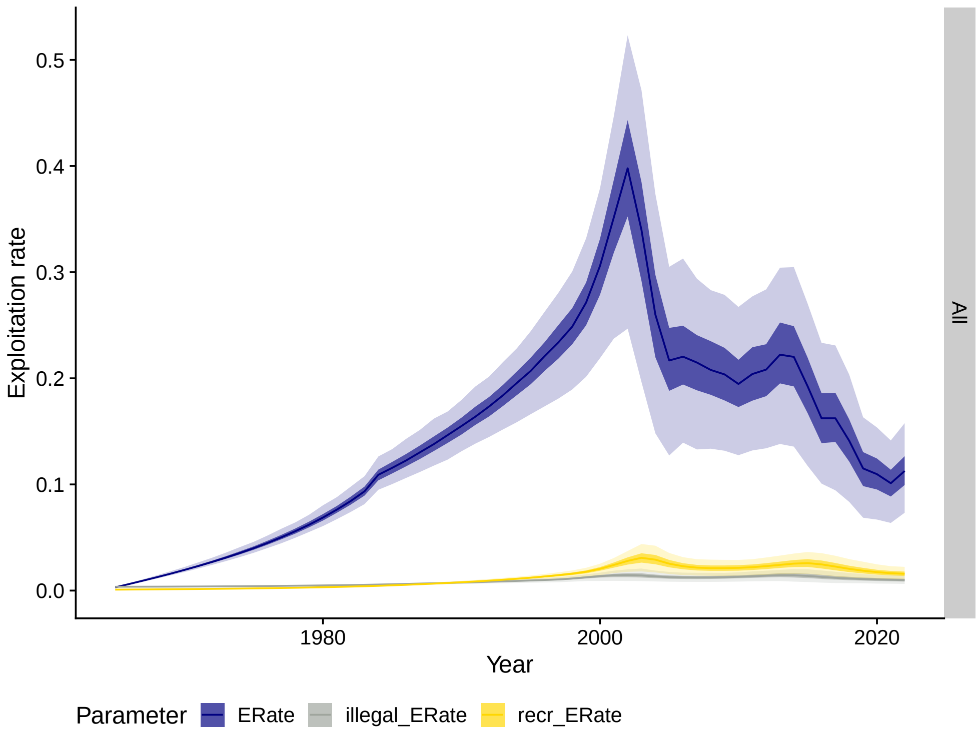

Figure A-13: Estimated exploitation rates for commercial (ERate), illegal and recreational (recr.) catch components (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)) for the base-case stock assessment model for quota management area PAU 5D.

A.6 Status and projections

Table A-2: Stock status and fishery indicators for the last fishing year considered in this assessment and projections for key fishery indicators from the base-case stock assessment model for for quota management area PAU 5D. Shown are values for current catch (indicated by the asterisk), and 20% and 50% increases and reductions from current catch. Results at equilibrium (Eq.) are also included (assumed to be reached after 50 years). Columns are: probabilities of being above 40% (P(SSB>0.4SSB_0)) and 20% (P(SSB>0.2SSB_0)) of unfished spawning stock biomass (SSB), the probability that SSB in the projection year is above current SSB, the posterior median relative SSB, the posterior median relative available biomass (B^{avail}), the posterior median relative available spawning biomass (SSB^{avail}), the probability that B^{avail} in the projection year is above current B^{avail}, and the probability that the exploitation rate (U) is greater than the exploitation rate leading to 40% SSB.

		Fishery indicator							
Year	Catch (t)	P($SSB > 0.4SSB_0$)	P($SSB > 0.2SSB_0$)	P($SSB > SSB_{\text{current}}$)	Mean rel. SSB	Mean rel. B^{avail}	Mean rel. SSB^{avail}	P($B^{\text{avail}} > B^{\text{avail}}_{\text{current}}$)	P($U > U_{40\%\text{SSB}_0}$)
2023	54	0.36	1.00	0.69	0.38	0.28	0.64	0.76	0.32
2024		0.43	1.00	0.82	0.40	0.29	0.65	0.86	0.29
2025		0.48	1.00	0.87	0.41	0.30	0.65	0.90	0.27
2026		0.53	1.00	0.90	0.42	0.31	0.65	0.92	0.26
2027		0.59	1.00	0.92	0.44	0.32	0.66	0.94	0.24
Eq.		0.99	1.00	1.00	0.68	0.58	0.75	1.00	0.09
2023	67.57*	0.36	1.00	0.69	0.38	0.28	0.64	0.76	0.44
2024		0.41	1.00	0.73	0.39	0.28	0.64	0.76	0.43
2025		0.44	1.00	0.76	0.40	0.29	0.64	0.76	0.41
2026		0.48	1.00	0.81	0.41	0.30	0.64	0.78	0.40
2027		0.51	1.00	0.83	0.42	0.30	0.65	0.80	0.39
Eq.		0.95	1.00	0.98	0.61	0.50	0.73	0.98	0.18
2023	89	0.36	1.00	0.69	0.38	0.28	0.64	0.76	0.61
2024		0.38	1.00	0.59	0.38	0.27	0.64	0.56	0.61
2025		0.39	0.99	0.59	0.39	0.27	0.63	0.52	0.61
2026		0.39	0.99	0.59	0.39	0.27	0.63	0.51	0.61
2027		0.41	0.99	0.60	0.39	0.27	0.62	0.51	0.61
Eq.		0.66	0.94	0.78	0.46	0.35	0.64	0.74	0.46

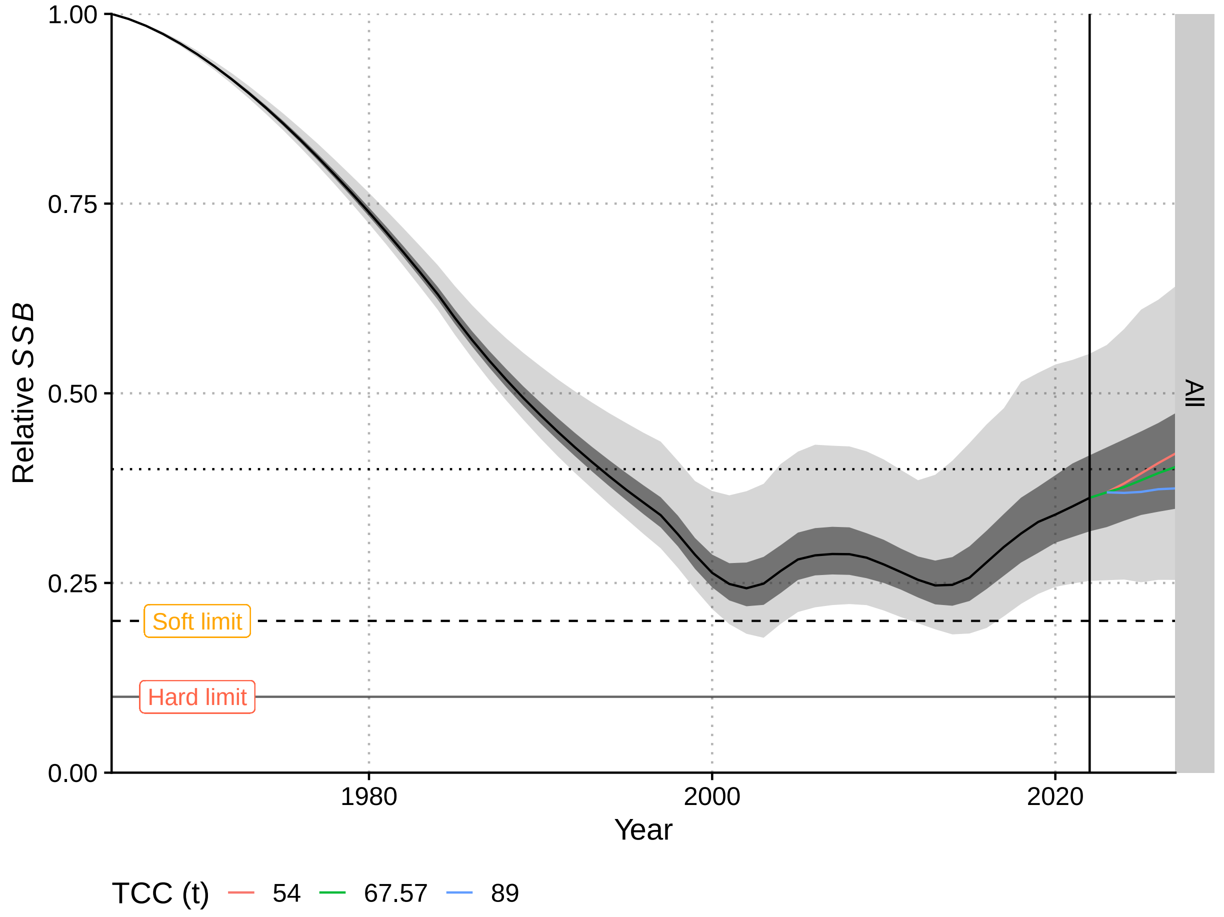

Figure A-14: Estimated (left of solid vertical line) and projected (right of solid vertical line) relative spawning stock biomass (SSB) trend for pāua for the base-case stock assessment model for quota management area PAU 5D (black line (current/observed catch) and 95% confidence interval). Projections under alternative total commercial catch levels (TCC) are for current catch (green line) and 20% reduction in catch (red) and the current TACC (blue). Confidence interval corresponds to current catch (blue) projections only.

APPENDIX B: KEY ASSESSMENT SENSITIVITIES

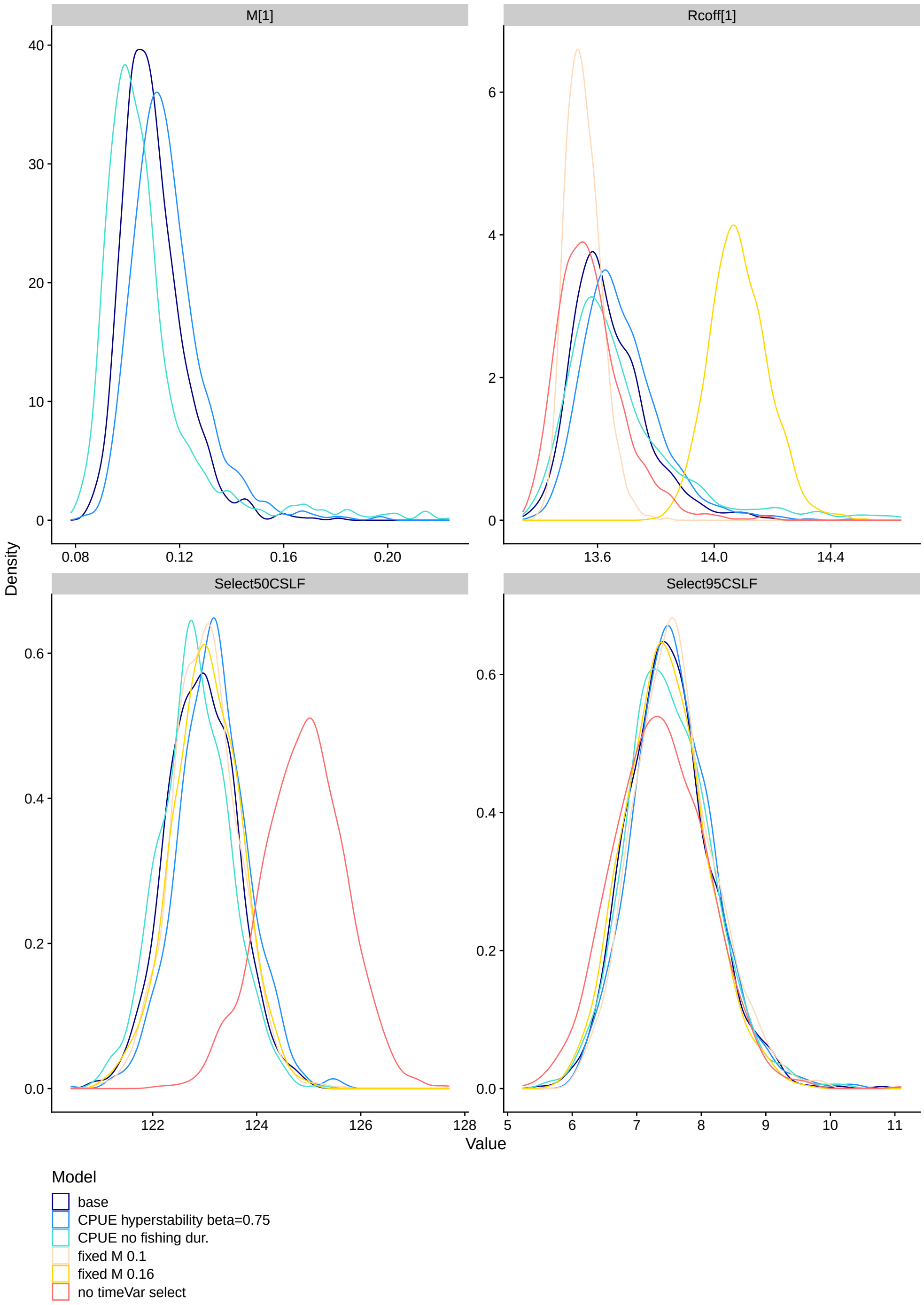

Figure B-1: Comparison of posterior densities for parameters for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

