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Developing an operating model and testing management procedures for pāua (*Haliotis iris*) fisheries in PAU 3B

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EXECUTIVE SUMMARY

Neubauer, P.[1]; Kim, K.[1] (2023). Developing an operating model and testing management procedures for pāua (*Haliotis iris*) fisheries in PAU 3B.

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Pāua (*Haliotis iris*) quota management area (QMA) PAU 3B was established in 2021 as the southern area of the former QMA PAU 3, which had the northern area closed between 2017 and 2021, following the 2016 Kaikōura earthquakes. The southern area remained open for pāua fisheries, albeit at a Total Allowable Commercial Catch (TACC) of half the original TACC of QMA PAU 3 (46 t).

Although there was an existing stock assessment for PAU 3 prior to the earthquakes, the assessment was considered to be poorly representative of southern areas, which were fished considerably less frequently than the Kaikōura area (now PAU 3A). In addition, no representative growth data were available from the area, leading to marked uncertainties about stock status. With the establishment of PAU 3B, there has been increased interest in understanding the stock status of the area, and to develop management measures that can maintain the fishery at target levels. The present project aimed to develop models to understand stock status, and to test potential management procedures in PAU 3B.

For this study, catch, catch-per-unit-effort (CPUE), and length-frequency information were compiled to inform models for stock in PAU 3B. Catch and CPUE information is only known with some certainty since the early 2000s and the establishment of fine-scale pāua statistical areas, which allow partitioning of PAU 3 catches and catch-effort data into PAU 3A and PAU 3B components. Assumptions about spatial catch splits needed to be made to reconstruct catches prior to 2002. Nevertheless, early catches were likely relatively low as the area was less targeted by commercial fisheries than the northern area of PAU 3. The CPUE has remained relatively constant through the 2000s, with a small increase in recent years.

An initial attempt to fit stock assessment models was unsuccessful based on the flat or increasing CPUE, which occurred in the context of increasing catch over time. In the absence of a robust stock assessment model, we explored the use of CPUE (kg/h) relative to CPUE in other areas as a measure of potential stock status or exploitation rate. This approach suggested a relatively low exploitation rate and high stock status near 60% of unfished biomass.

To test potential harvest control rules, we used empirical estimates of stock status to condition operating models using depletion-based stock reduction analysis. The operating models produced a range of outcomes depending on productivity assumptions and conditioning constrains, and were used to test the suitability of control rules to maintain target catch rates.

[1] Dragonfly Data Science, New Zealand.

1. INTRODUCTION

In most pāua (*Haliotis iris*) quota management areas (QMAs), the management of stocks relies on stock assessments to estimate population status. Of these quota management areas, PAU 3 was most-recently assessed in 2013, with significant uncertainty about stock status outcomes. The uncertainty was due to a lack of conclusive biological data that could support conclusive estimates of stock productivity. Nevertheless, relatively stable catch-per-unit-effort (CPUE) and length frequencies suggested a stable fishery.

The area on the north-east coast of South Island Te Waipounamu was strongly affected by the 2016 earthquakes that struck near Kaikōura and caused substantial coastal uplift and associated pāua mortality in areas of PAU 3 and PAU 7. The area was subsequently closed to all fishing for five years, and dive surveys have been used since then to monitor the rebuild of biomass following the earthquakes (McCowan & Neubauer 2021). In the meantime, areas of PAU 3 south of the Conway River remained open at a reduced (halved) Total Allowable Commercial Catch (TACC). To facilitate separate management of the earthquake-affected area and the remaining area of PAU 3, the QMA was divided into PAU 3A (Kaikōura) and PAU 3B (Canterbury coast and Banks Peninsula).

To manage these sub-divided fisheries, a series of projects attempted to build models and evaluate management options for both of these areas. The development of management options followed the implementation of industry-determined control rules in the PAU 5 areas (Neubauer 2019, 2021). The perceived success of more formalised, responsive management rules led to their adoption as strategies for managing pāua fisheries in so-called "fisheries plans" for PAU 3, and other areas. These plans are strategic documents, which stipulate that fisheries ought to be managed on the basis of harvest control rules. To test these control rules, operating models were required for the newly subdivided QMAs of PAU 3.

The present project initially attempted to develop a stock assessment model for PAU 3B to estimate stock status, and to serve as an operating model to test harvest control rules. The model was developed to align with management at the scale of industry management zones (Figure 1; hereafter also referred to as regions), which partition catch among spatial strata and allow the fishing industry to set area-specific minimum harvest sizes (MHSs). Despite increases in catch over a number of years, the lack of signal from CPUE prevented the fitting of stock assessment models. Observed CPUE has remained high relative to other areas, suggesting a relatively strong fishery. For this reason, the present assessment used a direct meta-analysis across fisheries to provide information about the likely stock status. The meta analysis was also used to constrain the stock assessment model *a priori* so that it would function as an operating model that can be used for testing management options. Management options were developed with stakeholders, and evaluated on the basis of the constrained model.

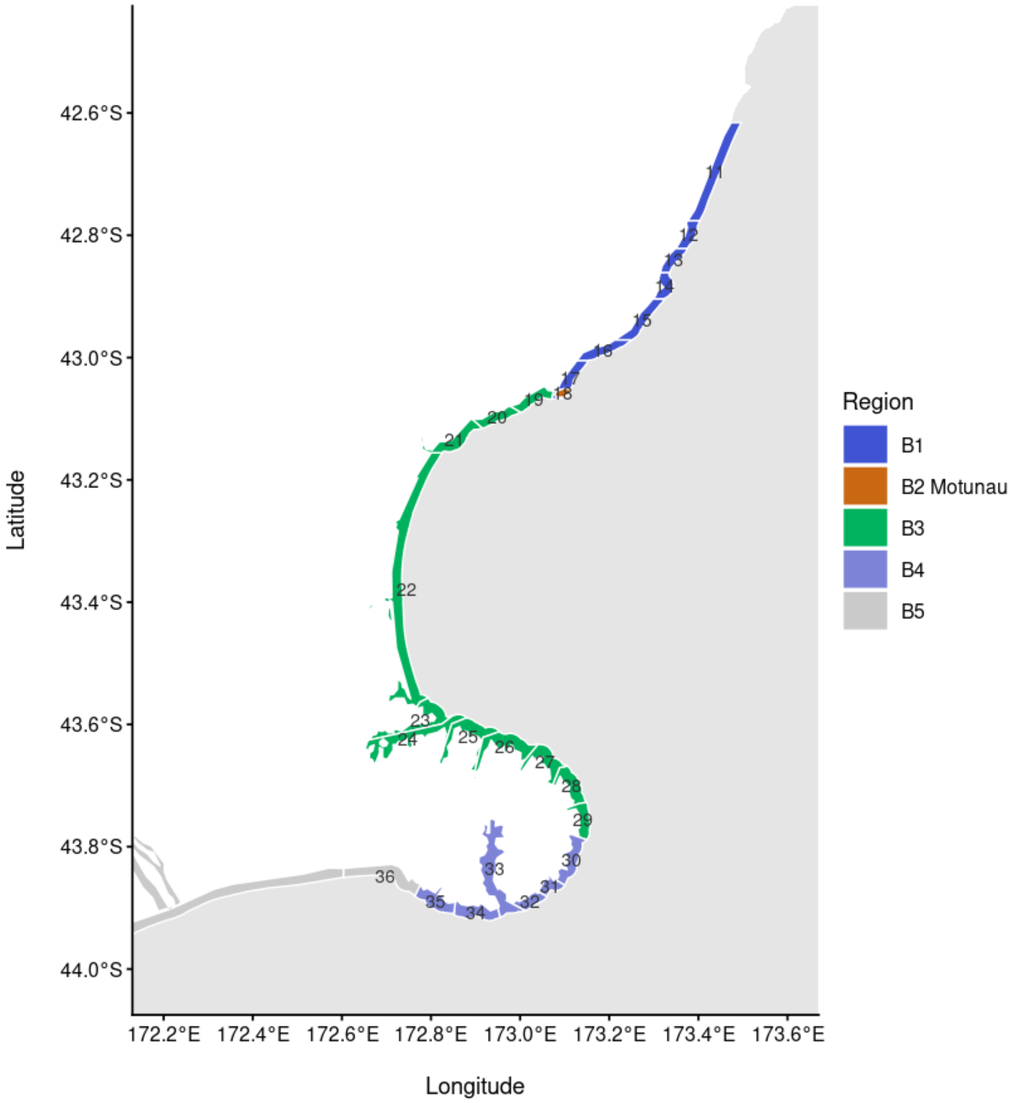

Figure 1: Pāua quota management area (QMA) PAU 3B (Canterbury coast and Banks Peninsula), including key spatial divisions used for industry management. Catch reporting was initially at a lower spatial resolution of large statistical areas (not shown), and subsequently changed (in 2002) to fine-spatial scale pāua statistical areas shown here (coloured).

2. METHODS

2.1 Inputs

Inputs for the PAU 3B stock model consisted of data of commercial catch, CPUE data from (Paua) Catch Effort Landing Return ((P)CELR) forms and the Electronic Reporting System (ERS), length-frequency data from commercial sampling (CSLF). Catch assumptions for recreational, customary, and illegal take were agreed by the Shellfish Working Group (SFWG), and treated as known. Only limited biological data (i.e., growth data) are available for PAU 3B, and these data are not considered representative of the fished areas (Fu 2014, Fu et al. 2014); only distributions derived from meta-analyses were used in models for PAU 3B.

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 2021). Data sources for early catch included early reports on commercial pāua catch (Murray & Akroyd 1984), the Fisheries Statistical Unit (FSU) database (1983–1989), and catch effort data supplied by Fisheries New Zealand (Table 1, Figure 2).

Table 1: Sources of pāua catch data, 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 in 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 3B cannot be reconstructed with precision prior to the introduction of fine-scale statistical areas 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 Area 018, straddled PAU 7, PAU 3A, and PAU 3B. The majority of catch is considered to have been from areas north and south of Kaikōura Peninsula, which currently encompasses PAU 3A. This assumption is supported by more recent data from the area, which shows between 5 and 15% of annual catch from Statistical Area 018 from PAU 3B (Figure 3). For all data prior to 2002, it was assumed here that 10% of catch reported from Statistical Area 018 came from PAU 3B. Similarly, it was assumed that 18% of landings from PAU 3 were from PAU 3B over time, which amounts to the average of landings over the period of reporting years with PCELR forms.

Since 2002, catch has been relatively stable spatially, with zone B3 fished sporadically. Increases in catch in recent years have mainly been supported by shifting more effort to areas that previously supported relatively low catch (Figure 4).

For the early part (1974–1983) of the catch history, the commercial catch reconstruction used data from Murray & Akroyd (1984); the FSU data were used from 1983 to 1988, whereas from 1990 onwards, estimated catch data from CELR forms were used. Catch in 1989 was interpolated between 1988 and 1990. All catch sources were attributed to PAU 3B according to different proportions (see Table 1).

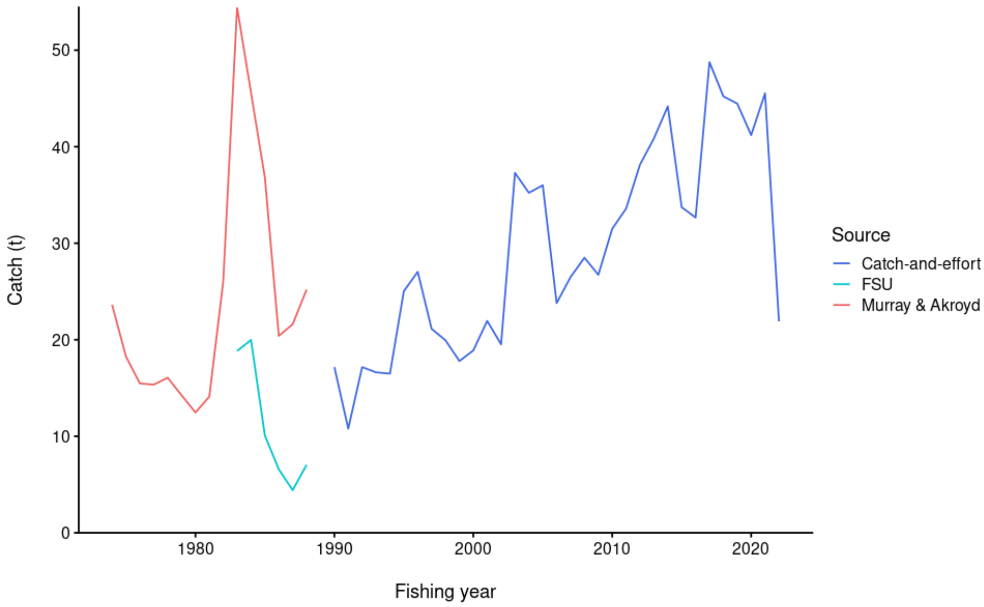

Figure 2: Commercial catch history for pāua quota management area (QMA) PAU 3B from 1974 to 2021. Catch to 1983 was reconstructed from data reported by Murray & Akroyd (1984; red line). Data from 1983–1986 were from the Fisheries Statistical Unit (FSU) database (teal line; these data were not used in the present assessment due to unrealistically low catches). Catch-effort data from 1989 was supplied by Fisheries New Zealand (catch-and-effort, blue). (Note, no other sources of catch were available due to the recent sub-division of QMA PAU 3.)

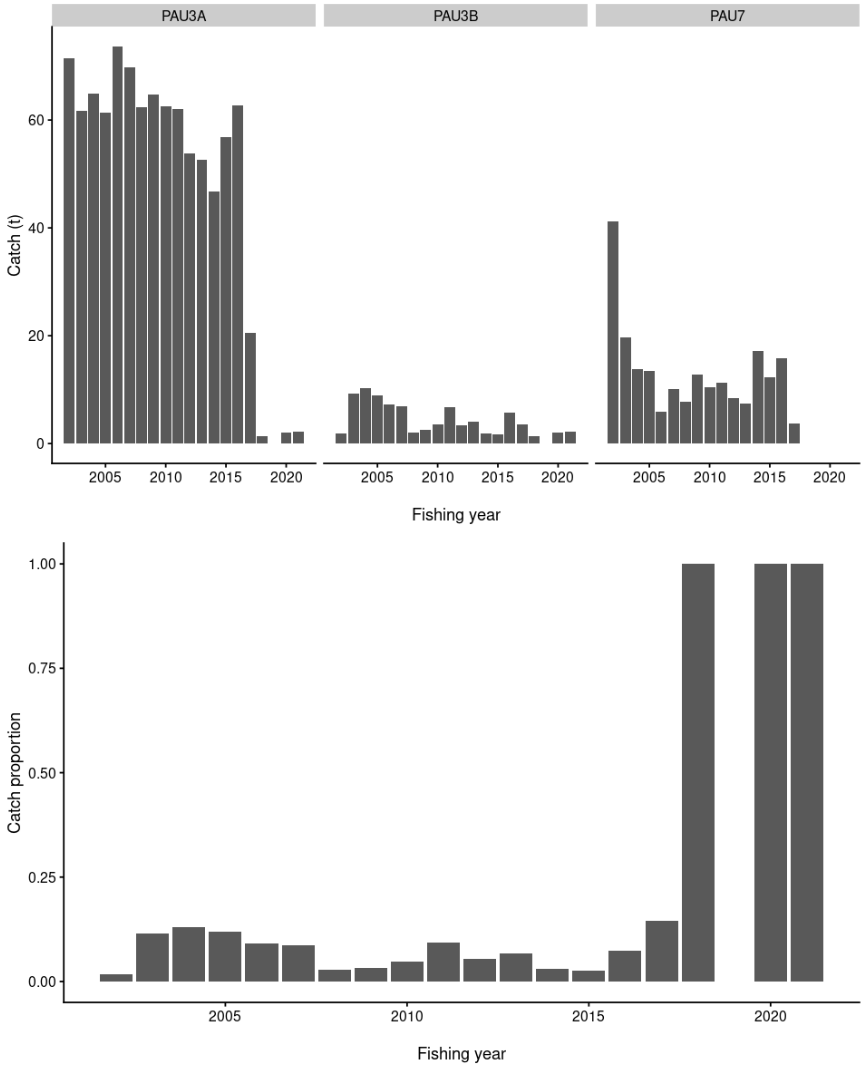

Figure 3: Estimated pāua catch (top) from Statistical Area 018 by quota management area (QMA) since introduction of Pāua Catch Effort Landing Return (PCELR) reporting, and proportion of catch (bottom) assigned to PAU 3B. (Note, high proportions of catch since 2017 were due to the closure of PAU 7 and parts of Statistical Area 018 in PAU 3A following the 2016 earthquakes in Kaikōura. Some fishing occurred in the 2017 fishing year prior to the earthquakes, so that remaining records in PAU 3A since 2017 are likely recording errors in the statistical area reported on PCELR or Electronic Reporting System.)

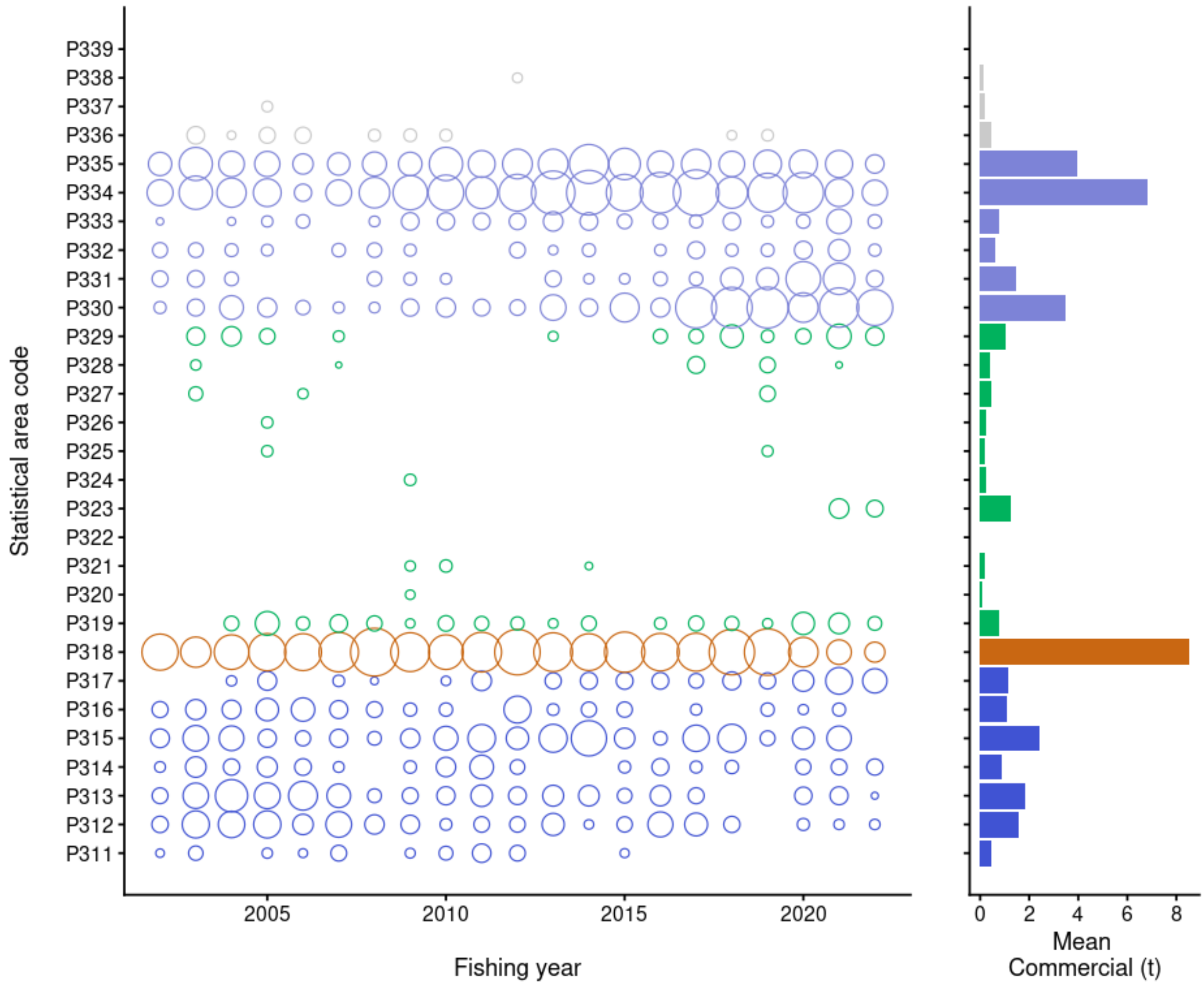

Figure 4: Relative trend in pāua catch (kg) over time by pāua statistical areas in quota management area PAU 3B for the period from 2002 to 2022, with total catch over the same time period (right-hand side). Current commercial management zones within PAU 3B are colour coded (blue: zone B1 (North); orange: zone B2 (Motunau Island); green: Zone B3 (Motunau to northern Banks Peninsula); purple: zone B4 (Akaroa and southern Banks Peninsula); and grey: zone B5 (South of Banks Peninsula).

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 16.98 t (coefficient of variation, CV, of 31%) of pāua were taken by recreational fishers in the whole of PAU 3 for 2011–12 (Wynne-Jones et al. 2014). This estimate was combined for all areas of PAU 3A and PAU 3B, and most of this take was considered to have been from PAU 3A. In 2017–18, the national panel survey was repeated and the estimated recreational catch was 8.79 t (CV of 35%) (Wynne-Jones et al. 2019). Due to the closure following the earthquake, this estimate was considered to represent only PAU 3B. Although the latter estimate is over half of the 2012 estimate for PAU 3 combined, the earthquake closure of PAU 3A is deemed to have shifted recreational take into PAU 3B in recent years. For this reason, the Shellfish Working Group decided to assume a linear increase in recreational take from 1 t in 1974 to 8.79 t in 2017, with stable catch since then.

There is no comprehensive information available on customary take in recent years. Owing to this lack, the Shellfish Working Group agreed to assume that customary catch was 1 t in 1974, increasing linearly to 2 t between 1974 and 2012, and then remaining at 2 t. Illegal catch was considered to be high during the 1990s when pāua prices increased, with subsequent enforcement efforts since the early 2000s likely to have led to marked reductions in illegal take. For this catch component, the Shellfish Working Group agreed to assume an increase in illegal catch from 1 t per year up to 1974 to 10 t annually by the 1990 fishing year; subsequent illegal take was assumed to remain at 10 t throughout the 1990s. Subsequent reductions from 10 t to 2 t between 2000 and 2010 reflected increasing enforcement, with steady illegal take at 2 t assumed for years since 2010.

Based on the different catch components, estimates of the total catch by area (Figure 5) were used in the spatial assessment, compared with total catch estimates for the area overall (Figure 6).

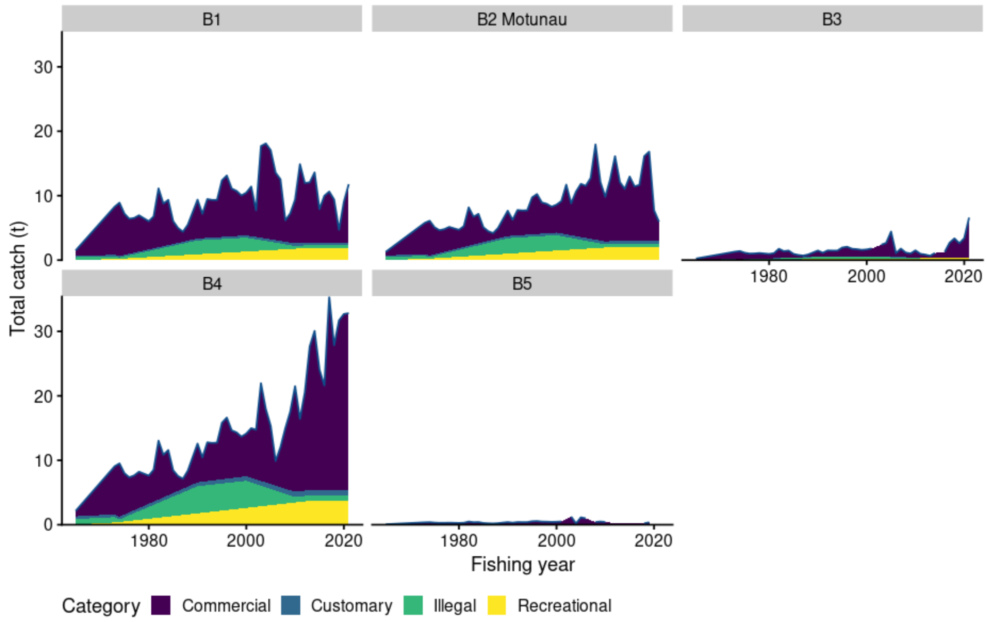

Figure 5: Estimated total pāua catch history for quota management area (QMA) PAU 3B from 1974 to 2020 by fishery component and reporting area. Fishery categories were commercial customary, illegal, and recreational and catch. Commercial catch was reconstructed up to 1995 when the QMA was created, and based on landing records thereafter.

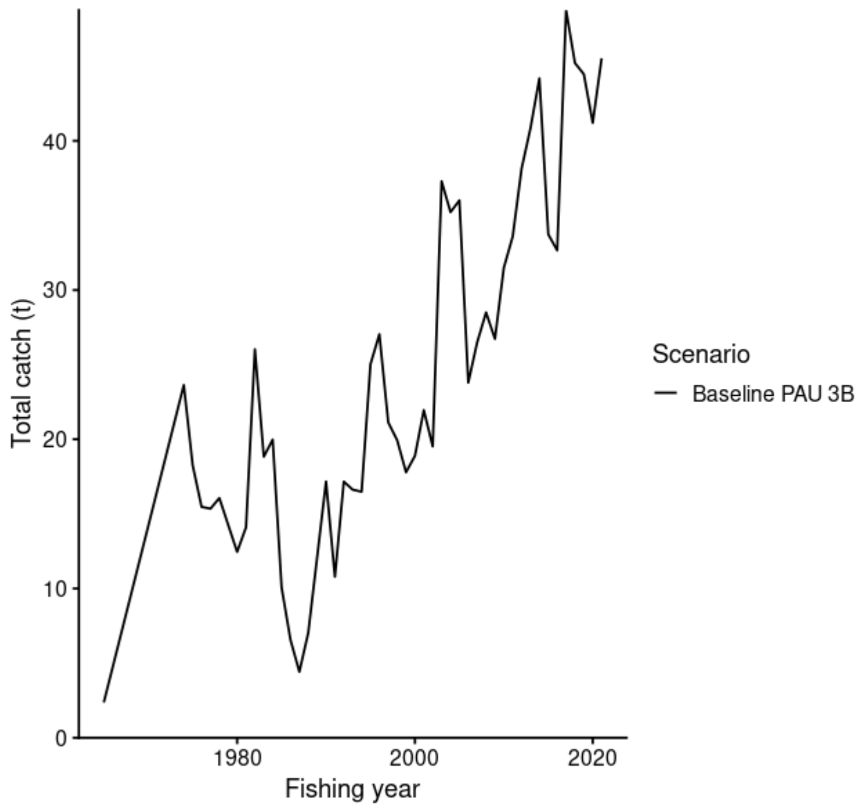

Figure 6: Total pāua catch history used in the single area stock assessment for quota management area PAU 3B from 1974 to 2020 as the sum of all catch components (commercial, customary, recreational, illegal).

2.1.3 Catch-per-unit-effort (CPUE)

The present assessment only considered PCELR (2002 to 2019) and ERS data (2020 to 2021). Although data from the FSU database and CELR forms were used in previous assessments (CELR data were used up to 2020), 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 Area 018 to 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). Alternative data preparation procedures for ERS data (Neubauer 2023) were meant to correct for potential misreporting in ERS data or differences relative to data reported on PCELR forms. Nevertheless, these data preparation steps did not change the CPUE in areas of interest for the assessment and were, therefore, not applied in the present analysis.