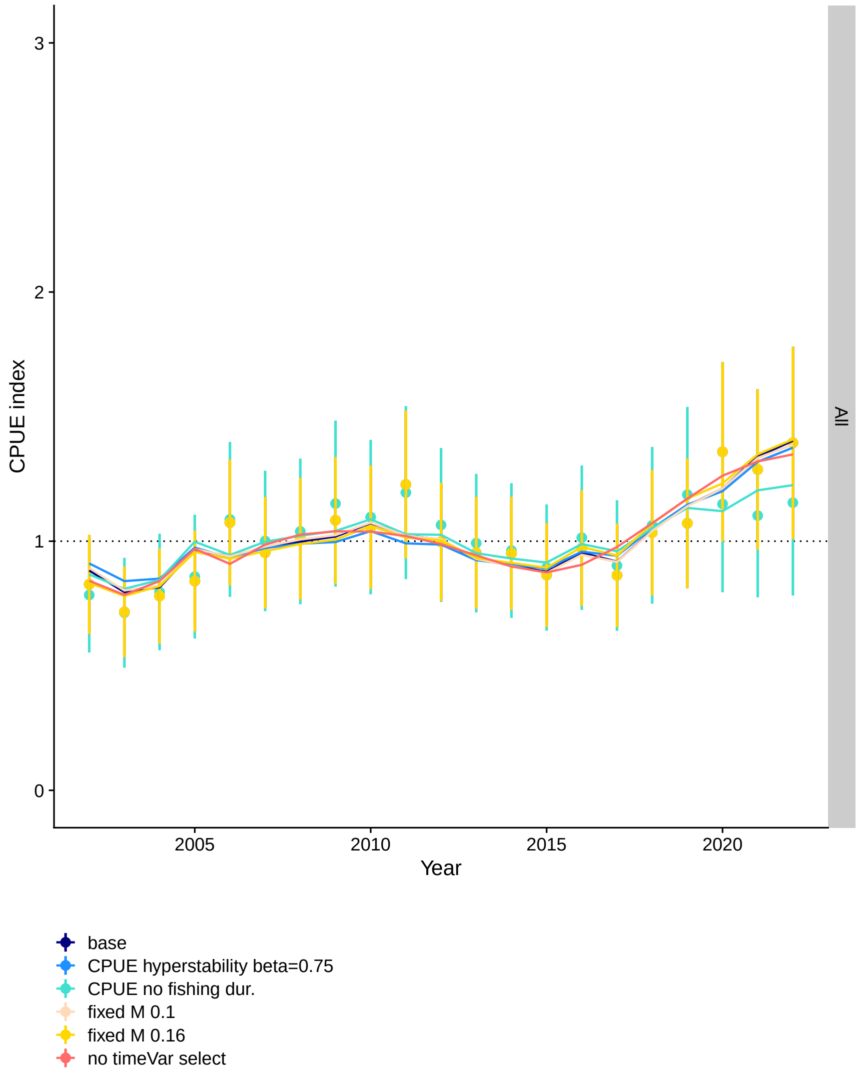

Figure B-2: Comparison of posterior median predicted catch-per-unit-effort (CPUE) for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

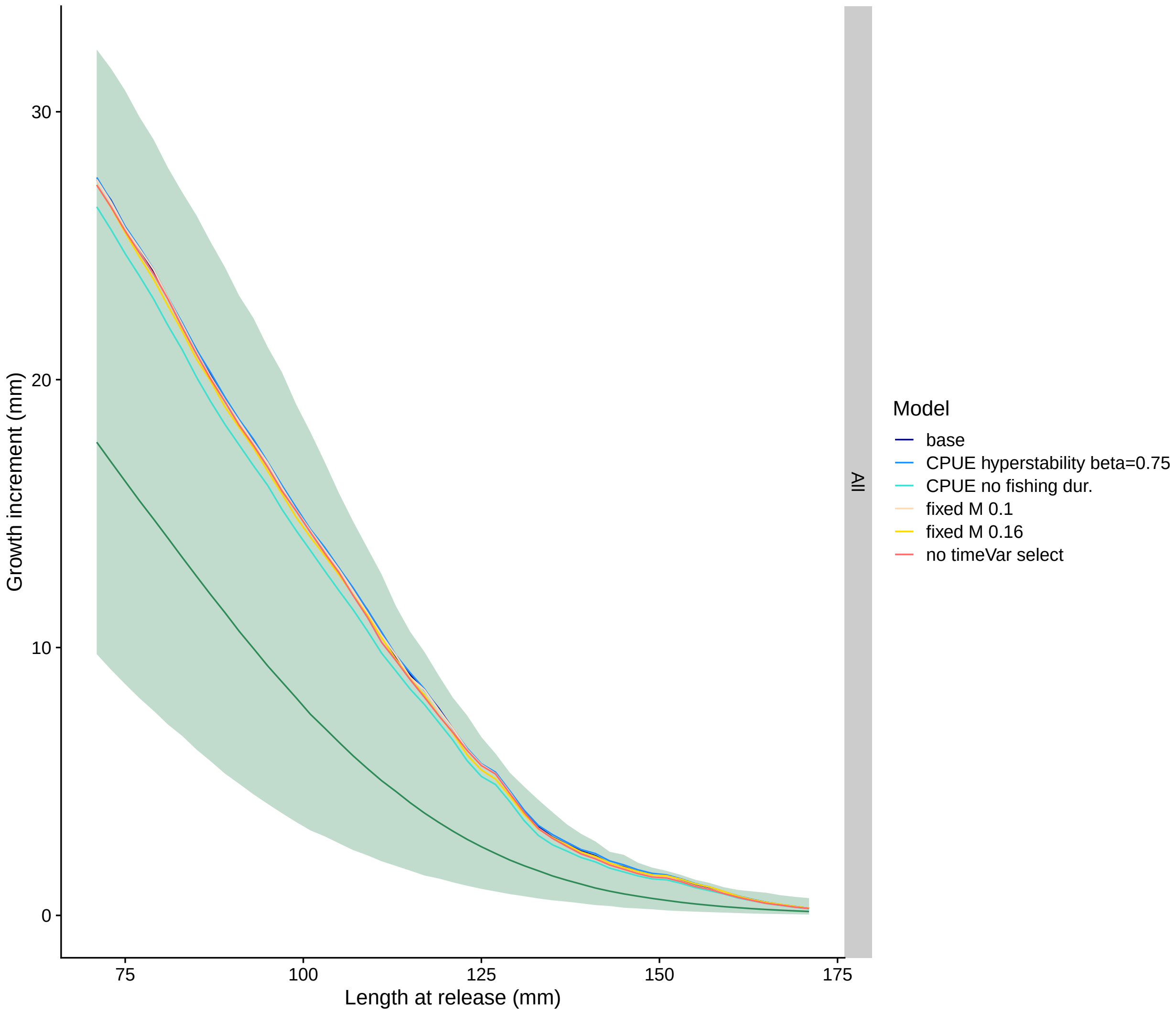

Figure B-3: Comparison of prior and median posterior growth for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D. Prior for population mean growth (prior mean, green line; 95% prior interval, green shading), and posterior mean growth.

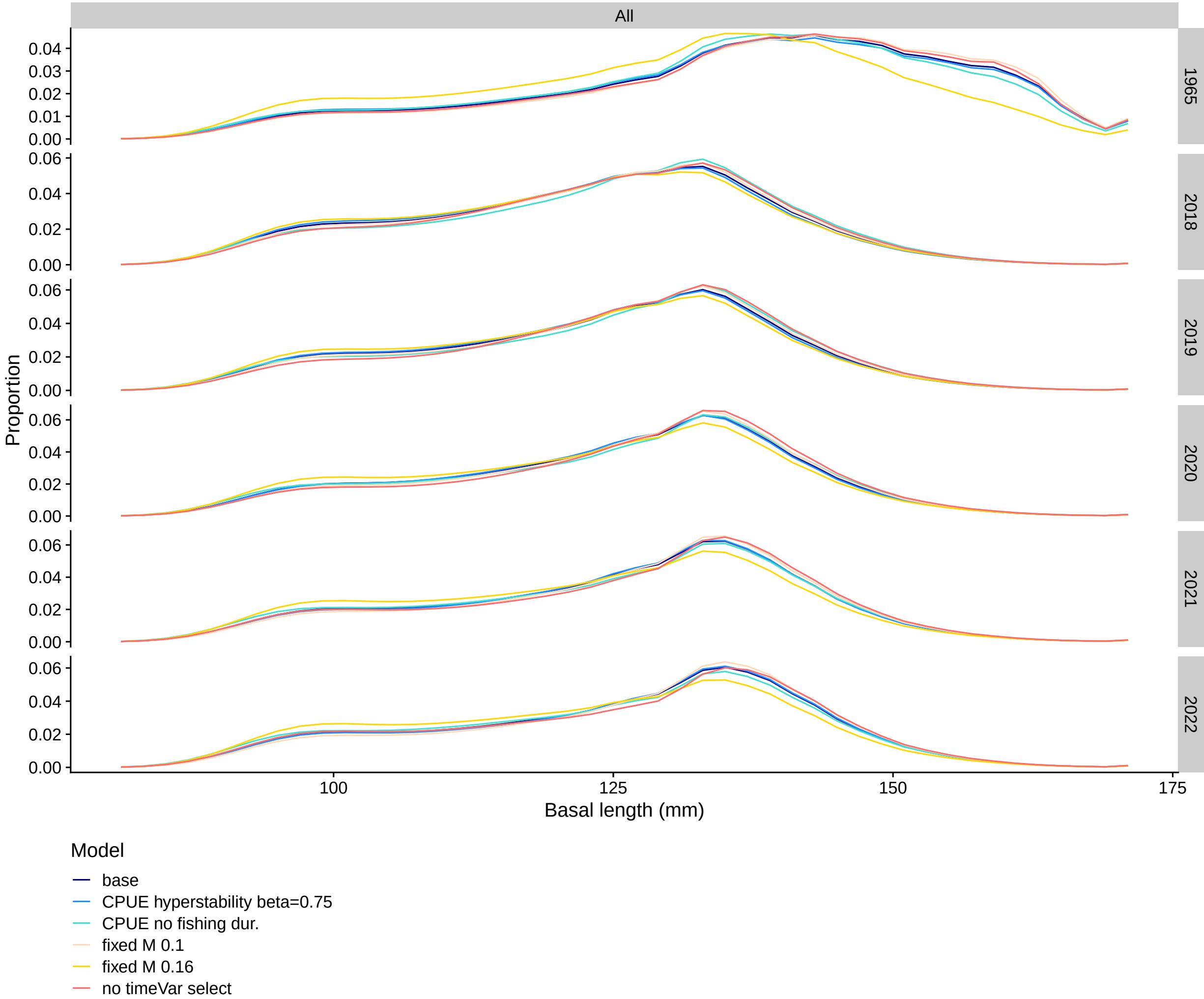

Figure B-4: Comparison of posterior mean proportions-at-length for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