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	2020	Total	% retained
All	101	212	158	188	102	120	166	141	153	173	190	225	219	179	169	237	225	233	10	3201	100.00
Missing fields	101	212	158	188	102	120	166	141	153	173	190	225	219	179	169	237	225	231	10	3199	99.94
Stat-area years ≥ 5	101	204	158	183	101	120	166	138	151	173	189	225	218	179	169	232	225	225	10	3167	98.94
FIN years ≥ 2	100	197	151	174	97	120	166	138	142	173	186	225	210	168	159	210	202	225	10	3053	95.38
Diver years ≥ 2	76	148	130	161	83	113	144	123	132	153	166	209	187	154	149	182	192	198	10	2710	84.66
No. of divers ≤ 4	76	148	130	161	83	113	144	123	132	153	166	209	187	154	149	182	192	198	10	2710	84.66
Fishing duration ≤ 10h	75	148	130	157	83	113	142	123	132	152	162	203	182	152	147	182	192	198	10	2683	83.82
10kg/h $\leq$CPUE $\leq$500kg/h	75	147	125	153	82	112	140	123	131	152	162	203	180	152	146	182	190	197	10	2662	83.16

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	Total	% retained
All	196	236	637	100.00
FIN years ≥ 2	196	236	637	100.00
Diver years ≥ 2	192	220	617	96.86
No. of divers ≤ 4	192	220	617	96.86
Fishing duration ≤ 10h	192	220	617	96.86
10kg/h $\leq$CPUE $\leq$500kg/h	174	208	585	91.84

The PCELR and ERS data from 2002 were combined to derive a single standardised, fishery-dependent index of abundance. The CPUE standardisation was carried out using Bayesian Generalised Linear Mixed Models (GLMM) which partitioned variation among fixed (research strata) and random variables. The CPUE was defined as the log of daily catch. Variables in the model were fishing year, estimated fishing effort, client identification number, research stratum, small-scale statistical area, and diver identification (PCELR).

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 zones B2 and B4, while zone B1 has remained largely stable. Client (ACE-holder) and diver ID had the strongest standardising effects for recent CPUE (Figure 9). The diver identification (PCLER) had a negative standardising effect in the standardisation model (Figure 10), and an increasing number of inexperienced divers entering the fishery reduced raw CPUE. Similarly, less efficient crews entered the fishery in most recent years, leading to a slight decrease in the CPUE (Figure 11). In combination, these adjustments had limited impact on the standardised CPUE relative to the raw series.

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.

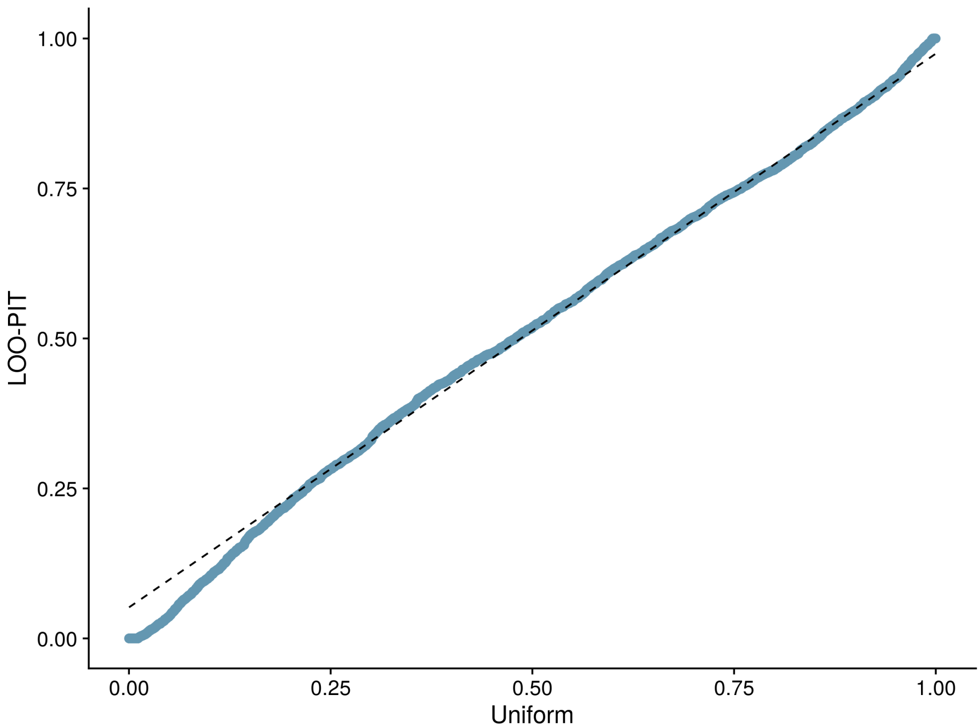

Figure 7: Fit of the log-normal generalised linear mixed model used for catch-per-unit-effort (CPUE) index standardisation. Shown is the cumulative distribution from posterior predictive draws from the model (i.e., predicting each data point; blue) compared with the empirical cumulative distribution (dashed black line). LOO-PIT, leave-one-out probability integral transform.

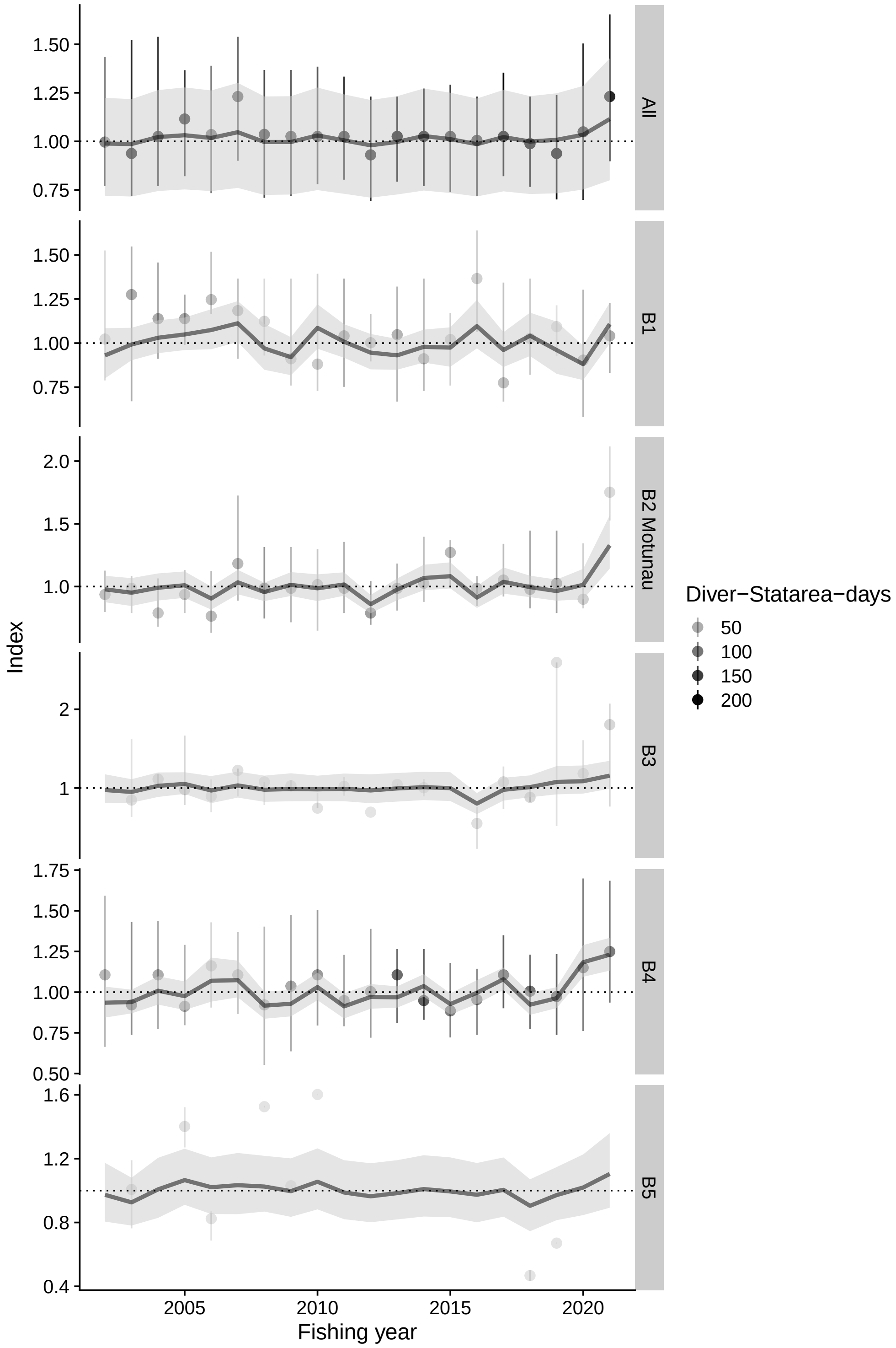

Figure 8: Standardised catch-per-unit-effort (CPUE) using a generalised linear mixed model with area-year interaction; showing CPUE by area. Black line and confidence interval show estimated CPUE index and 95% posterior quantiles, with data mean and inter-quartile range shown as points and error bars,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

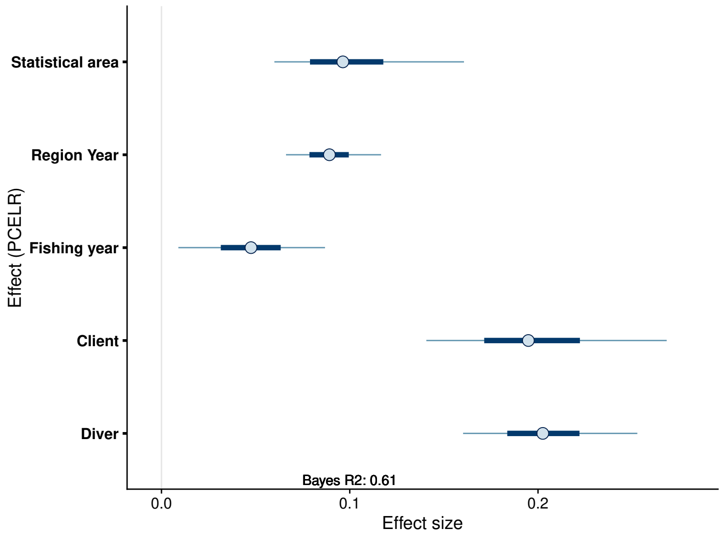

Figure 9: Effect size as variance explained for variables included in the random effects standardisation model. PCELR, Paua Catch Effort Landing Return.

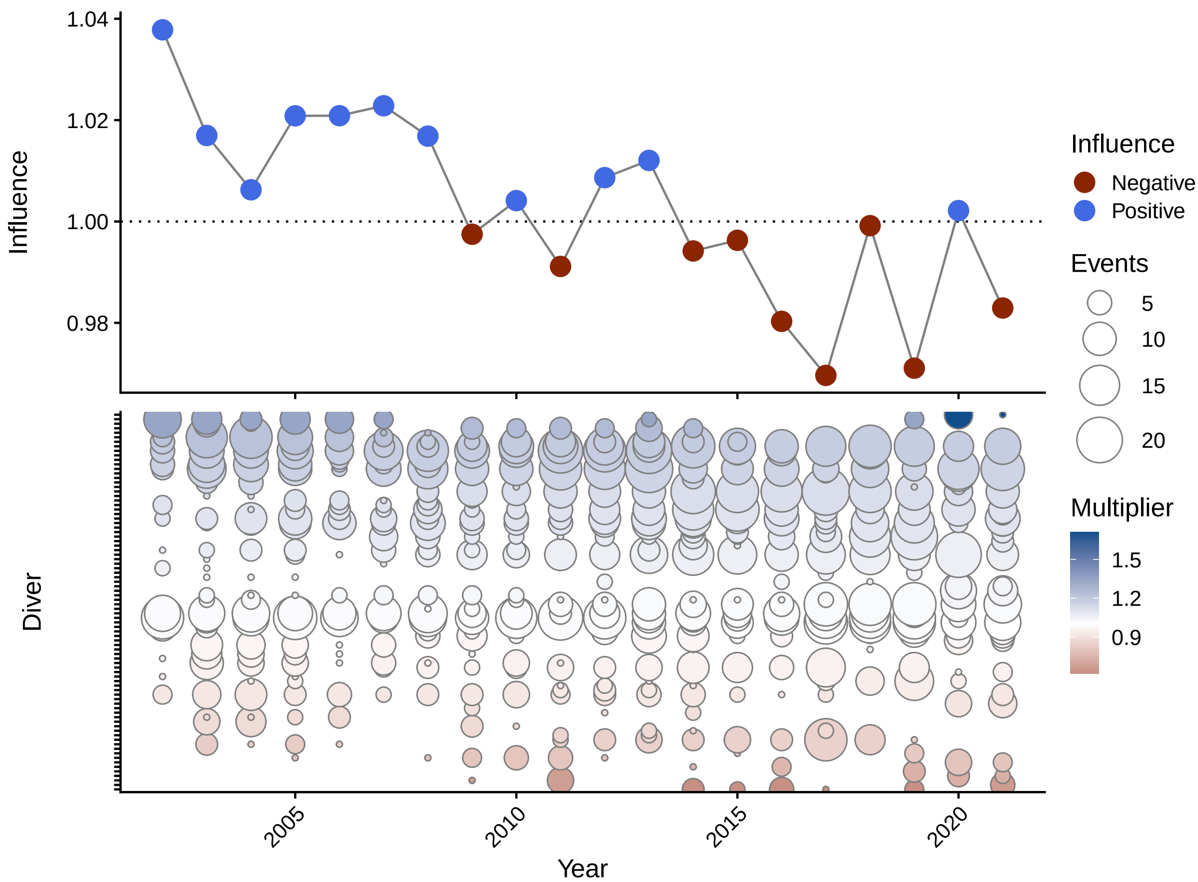

Figure 10: Influence plots for diver random effects, showing the effect on raw catch-per-unit-effort (CPUE; top graph) of applying estimated effect sizes (bottom graph) from the factor levels encountered each fishing year. A positive (>1) influence for a given time period means that the unstandardised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

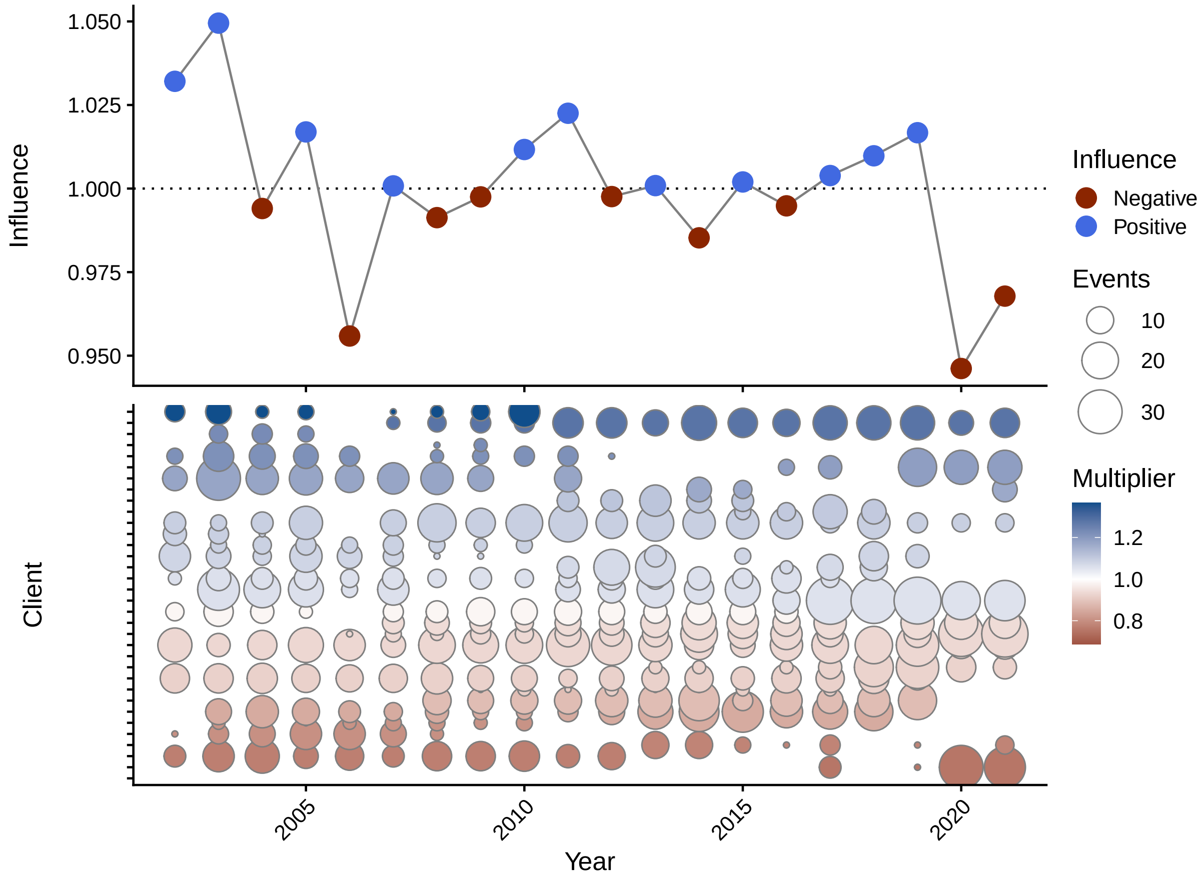

Figure 11: Influence plots for client number (FIN) effect, showing the effect on raw catch-per-unit-effort (CPUE; top graph) of applying estimated effect sizes (bottom graph) from the factor levels encountered each fishing year. A positive (>1) influence for a given time period means that the unstandardised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

2.1.4 Commercial catch sampling length-frequency (CSLF) data

The present modelling used a standardisation model for composition data (developed by Neubauer 2020) that 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 effectively 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 actual length frequencies. Random effects formulations ensure the sharing of information across strata (see Neubauer 2020 for more detail).

Composition standardisation was performed for CSLF data from 1989–90, although there was an extended gap between 1994 and 2005 when no CSLF samples were available. The model used statistical area, management zone (i.e., zones B1 to B5), and zone-year as standardising variables. Zone and year were entered as fixed effects, and zone-year and statistical area were entered as random effects.

The standardisation led to minor adjustments relative to raw removal estimates based on statistical areas for the 2019–20 fishing year (Figures 12, 13).

2.1.5 Growth and maturation

As for previous assessments since 2018, data from individual growth tagging sites in PAU 3B were not fitted. All growth tagging available for PAU 3B is currently from northern Banks Peninsula, in areas that are not commercially fished, and where pāua are known to be growing slowly. 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 14). 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 14 and 15). 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 16).

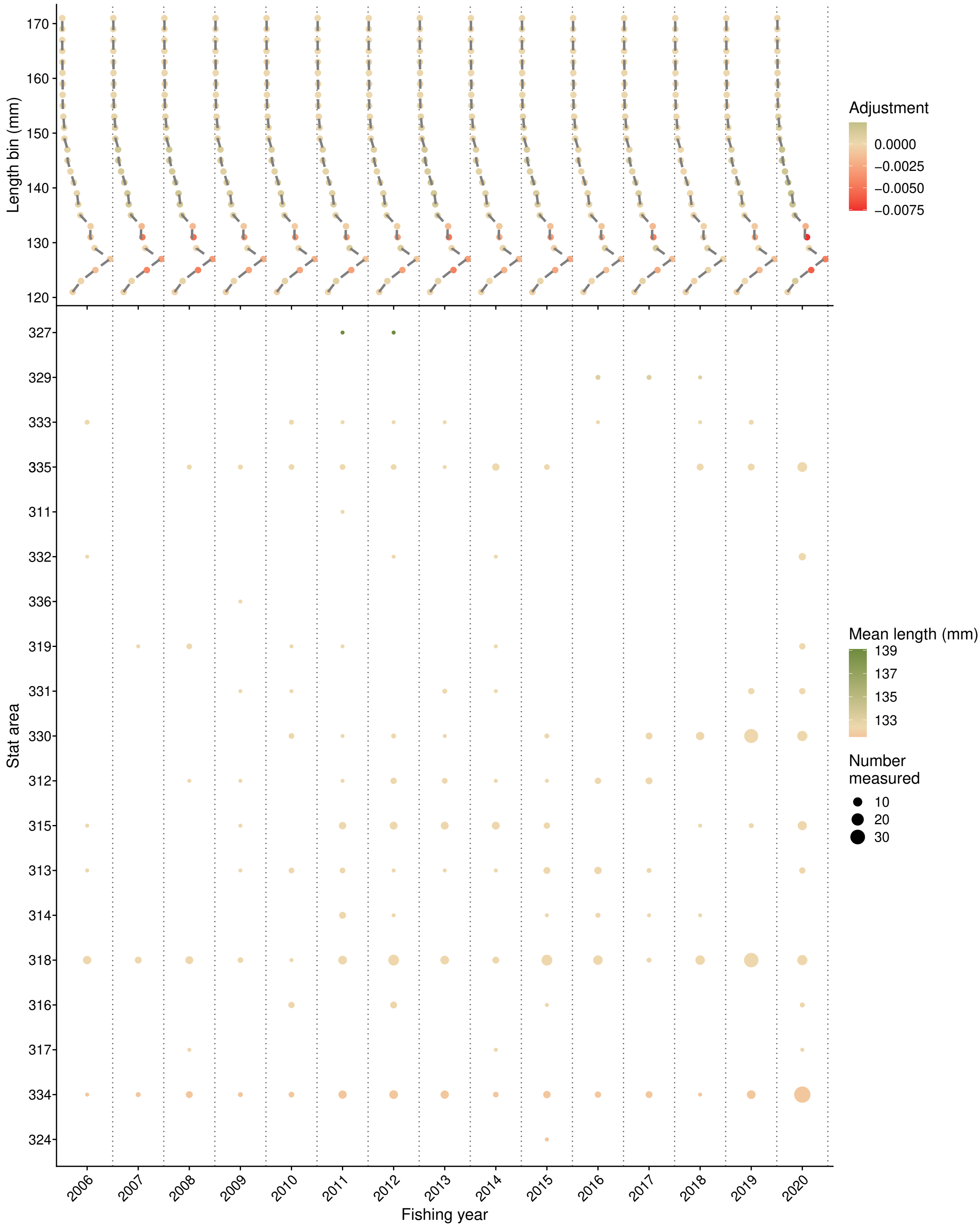

Figure 12: Effects plot for small-scale statistical area for pāua management area PAU 3B. The top panel displays the direction of the adjustment from the raw catch sampling length frequency (LF; coloured points for LF classes) in each year and length class in relation to the fishing pattern (shown in the lower panel). Strata in the lower panel are sorted by the observed mean length to allow comparisons of their influence on estimated deviations in the upper panel.

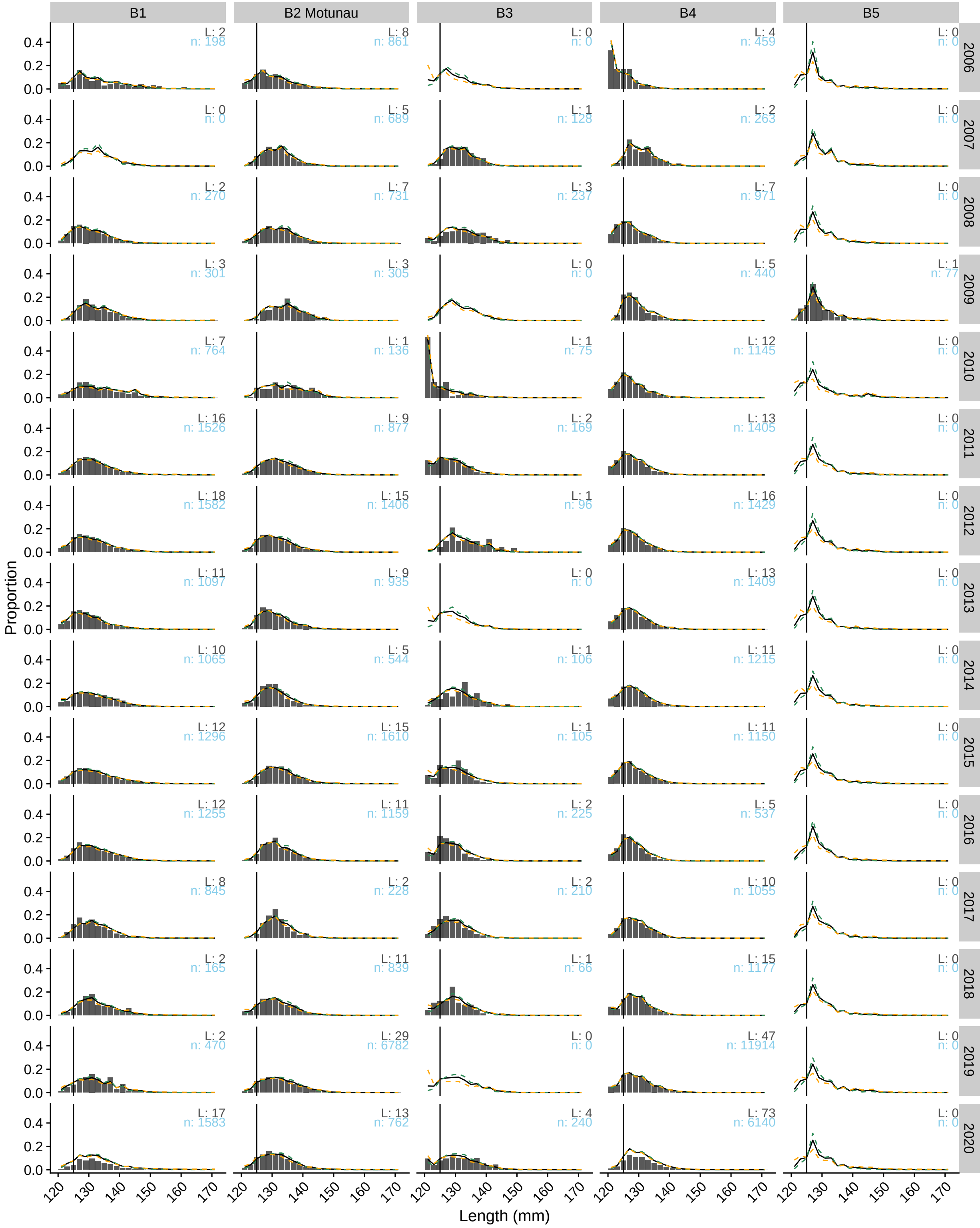

Figure 13: Dirichlet-Multinomial posterior distributions for estimated yearly proportions-at-length $\pi_{r,y}$ (black line) of commercial catch in each management zone in pāua management area PAU 3B, with 95% confidence intervals (dashed line). Raw catch sampling length frequency proportions are in grey; number of landings (L) in black; number of measurements (n) in blue.