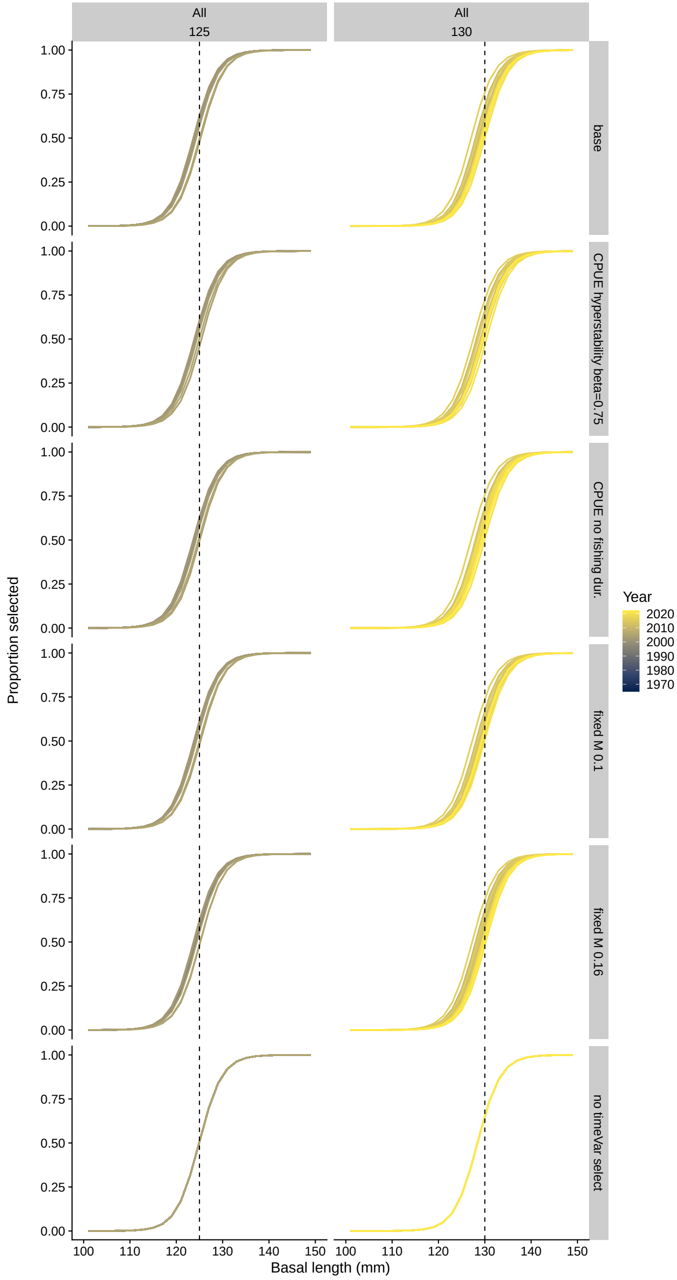

Figure B-5: Comparison of posterior mean selectivity-at-length for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

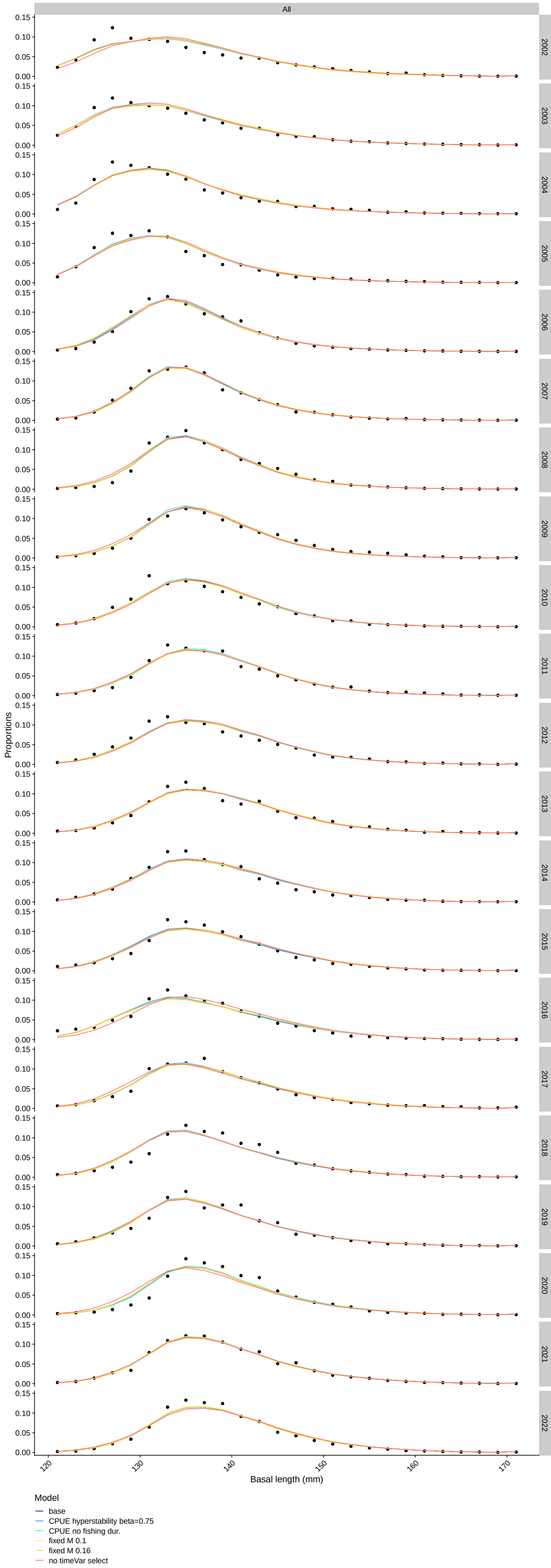

Figure B-6: Comparison of posterior mean predicted catch sampling length frequency (CSLF) with estimated CSLF proportions, for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

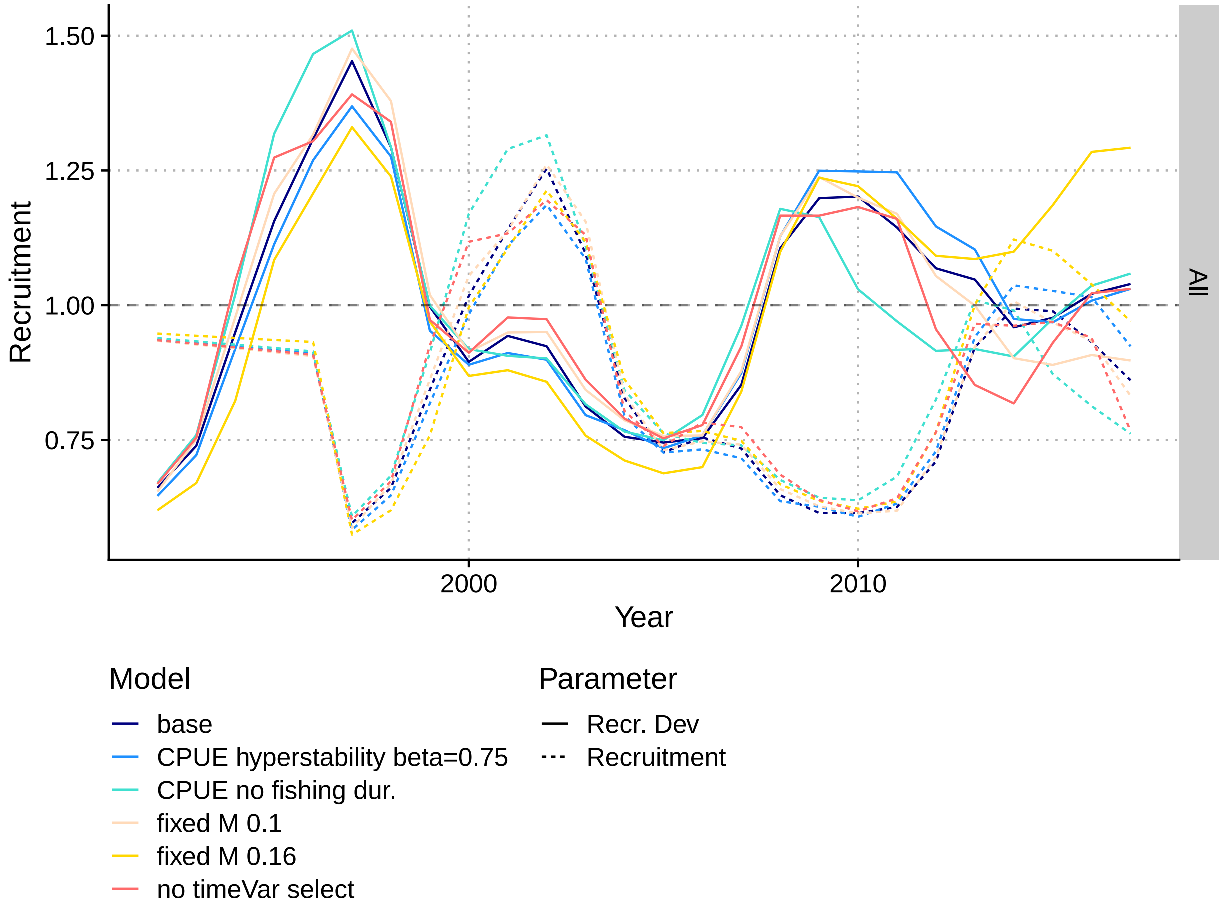

Figure B-7: Comparison of posterior mean recruitment deviations ($Rdev$) for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

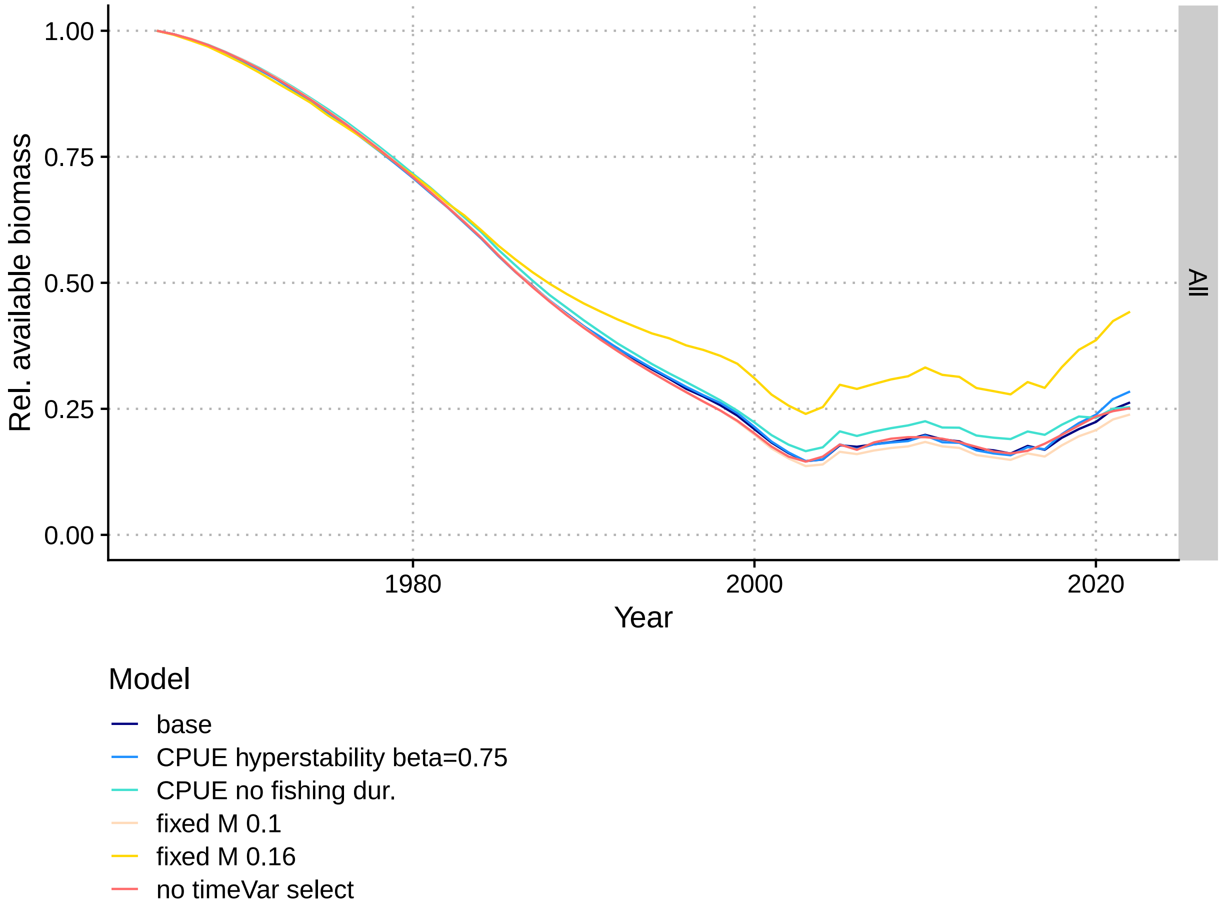

Figure B-8: Comparison of posterior median predicted relative available biomass trend for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

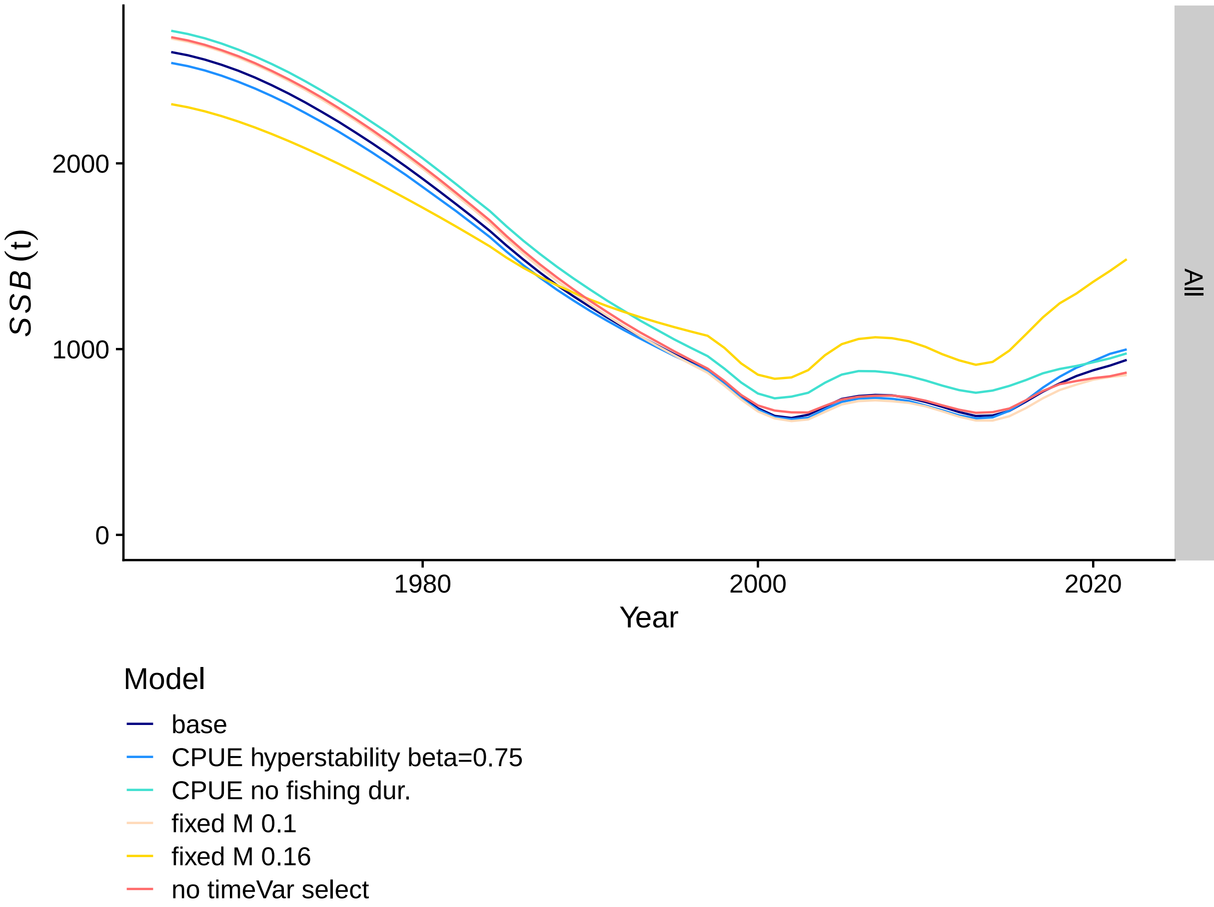

Figure B-9: Comparison of posterior median predicted spawning stock biomass (SSB) trend for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

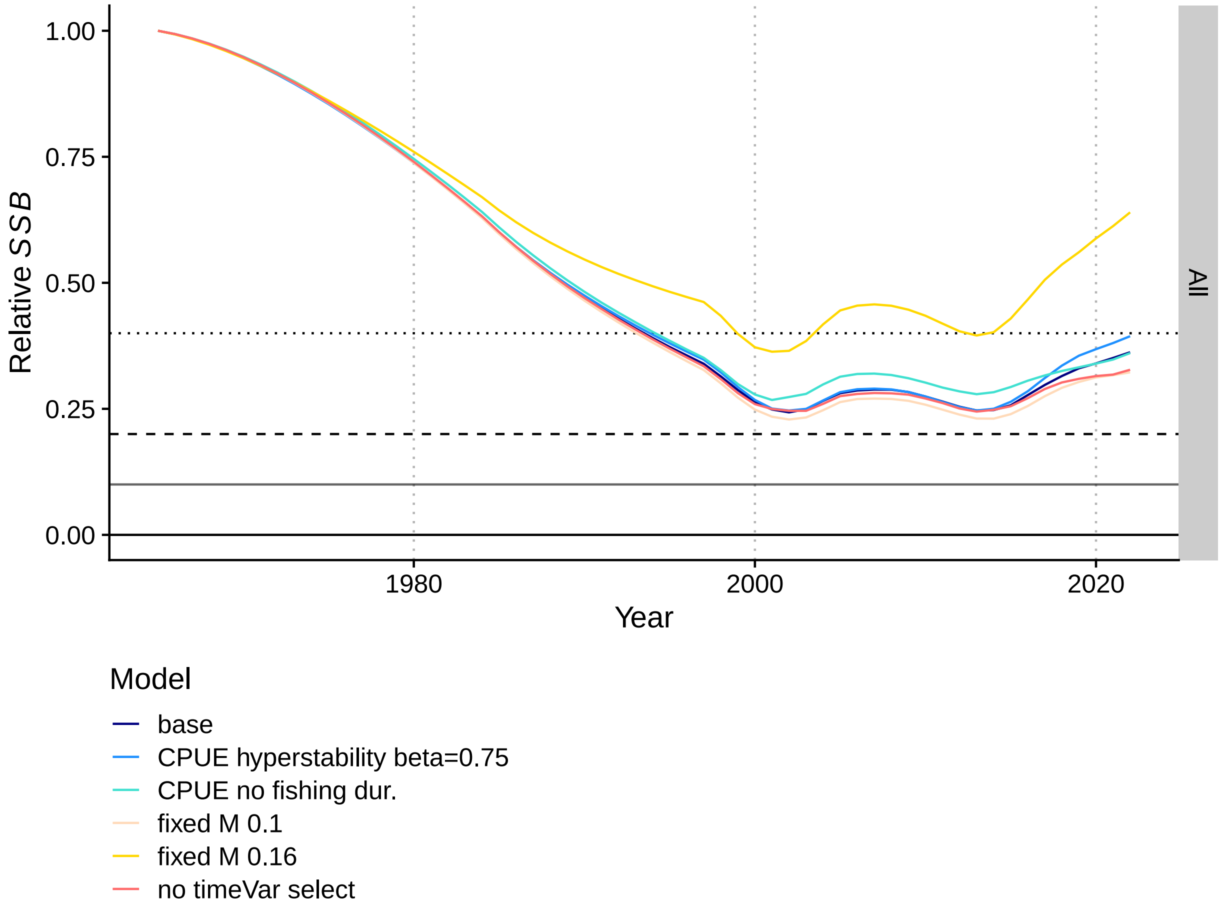

Figure B-10: Comparison of posterior median predicted relative spawning stock biomass (SSB) trend for key sensitivities (coloured lines; see Methods for description of individual models) for assessment assumptions used in the base case stock assessment for quota management area PAU 5D.

APPENDIX C: MANAGEMENT PROCEDURE EVALUATION: CONTROL RULE UPDATE

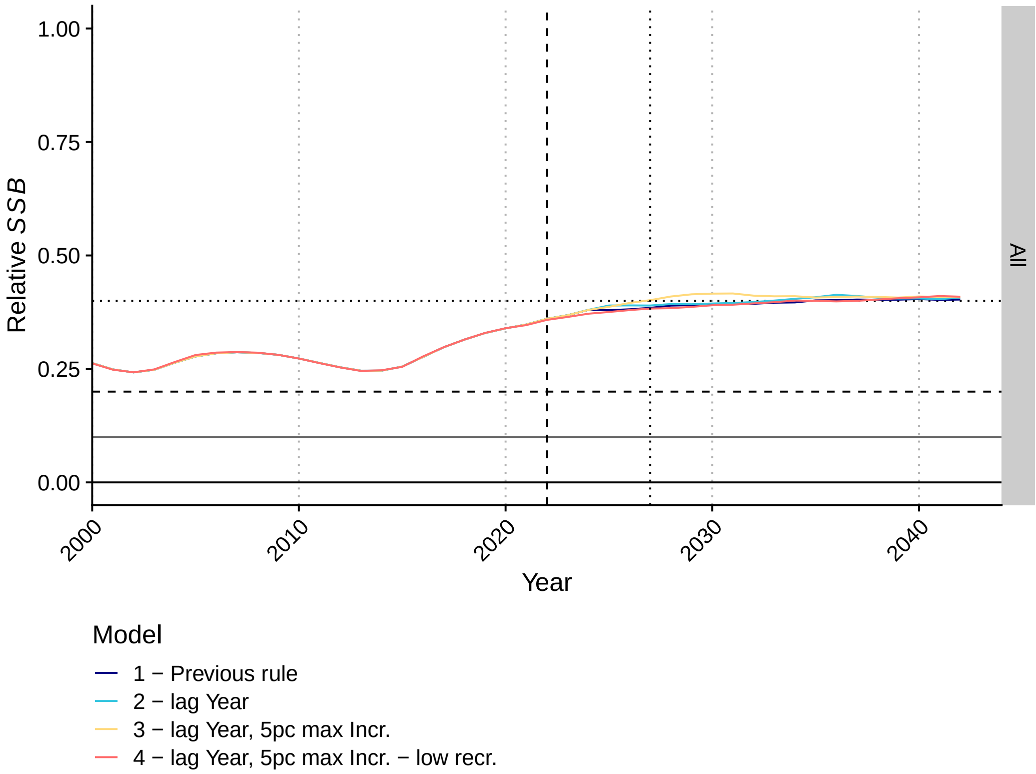

Figure C-1: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua, comparing rules with added lag year and limits to annual increases (5%) to previous control rules under the base-case and alternative recruitment assumptions (low recr.) for quota management area PAU 5D. Only medians from simulations are compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