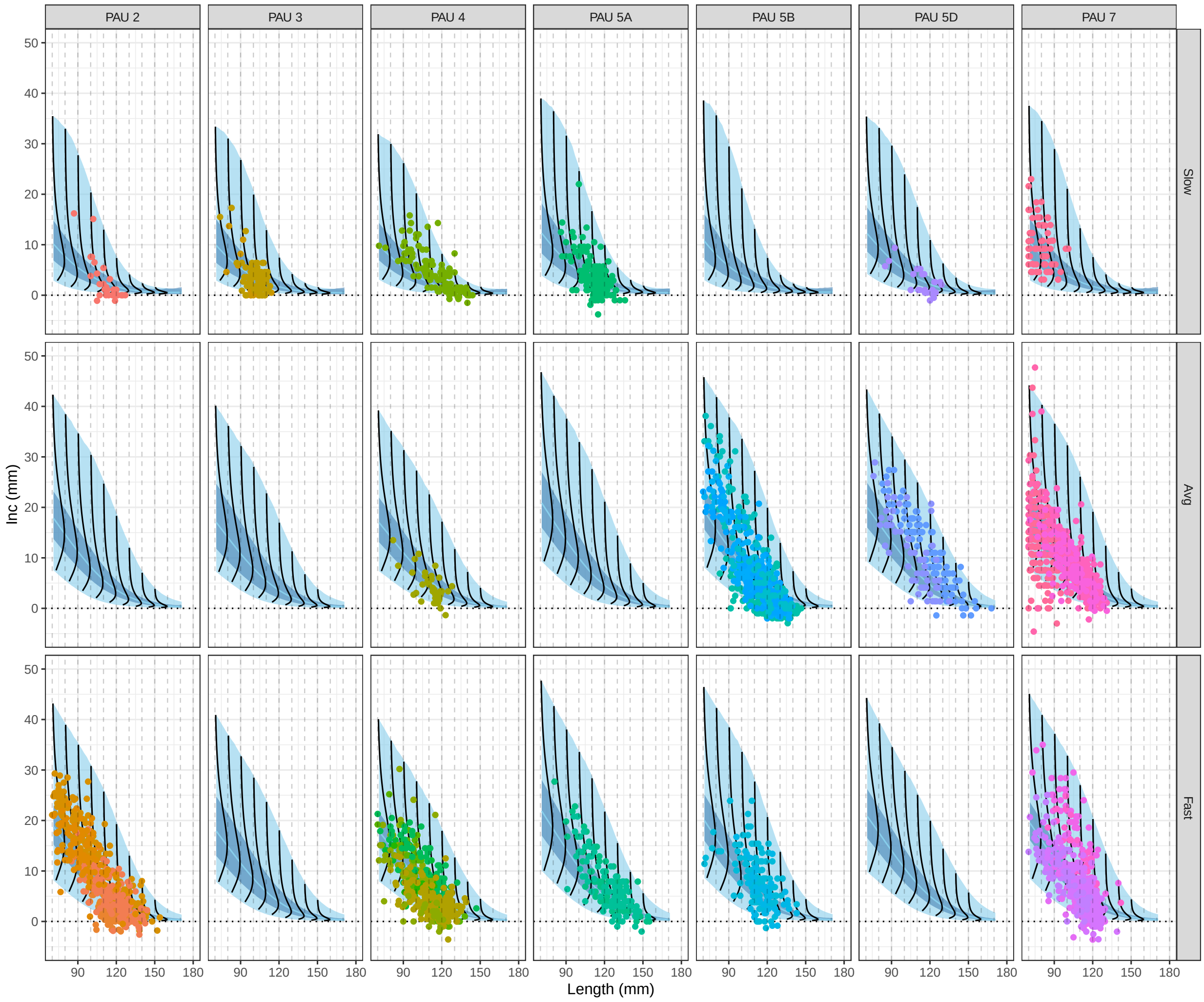

Figure 14: Priors derived from a meta-analysis of growth and maturity of pāua, based on model-fitting to all tag-increment and maturity data across quota management areas (QMAs). Shown is the joint prior for positive growth increments at size l by QMA and growth stratum. Dark blue shading shows uncertainty 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.

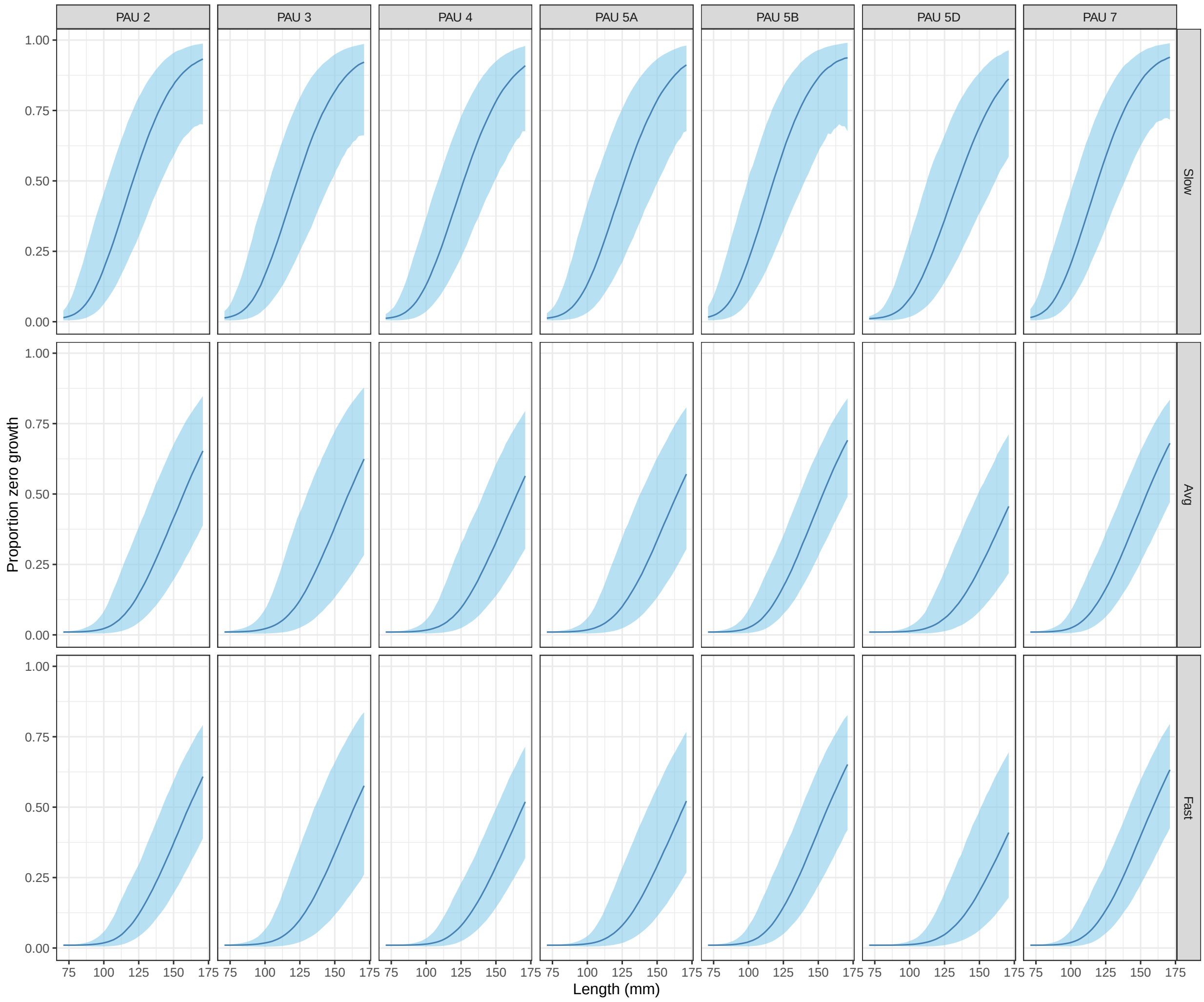

Figure 15: Priors derived from a meta-analysis of growth and maturity of pāua, based on model-fitting to all tag-increment and maturity data across quota management areas (QMAs). Shown is the expected proportion of local populations not growing at size l by QMA and growth stratum.

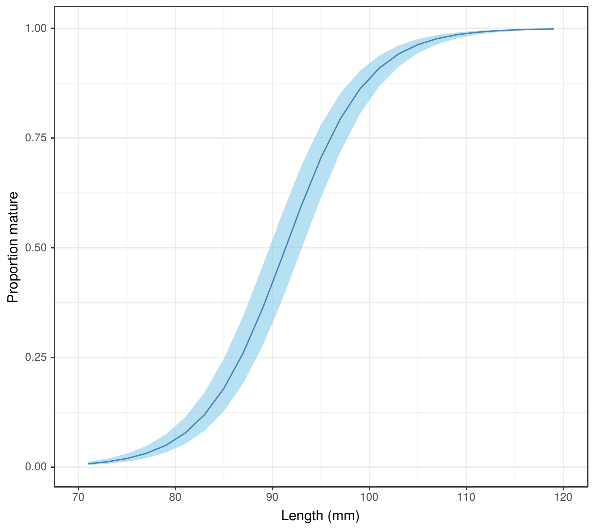

Figure 16: Priors derived from a meta-analysis of growth and maturity of pāua, based on model-fitting to all tag-increment and maturity data across quota management areas. Shown is the population level maturity.

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 $\tau_{PE_{CPUE}}$:

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

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

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 had been found to provide 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.

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	5	1.19×10^{11}	3.19×10^{16}
Recruitment deviations	R_{dev}	LN	0	0.4	1.08	0.45
Natural mortality	M	LN	log(0.1)	0.2	0.1	0.02
Catchability	q	LN	-13	100	∞	∞
Length at 50% selectivity	D_{50}	LN	log(123)	0.05	123.15	6.16
95% selectivity offset	D_{95}	LN	log(5)	0.5	5.67	3.02
Steepness	h	Beta			0.5	0.29
CPUE process error	$\mathrm{PE}_{\mathrm{CPUE}}$	$\mathrm{N}^0(0.05)$		0.04	0.03	
CSLF process error	$\mathrm{PE}_{\mathrm{CSLF}}$	$\mathrm{N}^0(1)$		0.80	0.6	

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 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

The model was initially aimed to be a stock assessment model, and a set of model runs were set up on the basis of a spatial model for the three dominant fishing zones (B1, B2, and B4). Data in zones B3 and B5 were considered to be too scarce to be included in an assessment model.

Initial models focused on models with assumed natural mortality, a broad growth prior, and a range of configurations for data weights. Other trial model runs were performed using fixed growth (with a range of fixed mean growth functions), low M, and fixed hyper-stability in CPUE.

2.4 Deriving alternative status and exploitation estimates

Because stock assessments appeared to not be feasible due to data conflicts and un-informative CPUE trends, alternative methods were sought to obtain information about possible stock status in PAU 3B. These estimates were then used to determine model conditioning via depletion-based stock reduction analysis (DB-SRA; Dick & MacCall 2011), which can be considered a catch-informed Bayesian prior on a stock assessment model (Walters et al. 2006, Neubauer 2020).

Estimated (standardised) mean CPUE for the period between 2018 and 2021 was used as a reference, and compared with CPUE from QMAs with informative CPUE and assessment outcomes. The analysis was performed in two ways:

1. Stock status was regressed against CPUE in each area and assessment year, using logistic regression with a random offset for each QMA. The regression model was then used to predict status for PAU 3B based on local CPUE, and accounting for differences between QMAs in the relationship between CPUE and estimated stock status. In computer science, such a process is known as "emulation", with the regression model acting as an emulator of a full assessment model.

For predictions, the standardised 2019 CPUE for PAU 3B was used to avoid possible impacts of ERS reporting on CPUE. Because recent (2020–2021) CPUE was higher than it was in 2019 in most zones, this approach represents a precautionary starting point.

2. Available biomass was predicted from the relationship between biomass density of available biomass and CPUE. To derive biomass density, available biomass estimated in stock assessments was divided by habitat area derived from the Department of Conservation Marine Habitat classification (Rowden et al. 2018). Habitat area was defined as reef to 10 m depth, excluding any beach or estuary (e.g., Figures 17 and 18). In addition, statistical areas that were not part of the fishery or relevant stock assessments were excluded from the habitat area. Biomass density was then predicted for PAU 3B based on the habitat area in the QMA, allowing for an exploitation rate to be calculated.

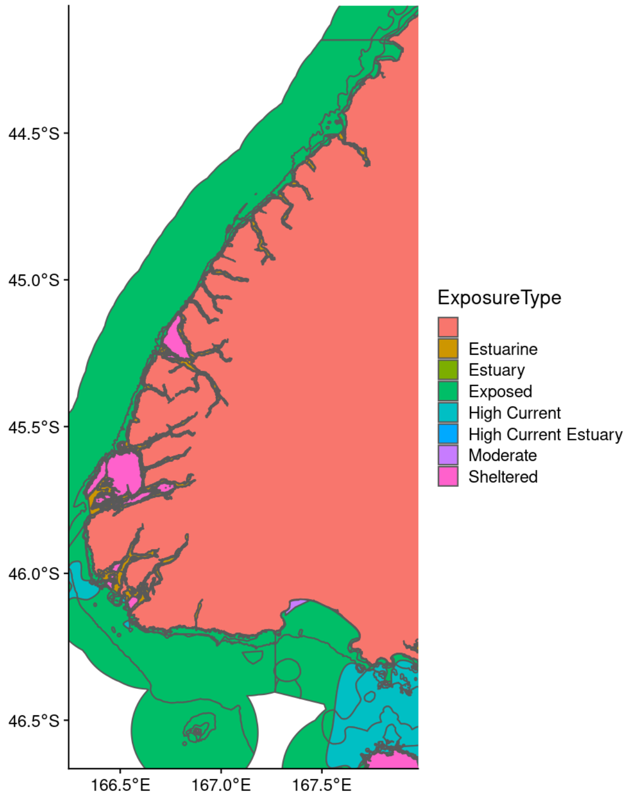

Figure 17: Coastline habitat above the 10 m isobath (Department of Conservation marine habitat classification layers) for PAU 5A as an example of the use of habitat classification layers to derive pāua habitat.

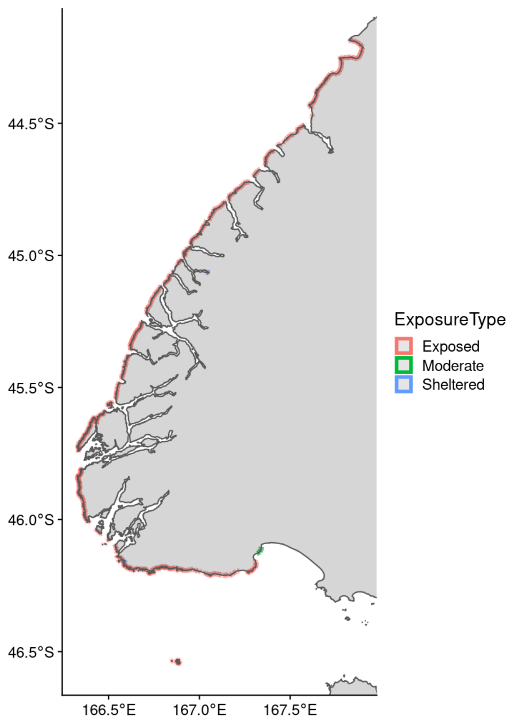

Figure 18: Coastline habitat retained for density estimation in PAU 5A, with exposure categories (from Department of Conservation marine habitat classification layers).