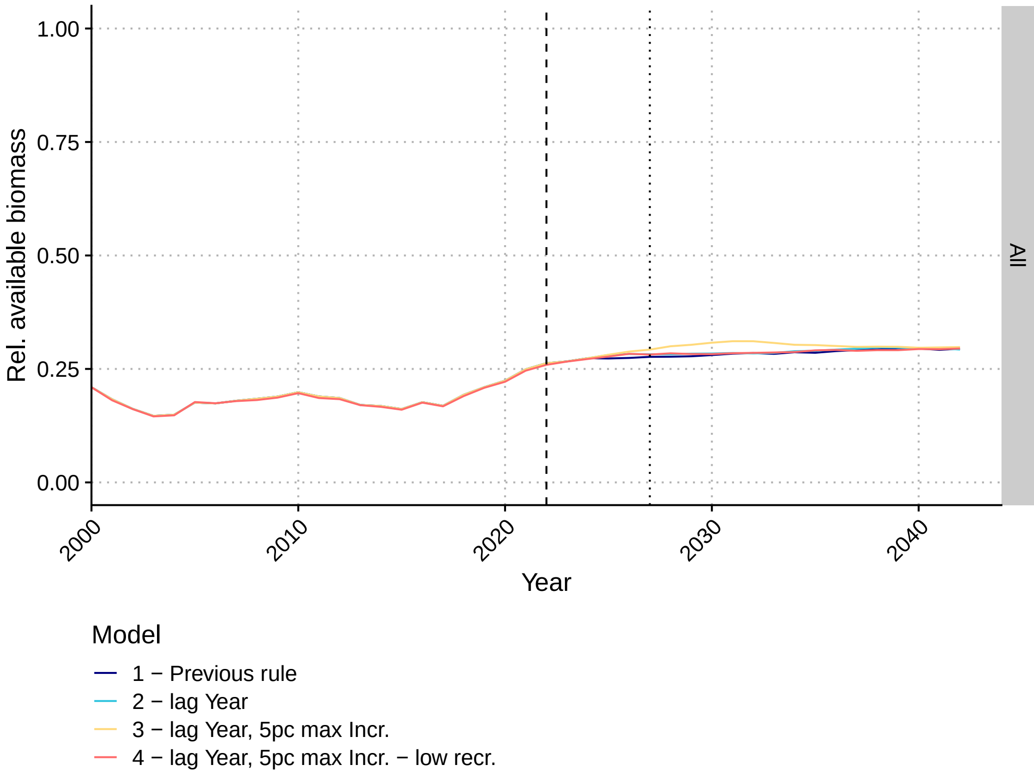

Figure C-2: Estimated and projected relative available biomass trend for pāua, comparing rules with added lag year and limits to annual increases (5%) to previous control rules under the base-case and alternative recruitment assumptions (low recr.) for quota management area PAU 5D. Only medians from simulations are compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

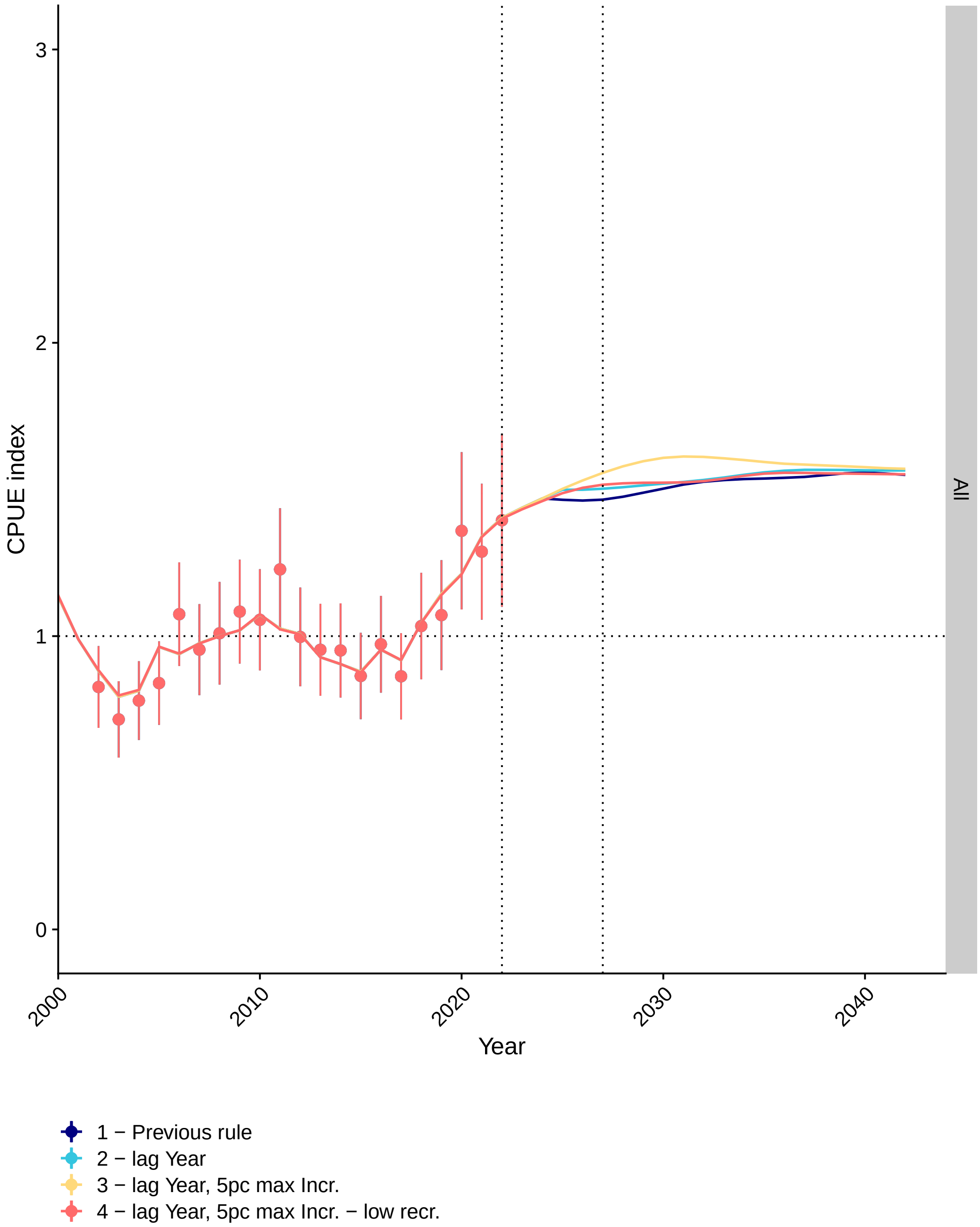

Figure C-3: Estimated and projected catch-per-unit-effort (CPUE) trend for pāua, comparing rules with added lag year and limits to annual increases (5%) to previous control rules under the base-case and alternative recruitment assumptions (low recr.) for quota management area PAU 5D. Only medians from simulations are compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

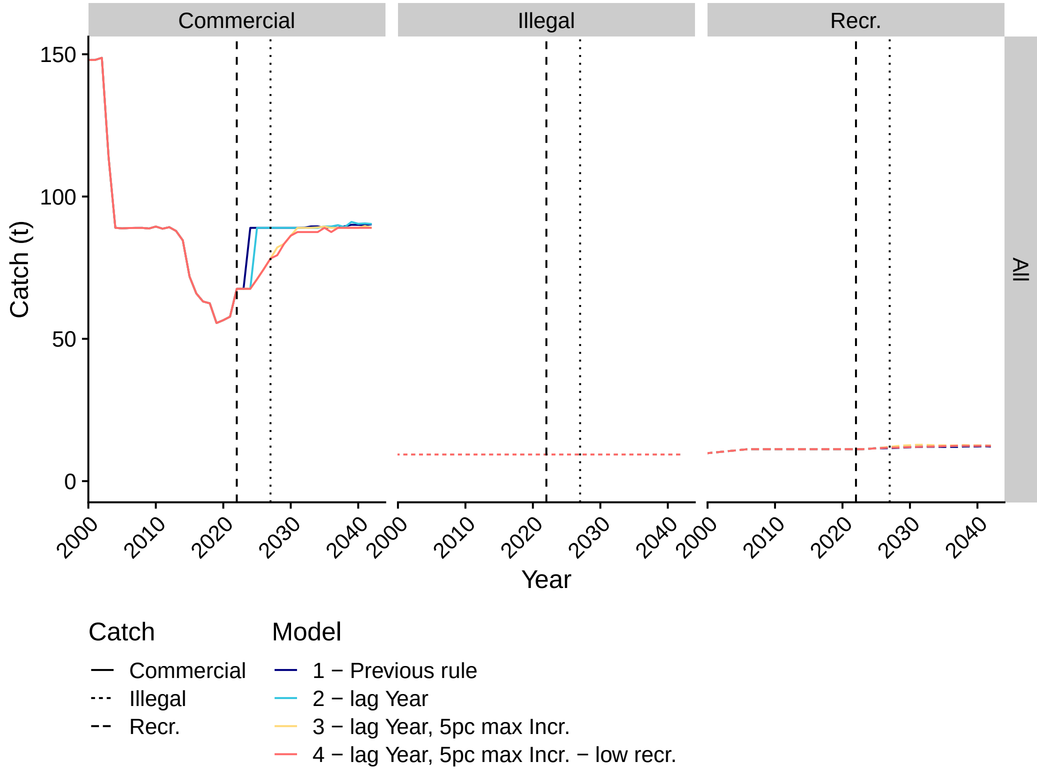

Figure C-4: Assumed and projected catch by sector, comparing rules with added lag year and limits to annual increases (5%) to previous control rules under the base-case and alternative recruitment assumptions (low recr.) for quota management area PAU 5D. Only medians from simulations were compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

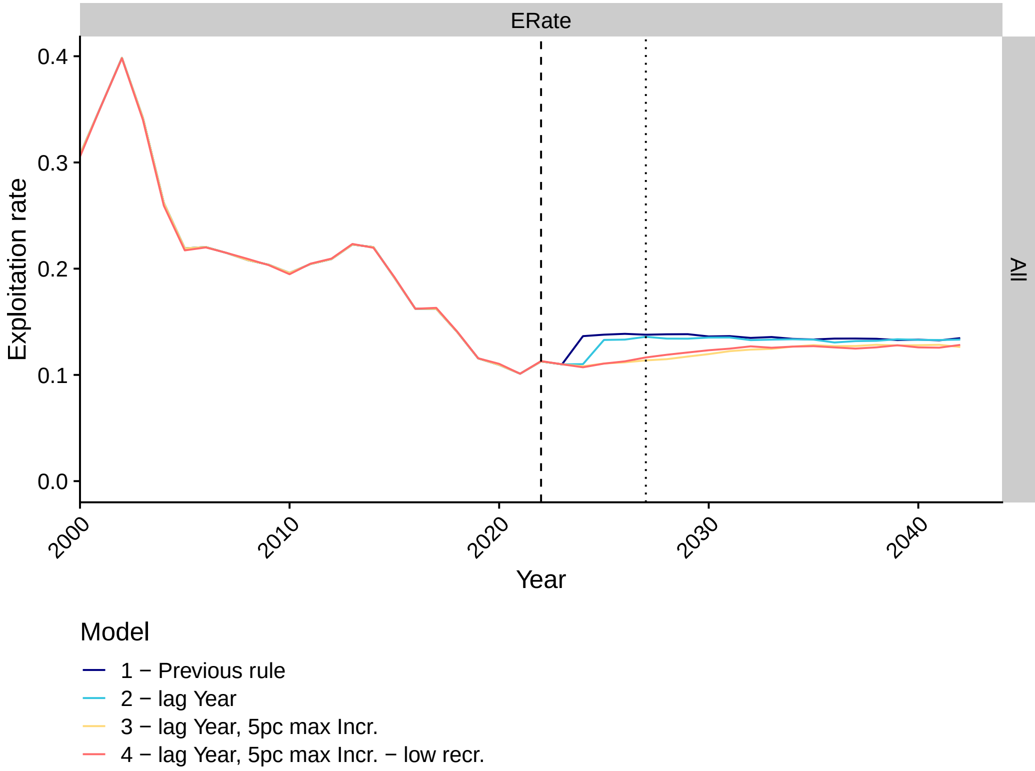

Figure C-5: Estimated and projected exploitation rate for the commercial pāua fishery (median line), comparing rules with added lag year and limits to annual increases (5%) to previous control rules under the base-case and alternative recruitment assumptions (low recr.) for quota management area PAU 5D. Model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

Table C-1: Performance of tested management procedures, comparing rules with added lag year and limits to annual increases (5%) to previous control rules under the base-case and alternative recruitment assumptions (low recr.) for quota management area PAU 5D. *SSB*, spawning stock biomass; CPUE, catch-per-unit-effort.

Model	Area	Mean rel. *SSB* (2026)	Mean rel. *SSB* (2042)	P(rel. *SSB* (2026) > 0.4)	P(rel. *SSB* (2042) > 0.4)	P(rel. *SSB* (2026) < 0.2)	P(rel. *SSB* (2042) < 0.2)	P(rel. *SSB* (2026) < 0.1)	P(rel. *SSB* (2042) < 0.1)	Mean rel. *SSB* (2021–2042)	Mean catch (t)	Mean CPUE (kg/h)
Previous rule	All	0.40	0.43	0.43	0.51	0.01	0.04	0.00	0.00	0.41	88.3	49.31
lagYear	All	0.41	0.44	0.47	0.51	0.01	0.04	0.00	0.00	0.42	87.2	49.89
lagYear 5% Incr.	All	0.41	0.43	0.51	0.53	0.01	0.04	0.00	0.00	0.42	82.5	51.22
lagYear 5% Incr. Low R.	All	0.40	0.42	0.41	0.53	0.00	0.03	0.00	0.00	0.41	81.2	49.52

APPENDIX D: MANAGEMENT PROCEDURE EVALUATION: UPDATED CONTROL RULE

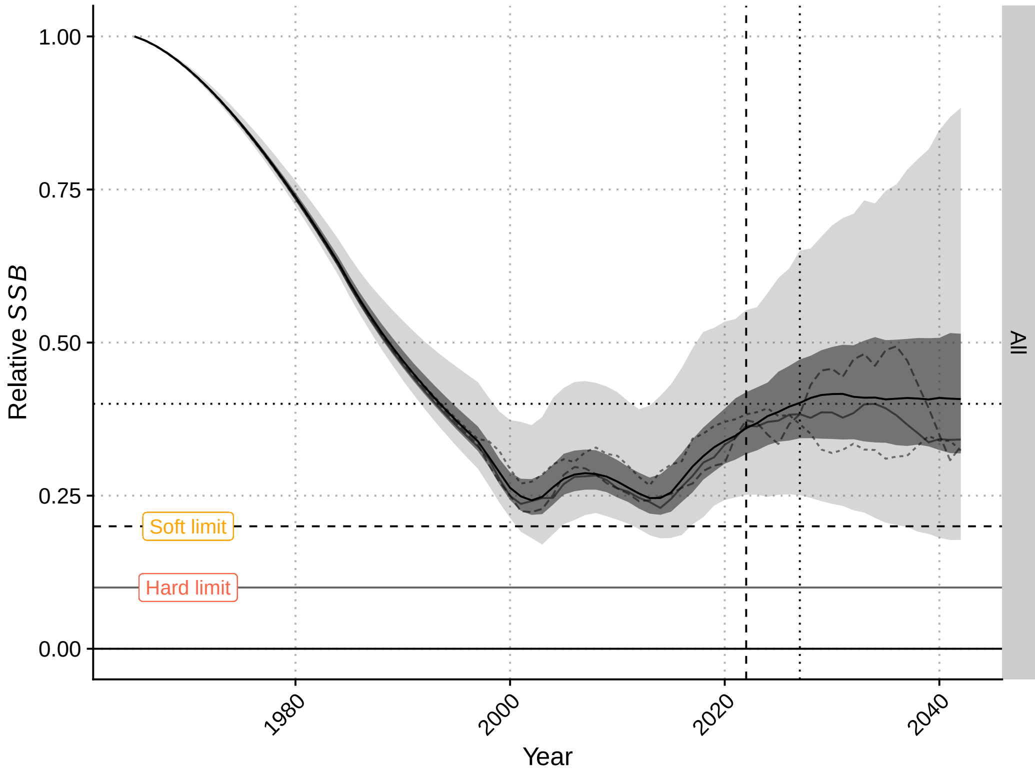

Figure D-1: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua for the updated control rule, evaluated under the base caste stock assessment model for quota management area PAU 5D (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)). Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. Three randomly-chosen realisations from the stochastic simulations are shown as grey lines. The final projection year was 2042.

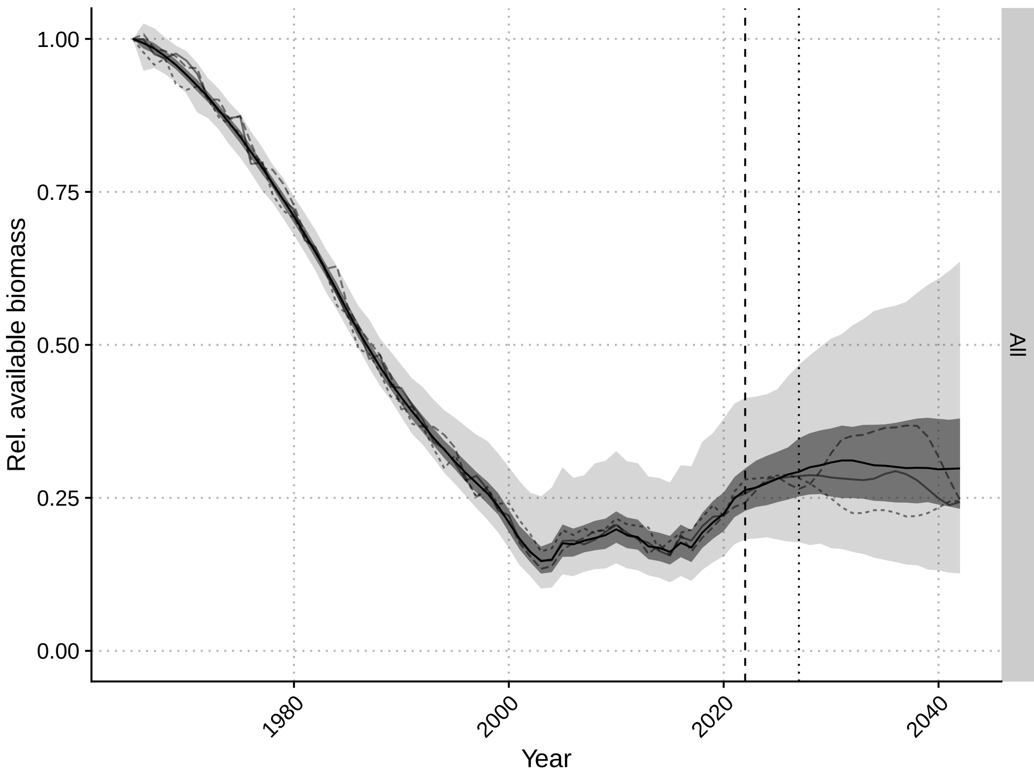

Figure D-2: Estimated and projected relative available biomass trend for pāua for the updated control rule, evaluated under the base caste stock assessment model for quota management area PAU 5D (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)). Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. Three randomly-chosen realisations from the stochastic simulations are shown as grey lines. The final projection year was 2042.

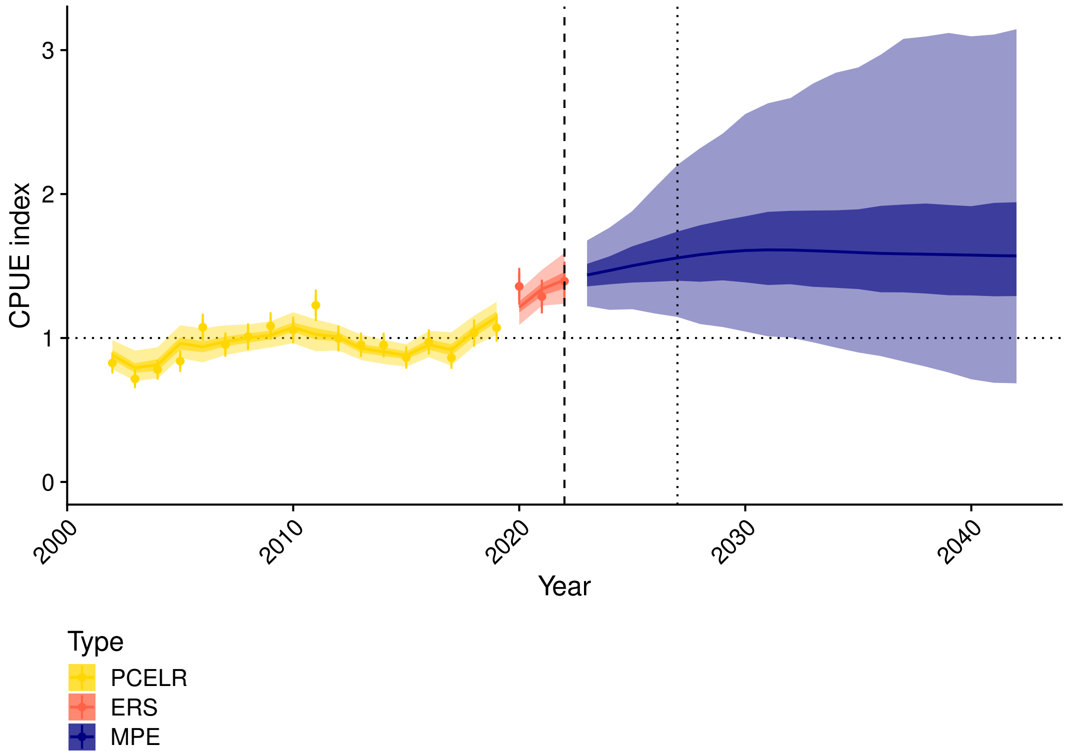

Figure D-3: Predicted catch-per-unit-effort (CPUE) trends for past and future fishery for pāua for the updated control rule, evaluated under the base caste stock assessment model for quota management area PAU 5D (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)). The final projection year was 2042. (P)CELR, (Paua) Catch Effort Landing Return; ERS, Electronic Reporting System; MPE, management procedure evaluation.