Both models were set up in the Bayesian inference software brms (Bürkner 2017), allowing for error in both CPUE (via a measurement error model) and status or density (via an assumed meta-analysis type standard error) to be taken into account. For example, the brms model formulation for approach 2 was:

```
brm(log(biomass_density) | se(error) ~ me(CPUE,SD) + y(1|QMA),
                 data = assmnt_dfs ,
                 family = 'normal',
                 iter = 1000,
                 warmup = 500,
                 cores = 16,
                 chains = 2,
                 threads = 8,
                 prior = set_prior('normal(0,1)', class="sd") +
                   set_prior('normal(0,2)', class="b"),
                 backend = 'cmdstanr',
                 seed = 14).
```

2.5 Model conditioning based on depletion priors

To derive an operating model, depletion predictions (from step 1 above) were used to estimate potential unfished stock size and productivity, using stochastic stock reduction analysis across management zones B1 to B4. Zone B5 is too haphazardly fished to currenly include in the model; however, zone B3 was included in the models because they have a lower data requirement than full stock assessment models. This process is also known as depletion-based stochastic stock reduction analysis (DB-SRA). In this process, the model is iterated based on input priors (natural mortality, growth, unfished recruitment), and simulations are weighted according to the output prior on depletion. This process leads to a distribution over unfished stock size (technically, over unfished recruitment R_0, with unfished stock size the equilibrium conditioned under R_0 and priors/fixed growth and natural mortality). The present approach considered predicted status by zone from the above meta-analysis of status, and a conservative estimate of stock size and depletion, via a uniform distribution of status between 0.4 and 0.8.

2.6 Management procedure evaluation

Potential management procedures were determined in a meeting with fishers at a special meeting prior to the 2021 Annual General Meeting of PAU 3. A general proposal was to build control rules based on examples from PAU 5 QMAs, which adopted a set of three-step control rules, centred around a desired catch rate and corresponding catch (Table 5). Fishers suggested that a catch rate of 50kg/h was desirable, and the rule was developed assuming a $\pm$20% increment for steps around a 50kg/h target CPUE, with the current catch set as the mid-plateau of the control rule (see Figure 19).

The proposed control rules were evaluated based on conditioned models with a range of assumptions:

- Growth according to the meta-analytic prior mean (base model), with sensitivities with 20% increased and decreased growth.
- Growth drawn from the meta-analytic prior, but subject to re-sampling in the DB-SRA.
- Natural mortality was assumed to be 0.12 (with sensitivity at 0.09).
- R_0 was constrained using DB-SRA.
- Steepness was fixed to a low value (0.3) to emulate low resilience that is often attributed to abalone stocks.

Table 5: Target catch by management zone, with associated target catch-per-unit-effort (CPUE) and CPUE reference points (in kg/h) for fishery closure, and the CPUE at which a linear increase in catch is taken (upper slope start). All other parameters were derived from the targets. TCC, Total Commercial Catch.

Zone	Target TCC (t)	Target CPUE (kg/h)	Closure (kg/h)	Linear incr. from (kg/h)
B1	13.74	50.00	15	80
B2 Motunau	9.85	50.00	15	80
B3	1.15	50.00	15	80
B4	19.93	50.00	15	80

Catch splits were assumed to be consistent with control rules, with catch fully-aligned with control catch. Although this aspect is not the case in practice, the level of compliance with spatial control rule settings is difficult to predict. The ongoing development of the PAU 3B fishery and the continuing changes make it difficult to obtain a precedent. For this reason, it was assumed that the control rules were implemented without variation in spatial catch. The coefficient of variation (CV) of CPUE observation error was based on the residual error in CPUE in recent stock assessments, and was assumed to be 10%. Applying the management procedure evaluation with a CV of 20% did not notably affect outcomes.

The control rule was tested for a validity period of five years, with simulations projecting the stock for 20 years to ascertain long-term performance of the control rule. In addition, all simulations assumed average recruitment with no auto-correlation. Periods of prolonged below-average recruitment would significantly degrade fishery performance. For this reason, any indication of poor recruitment periods should lead to a review of the operating model assumptions and control rules. In addition, the evaluation performed here assumed a starting point based on recent (2019) conditions; however, implementation starting from a markedly different starting point (i.e., a lower starting point due to delayed implementation) would affect risk estimates, so that the control rule should be re-evaluated.

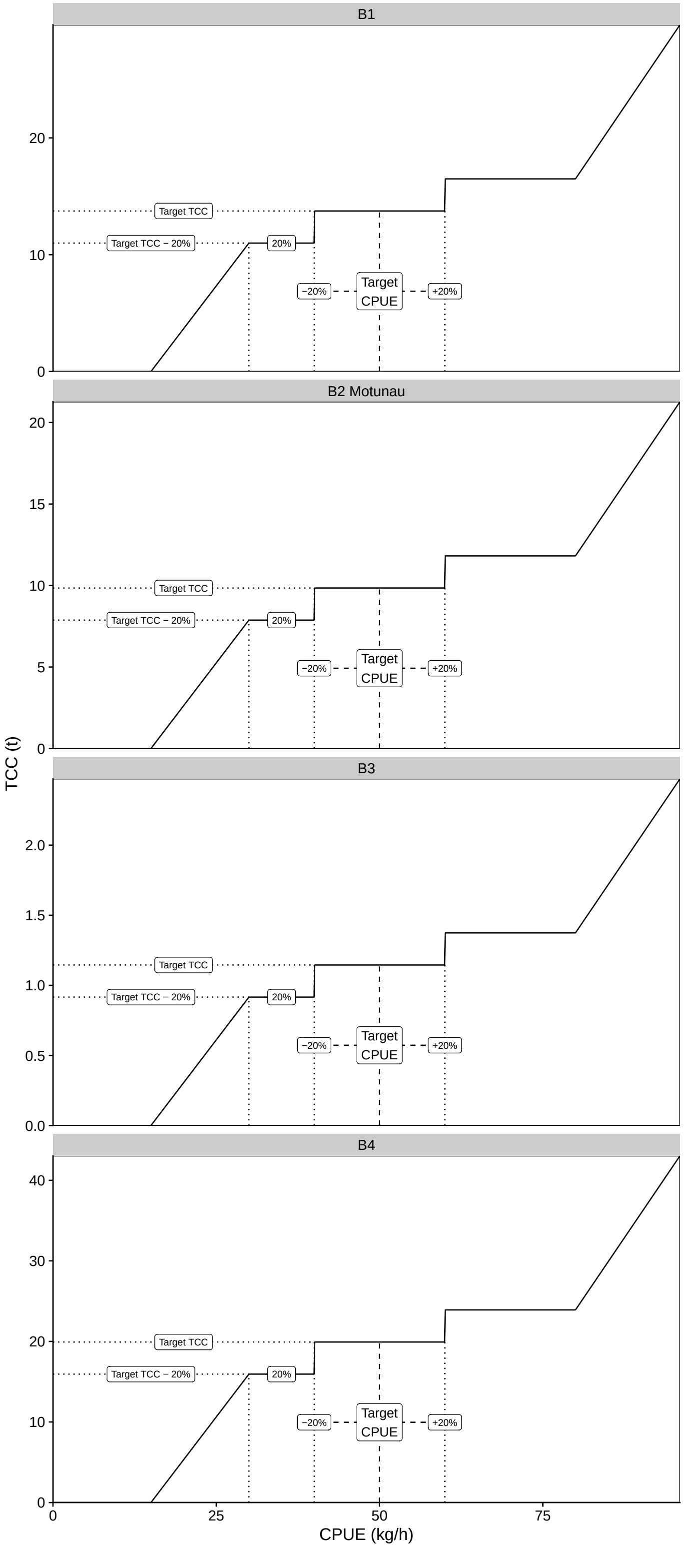

Figure 19: Harvest control rules proposed for PAU 3B (by management zone): total commercial catch (TCC) as a function of catch-per-unit-effort (CPUE), including key parameters. The latter include the width of the target plateau for expected and for natural variation around the target (here 20% of target), a lower buffer (20% of target), and catch and catch increments corresponding to the target and limit catch rates. All zones had CPUE above target in 2021.

3. RESULTS

3.1 Preliminary stock assessment runs

A range of stock assessment settings were attempted to derive a stock assessment model for PAU 3B. None of the attempted models were suitable, and the Fisheries New Zealand Shellfish Working Group did not accept these models as a robust basis for the management of the PAU 3B stock.

There are difficulties in fitting CPUE, length frequencies, and growth in a coherent way (see Appendix A, Figures A-1 to A-9 for a single model run with low CPUE weight; i.e., fitting mainly to length-frequency data): growth is largely estimated to be slow and attains smaller size relative to average growth in other QMAs, which determine the prior (Figure A-1). The slow growth allows the model to fit relatively small length frequencies (Figure A-3), with few individuals above 140 mm shell length, despite a relatively low depletion level (Figure A-6). Nevertheless, this fit is achieved at the expense of fits to CPUE data (Figure A-2). Forcing a fit to the flat or increasing CPUE led to markedly larger biomass estimates and stock status estimates near unfished conditions, which were considered implausible by the Shellfish Working Group.

3.2 Deriving alternative status and exploitation estimates

The relationship between assessed stock status and density of available biomass was consistently related to CPUE in all QMAs except for PAU 5A (Figure 20). The latter QMA showed markedly lower estimated available biomass density than other QMAs at equivalent CPUE. This inconsistency in PAU 5A may be due to insufficient delimitation of habitat in PAU 5A, poor assessment estimates, or a more patchy distribution of pāua in the area.

Both types of analysis, based on stock status and biomass density, suggested higher standing biomass and status in PAU 3B than in any of the assessed QMAs, with a status near 75% of unfished biomass, and a biomass density marginally higher than current biomass for PAU 5B. (Note, that for biomass density, only QMA-wide predictions were derived, because habitat metrics over small spatial scales are likely less reliable. For example, for Motunau Island; predicted densities may be subject to errors that average out over relatively large spatial scales.) For status predictions, the status for the main management zones was predicted to condition models using DB-SRA.

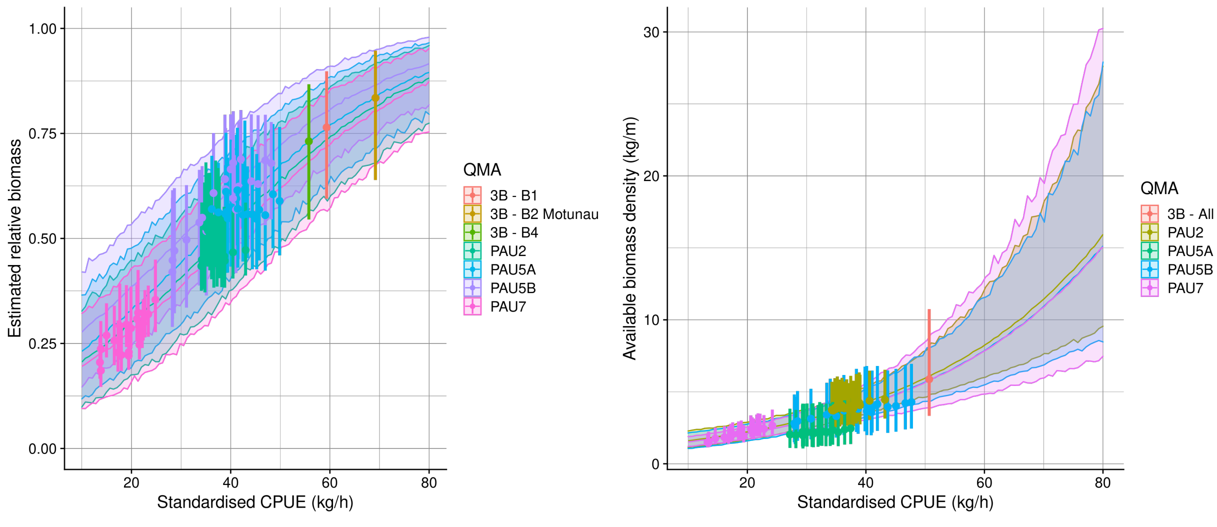

Figure 20: Predicted status and available biomass density for pāua in quota management area PAU 3B from a meta-analysis relating catch-per-unit-effort (CPUE) to stock assessment outcomes (stock status, biomass) across quota management areas (QMAs).

3.3 Model conditioning based on depletion priors

The conditioned model based on stock status estimates from meta-analysis produced stock trajectories corresponding with trajectories obtained with low CPUE weights in the stock assessment process (Appendix B, Figures B-1 to B-5). In particular, the model was consistent with recent depletion in zones that have had substantial increases in catch (e.g., zones B3 and B4). Overall, the exploitation rate was estimated to be low in zone B1 and recently in B2 Motunau, due to lower catch from the latter zone in recent years. Zone B3 showed a high exploitation rate near 50% due to high catch in recent years and small relative available biomass to the fishery in that zone. Zone B4 approached a 5% exploitation rate. The simulations were, therefore, relatively consistent with estimates of available biomass and exploitation rates from the preceding approach (see above, Figure 20).

3.4 Management procedure evaluation

The base model with mean expected growth from a meta-analysis prior, and stock size conditioned on the predicted stock status, suggested a range of outcomes (Figure 21, Appendix C, Figures C-1 to C-6). The model suggested agreed catches in 2022 were not compatible with current biomass levels in zones B1 and B4 over the long term, leading CPUE in these areas to decline (Figure C-1). In contrast, in zone B3, the agreed catch was much lower than recent catch, leading to an increase and stabilisation of catch in the zone; catch in zone B2 was predicted to likely remain stable. Overall, there was no risk of breaching limit reference points within each area, or in aggregate across the QMA (Figure C-1).

Correspondingly, available biomass levels were expected to either decline or remain stable across these zones (Figure C-1), leading to mirroring trends in CPUE (Figure C-4). Although the control rules adjusted catch to maintain CPUE to some extent, these adjustments were relatively slow (Figure C-5), and the rules primarily led to stable exploitation rates (Figure C-6).