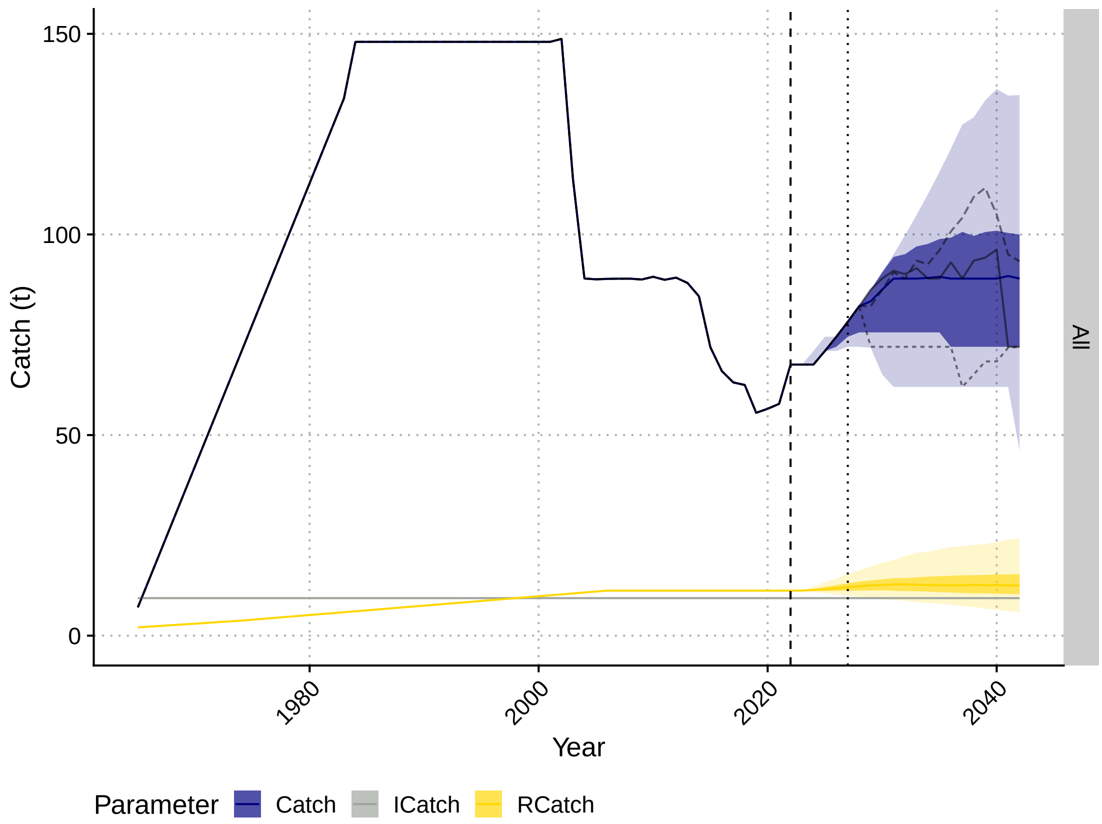

Figure D-4: Assumed and projected pāua catch by sector (I: illegal; R: recreational) for the updated control rule, evaluated under the base caste stock assessment model for quota management area PAU 5D. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. Three randomly-chosen realisations from the stochastic simulations are shown as black lines. The final projection year was 2042.

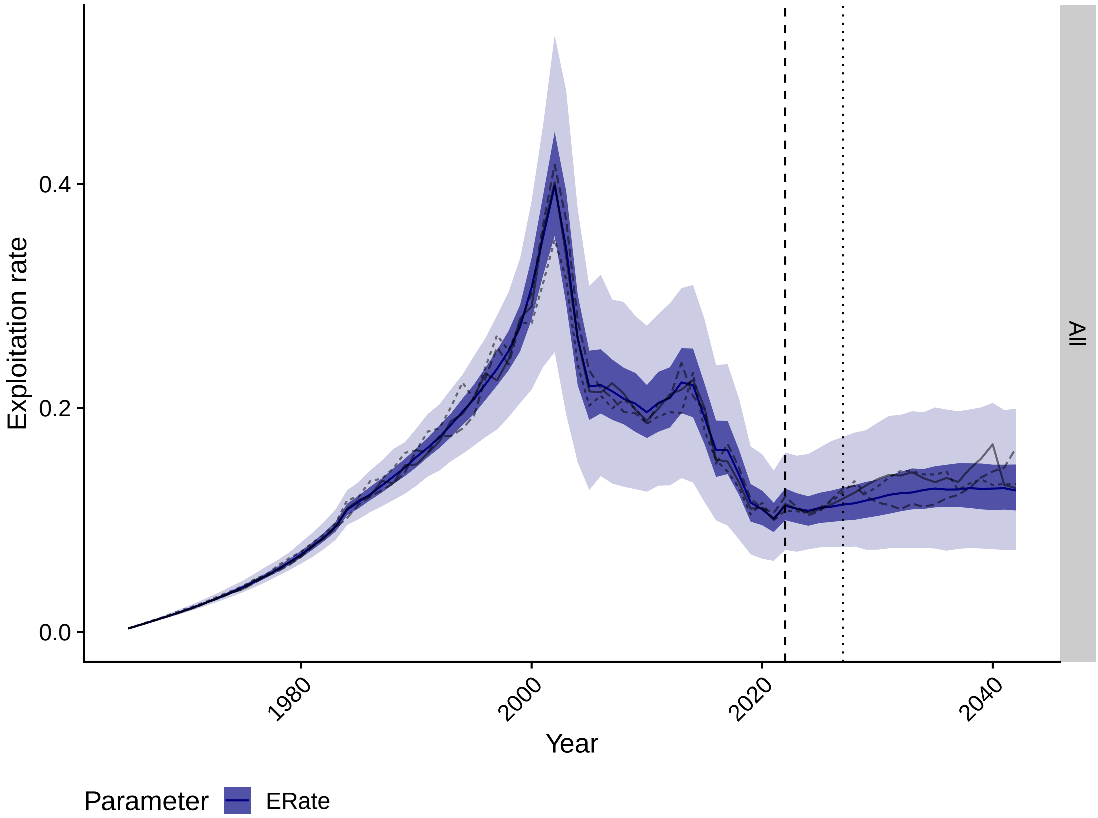

Figure D-5: Estimated and projected commercial exploitation rate (median line and 95% confidence interval) for the updated control rule, evaluated under the base caste stock assessment model for quota management area PAU 5D. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. Three randomly-chosen realisations from the stochastic simulations are shown as black lines. The final projection year was 2042.

APPENDIX E: MANAGEMENT PROCEDURE EVALUATION: MODEL COMPARISON

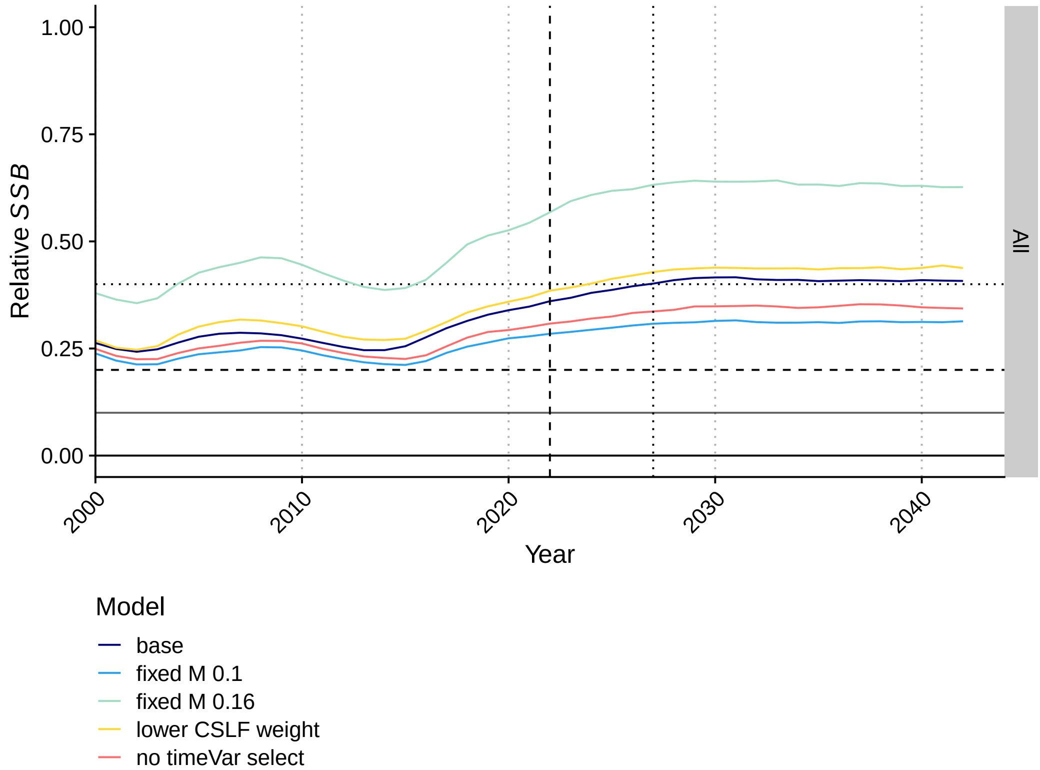

Figure E-1: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua, comparing models assuming different productivity parameters (mortality; LF, length frequency), with management according to the updated control rule in quota management area PAU 5D. Only medians from simulations are compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

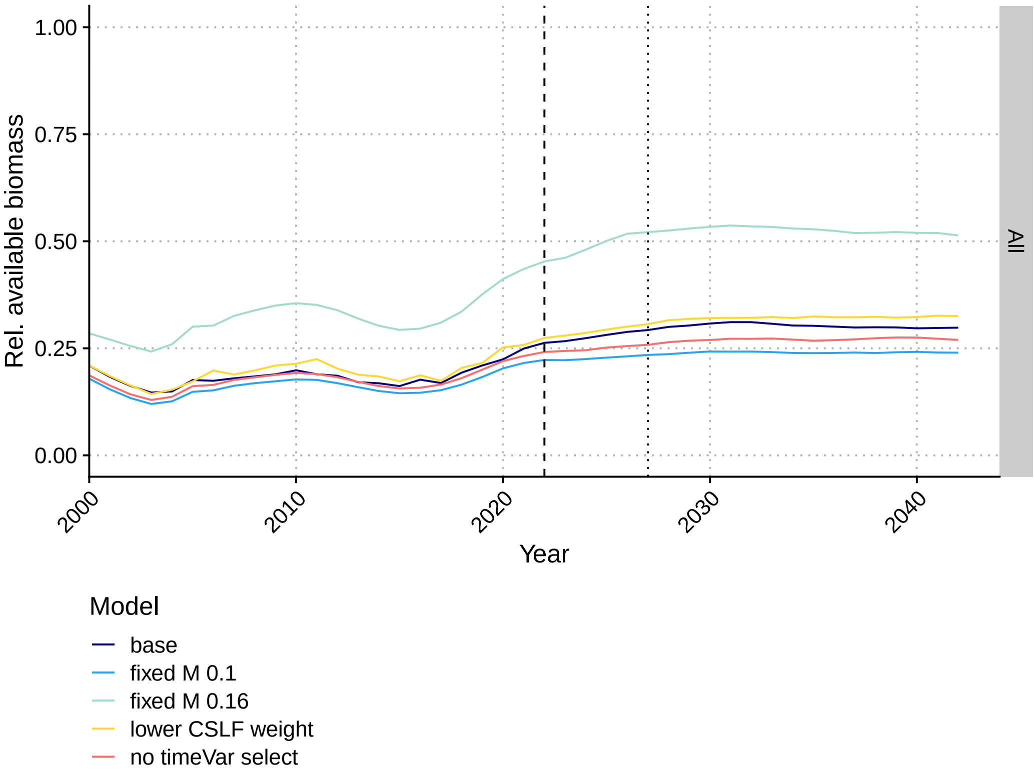

Figure E-2: Estimated and projected relative available biomass trend for pāua, comparing models assuming different productivity parameters (mortality; LF, length frequency), with management according to the updated control rule in quota management area PAU 5D. Only medians from simulations are compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