The simulation outcomes were strongly determined by the conditioning assumptions about stock status (Appendix D, Figures D-1 to D-6, Table D-1). Although a uniform distribution over stock status led to the lowest median current status, and highest depletion post-application of the control rule, the risk of breaching the soft limit of 20% of unfished spawning biomass did not exceed 5% for any area, and remained near zero in aggregate across all zones. Different model productivity assumptions forced after conditioning had a minor effect relative to the conditioning assumption about stock status itself (Appendix E, Figures E-1 to E-6, Table E-1). Therefore, they did not increase the risk of breaching limit reference points.

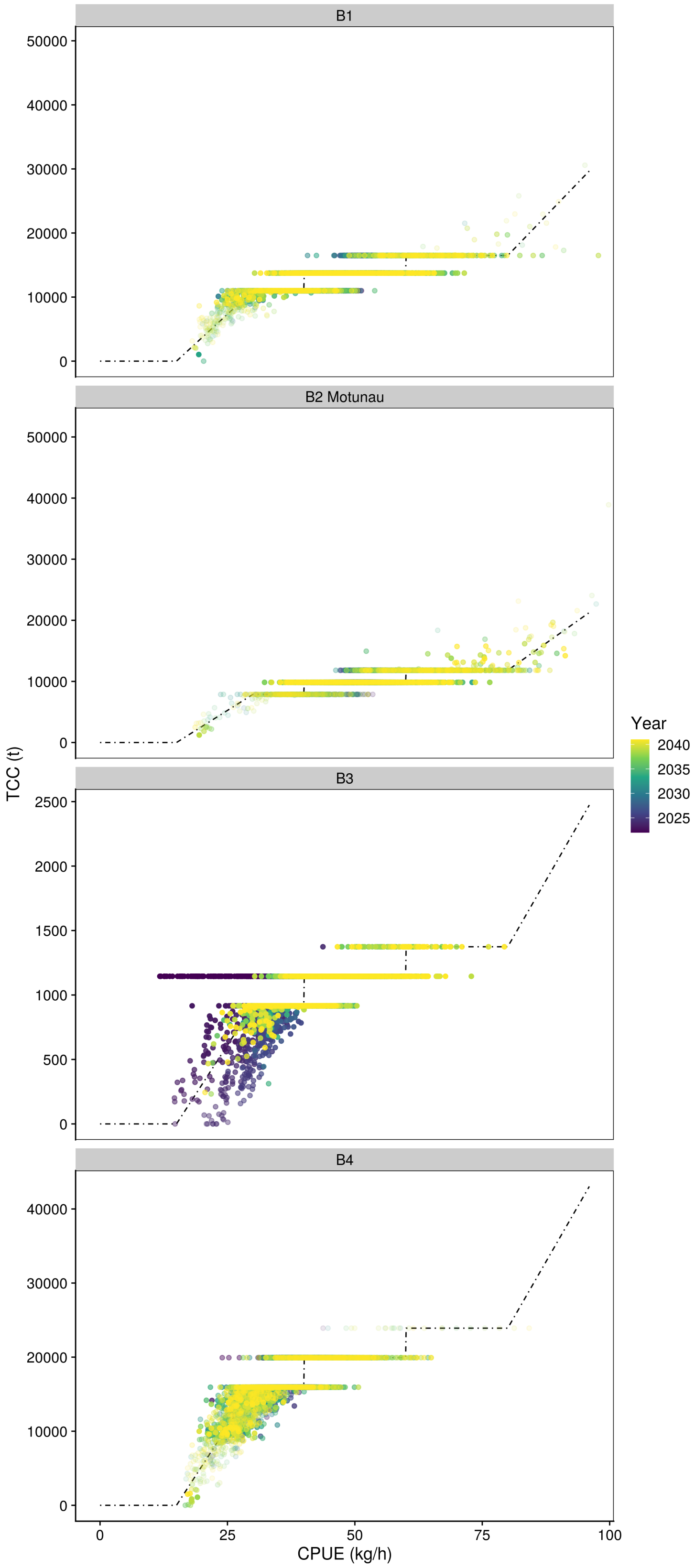

Figure 21: Realised catch and catch-per-unit-effort (CPUE) from control rule simulations for pāua. The underlying rule is shown as a dashed line. Realisations from the simulations were variable with respect to the rule due to simulated observation error in CPUE leading to decisions under the rule that do not follow the intended biomass signal (i.e., decisions do not match the dashed line).

4. DISCUSSION

The present project attempted to assess and evaluate management for the newly-created quota management area PAU 3B. The initial attempt to perform a stock assessment fell short, mostly because CPUE, which provides crucial information about biomass trends for most pāua stock assessments, showed no response to recent increases in catch. It is likely that the fishery is considerably underdeveloped, because many commercially-available areas were only lightly fished prior to QMA-wide increases in catch. Instead of increasing catch in core statistical areas, fishers expanded effort in lightly fished areas, which may have led to maintaining CPUE at consistent rates. It may, therefore, be some time before CPUE shows any trends at current catch levels. If current exploitation is at equilibrium with stock productivity spatially, then CPUE may not change notably in the medium term.

In the absence of any strong signals in CPUE, the model must assume that the standing stock is sufficiently large to allow fishing without a visible impact on available biomass. Nevertheless, it is likely that high CPUE can be maintained over periods of initial stock depletion due to small-scale serial depletion, and the extent of the fishing impact may not be evident for considerable time. For this reason, it would be imprudent to assume a near unfished stock size. The assessment was, therefore, rejected as a reasonable basis for management, and a conditioned stock model was used in its place to evaluate possible management procedures for PAU 3B.

The conditioning forces the model to a lower status and, therefore, assumes that fishing has had an impact, even if it is not yet evident in CPUE. This assumption leads to a conditional interpretation of outputs from the simulations: all simulations assumed that past and current catch have already led to a depletion, which, given the history of gradually increasing catch, was strongest in recent years. As a result, continued fishing at this level also led to further reduction in the stock under the current catch level, and CPUE cannot be maintained at the current level or near target in the simulations. As a result, the long-term outcome is close to that of other pāua fisheries, with CPUE between 30 and 40 kg/h. This trend, however, is a direct consequence of the conditioning assumptions and should, therefore, be considered in a conditional context: reductions in biomass and CPUE are only likely if recent catch has also led to some depletion despite the lack of CPUE signal. All scenarios tested here, therefore, represent different versions of the question of what would happen under this management regime if the stock is considerably lower than CPUE indicates.

The other strong assumption in the management strategy evaluation is that the use of CPUE as an indicator of status can be used to determine management in the future. Nevertheless, there is no trend in CPUE that would provide confidence that CPUE reflects abundance. Although some level of depletion is likely in the fishery, it may be minor given the length of coastline. The CPUE may be a varying reflection of this low depletion level and slow trend. For example, the PAU 2 fisheries cover a similar area, but yield nearly three times the catch at a consistent 120 t, with stable CPUE. It is currently unclear if the fishery can support the current catch levels long term; however, the present simulations indicate that by reducing catch in accordance with the control rules tested here, there is limited risk to the fishery over short- and long-term periods.

Future updates of this study could include the testing of alternative rules that allow more rapid reductions in catch to maintain target CPUE. This aspect appeared to be a shortcoming of the present rule with its relatively wide plateaus: the test rules do not maintain CPUE (cut catch sufficiently) in view of a declining stock. Nevertheless, we suggest that there is limited use in fine adjustments of the rule until there is confirmation that CPUE is a useful indicator for the PAU 3B fishery.

5. ACKNOWLEDGEMENTS

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APPENDIX A: ATTEMPTED STOCK ASSESSMENT

A.1 Growth

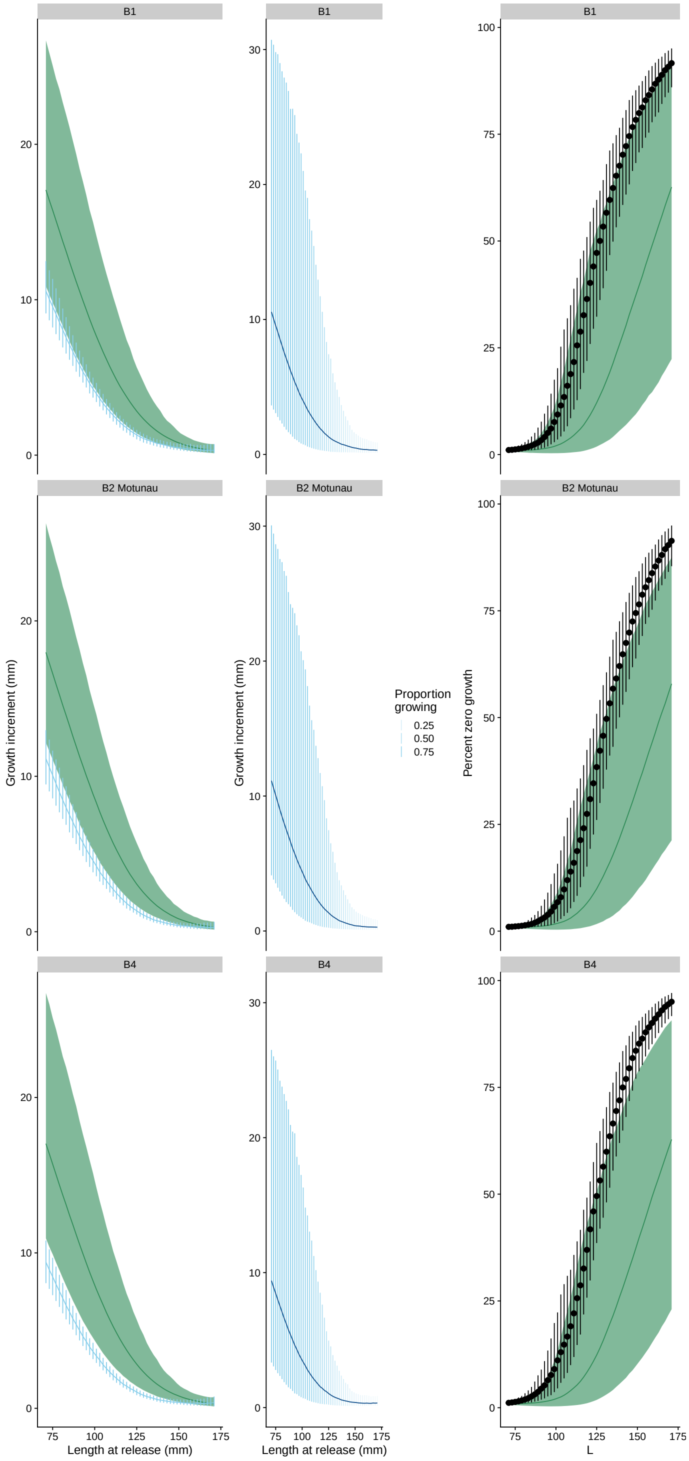

Figure A-1: Pāua growth for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B. Left: Posterior mean growth (population mean (dark blue line) and standard deviation of the estimate (light blue ribbon)), relative to the prior (dark green); middle: estimated 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 relative to the prior (green) for the attempted stock assessment model of zones B1, B2 Motunau and B4 within in quota management area PAU 3B.

A.2 Catch-per-unit-effort

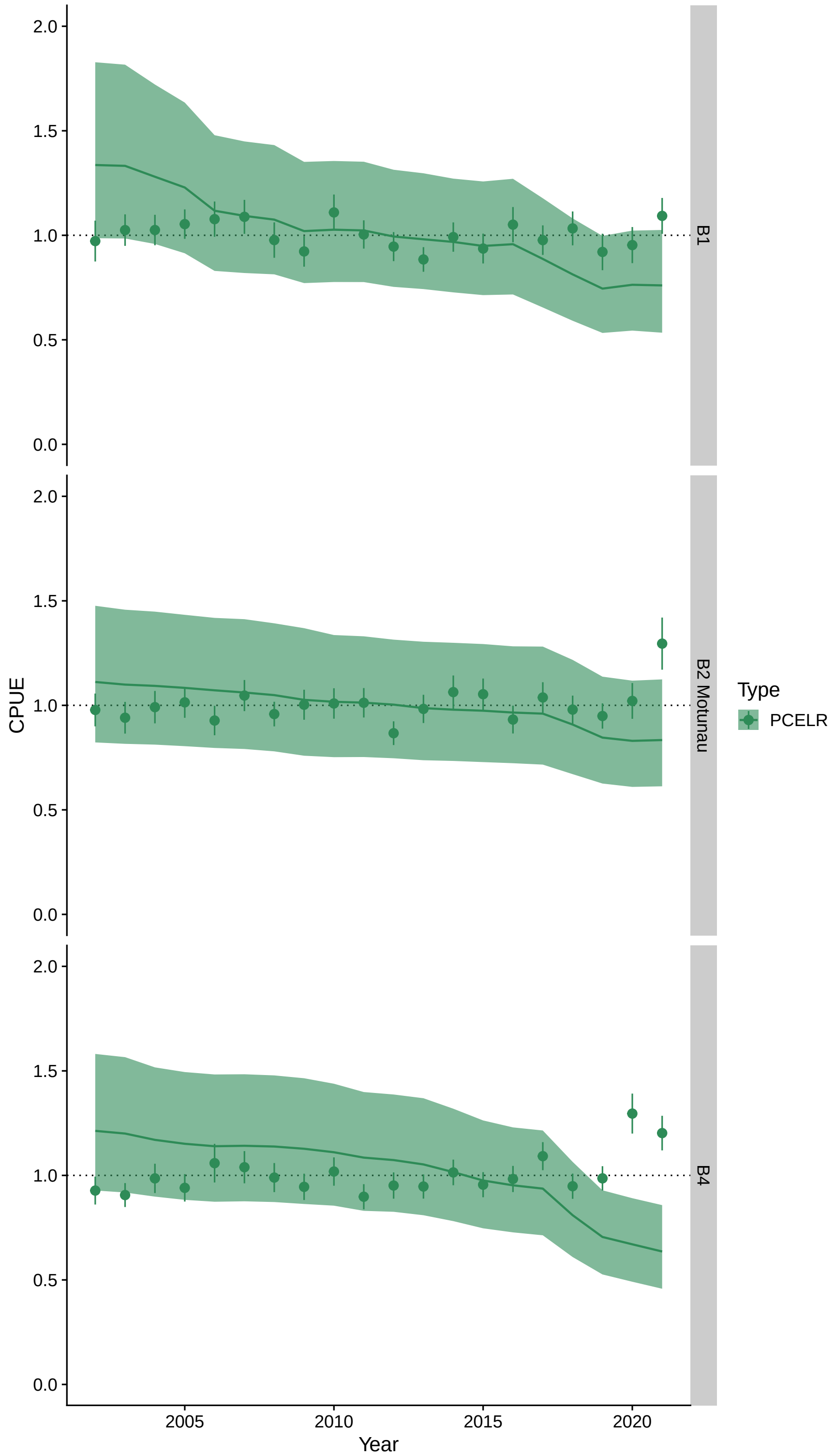

Figure A-2: Comparison of posterior median (line) and 95% confidence (shaded ribbon) predicted catch-per-unit-effort (CPUE) with estimated CPUE index and observation error for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B (black points and error bars; PCELR data from Paua Catch Effort Landing Return forms).