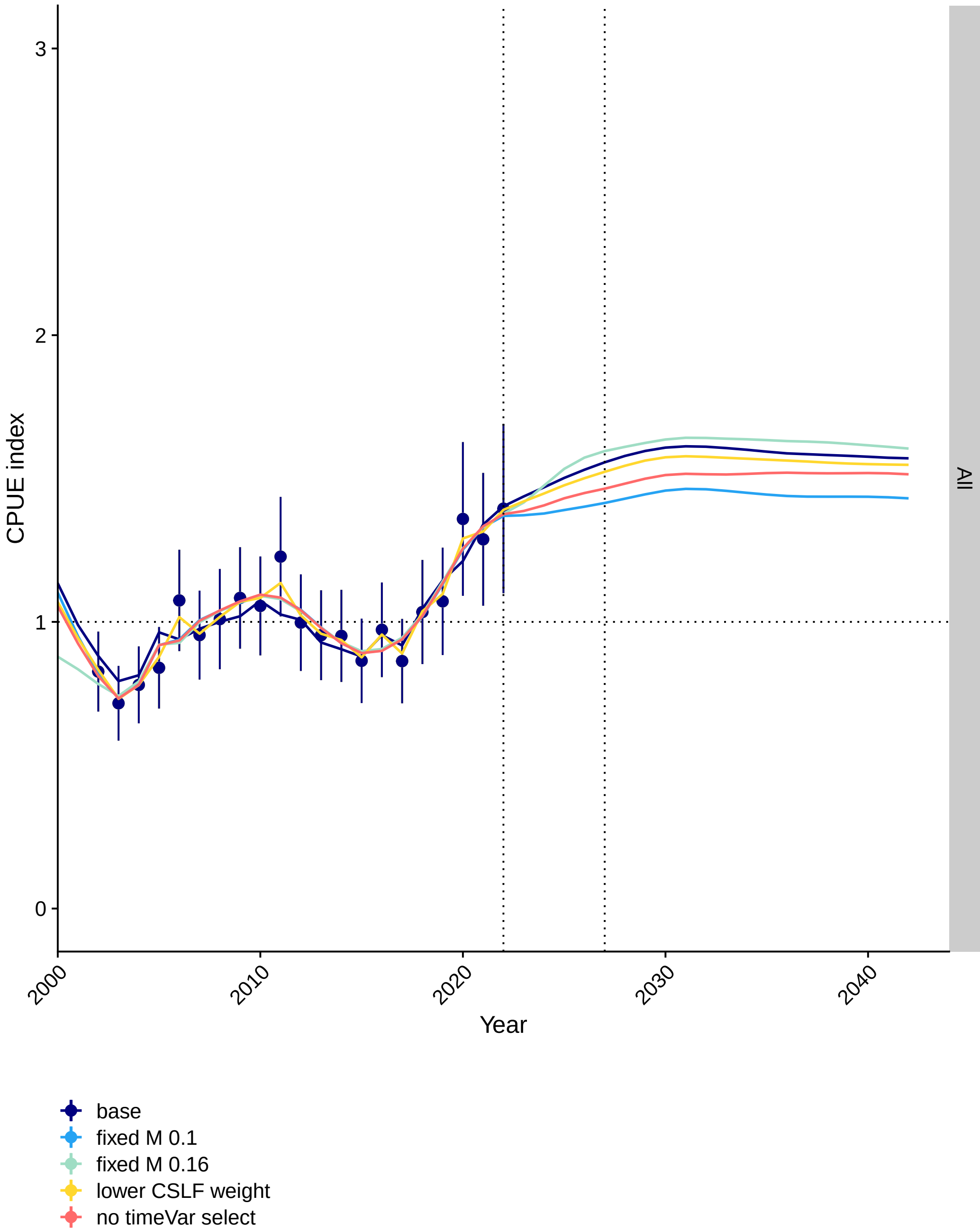

Figure E-3: Estimated and projected catch-per-unit-effort (CPUE) trend for pāua, comparing models assuming different productivity parameters (mortality; LF, length frequency), with management according to the updated control rule in quota management area PAU 5D. Only medians from simulations are compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

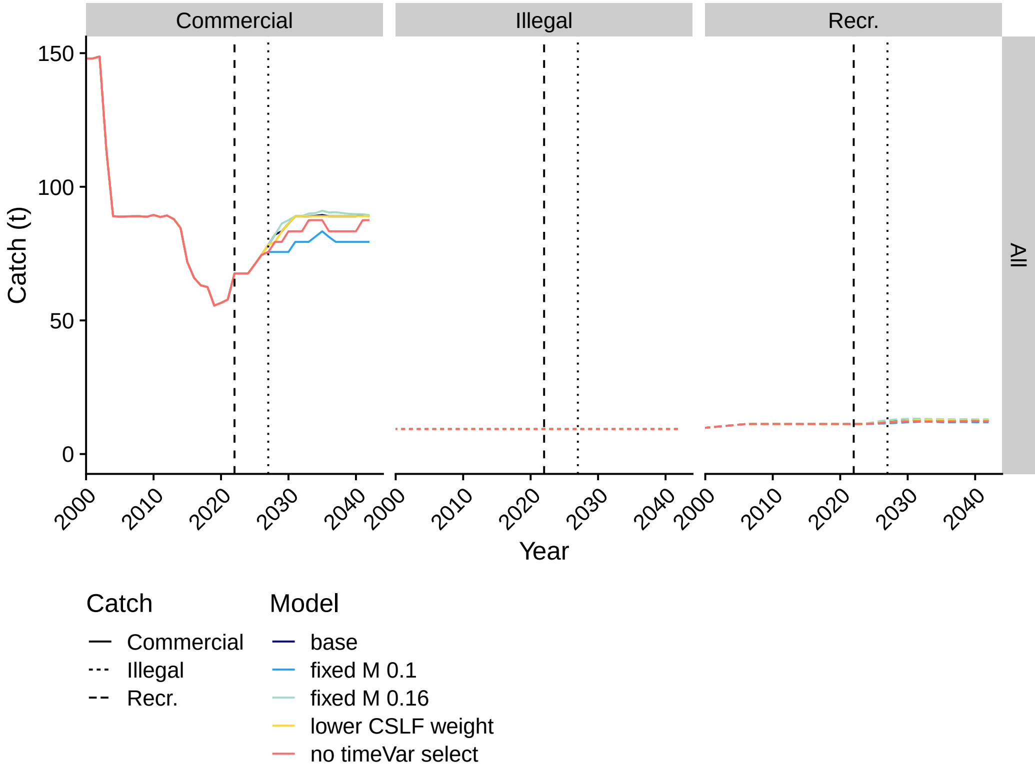

Figure E-4: Assumed and projected catch by sector, comparing models assuming different productivity parameters (mortality; LF, length frequency), with management according to the updated control rule in quota management area PAU 5D. Only medians from simulations were compared, and model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

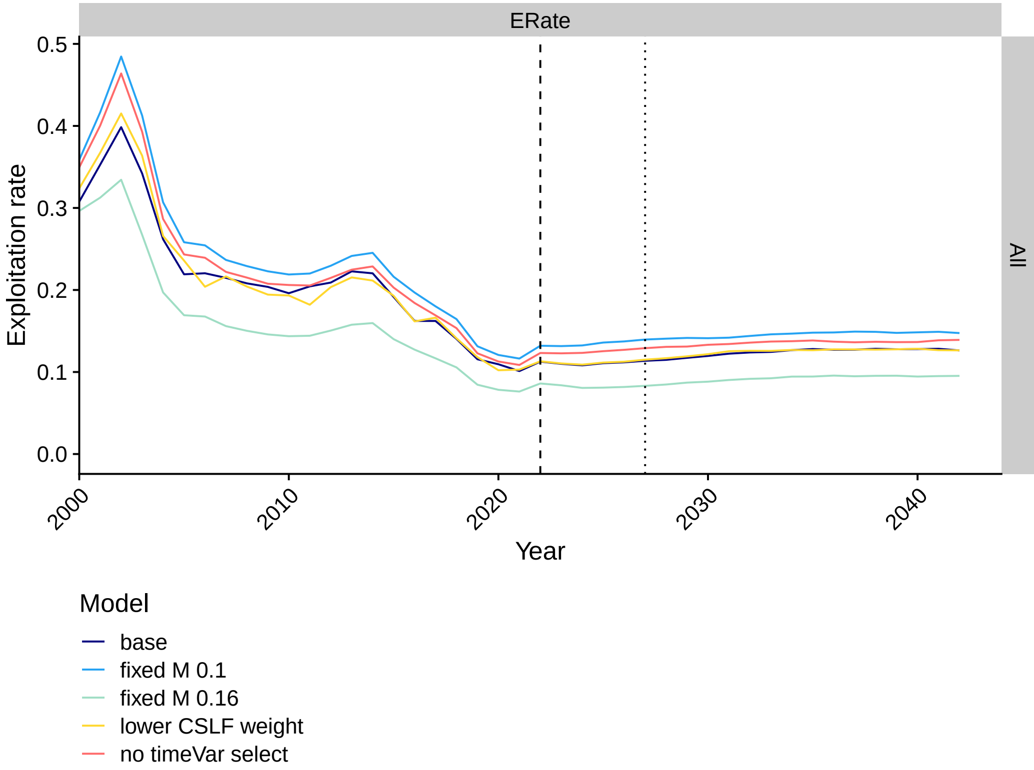

Figure E-5: Estimated and projected exploitation rate for the commercial pāua fishery (median line), comparing models assuming different productivity parameters (mortality; LF, length frequency), with management according to the updated control rule in quota management area PAU 5D. Model trajectories may overlap over parts or all of the time series, so that only one realisation may be visible. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule, dotted vertical line shows the tested limit of validity (5 years) of the tested rule. The final projection year was 2042.

Table E-1: Performance of tested management procedures, comparing models assuming different productivity parameters (mortality; LF, length frequency), with management according to the updated control rule in quota management area PAU 5D. *SSB*, spawning stock biomass; CPUE, catch-per-unit-effort.

Model	Area	Mean rel. *SSB* (2026)	Mean rel. *SSB* (2042)	P(rel. *SSB* (2026) > 0.4)	P(rel. *SSB* (2042) > 0.4)	P(rel. *SSB* (2026) < 0.2)	P(rel. *SSB* (2042) < 0.2)	P(rel. *SSB* (2026) < 0.1)	P(rel. *SSB* (2042) < 0.1)	Mean rel. *SSB* (2021–2042)	Mean catch (t)	Mean CPUE (kg/h)
Base	All	0.41	0.43	0.51	0.53	0.01	0.04	0.00	0.00	0.42	82.6	51.22
No time-var. select.	All	0.35	0.38	0.27	0.36	0.01	0.08	0.00	0.00	0.36	80.6	48.91
Fixed M=0.1	All	0.31	0.32	0.08	0.22	0.03	0.13	0.00	0.00	0.32	78.6	46.62
Fixed M=0.16	All	0.63	0.66	0.99	0.92	0.00	0.00	0.00	0.00	0.64	83.6	52.32
Lower LF weight	All	0.44	0.46	0.58	0.59	0.00	0.04	0.00	0.00	0.45	82.1	50.00