A.3 Length frequency

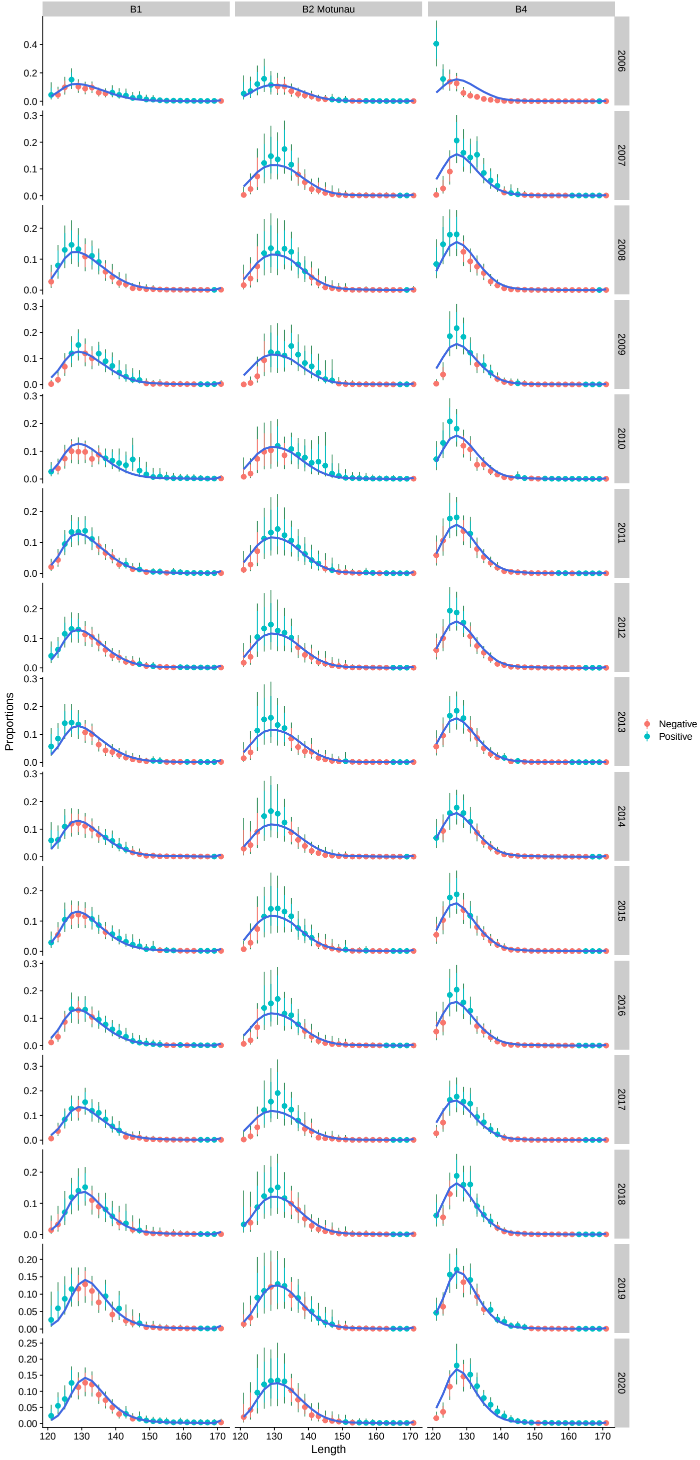

Figure A-3: Comparison of posterior mean predicted catch sampling length frequency (CSLF) with estimated CSLF proportions and observation error for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B. Length classes with positive residuals in blue, with negative residuals in red.

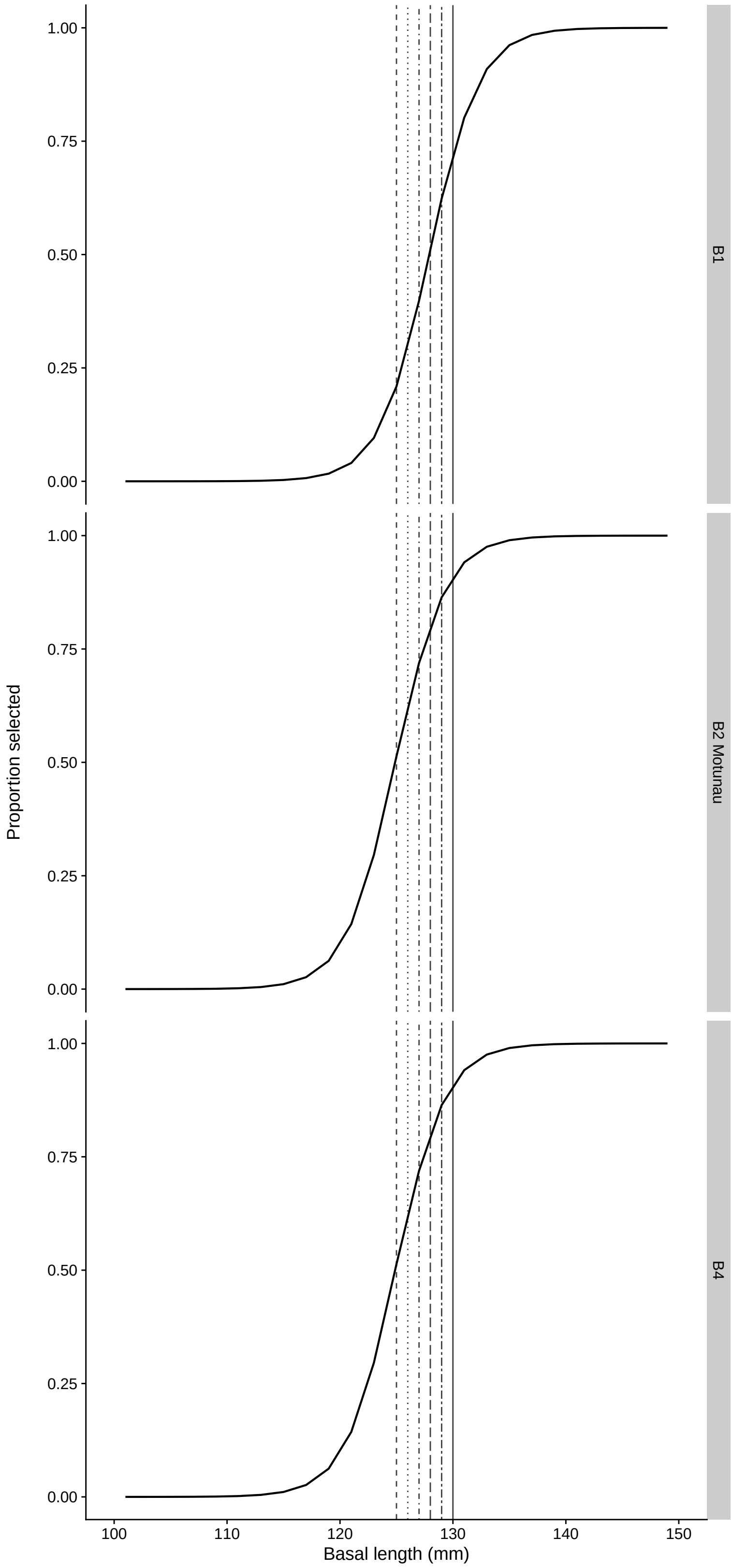

Figure A-4: Estimated selectivity (posterior mean) for pāua for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B.

A.4 Recruitment and biomass trends

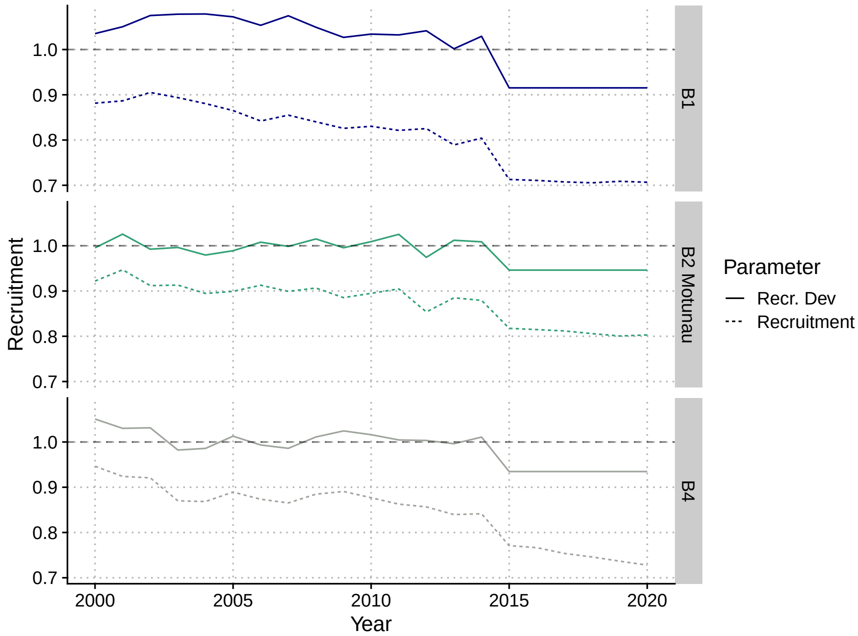

Figure A-5: Posterior mean recruitment for pāua for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B (R_{dev}, recruitment deviation).

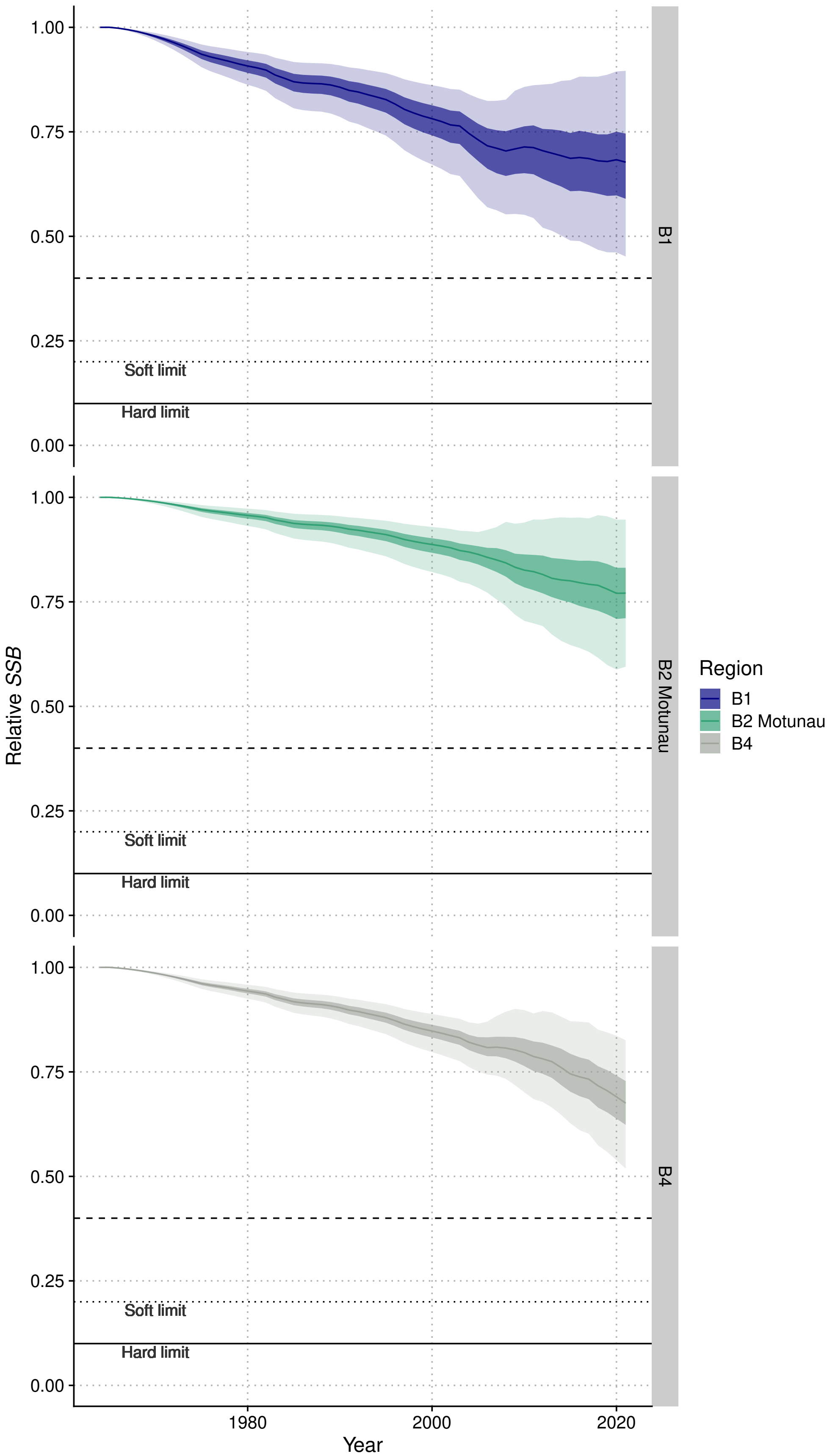

Figure A-6: Estimated relative spawning stock biomass (*SSB*) trend for pāua for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

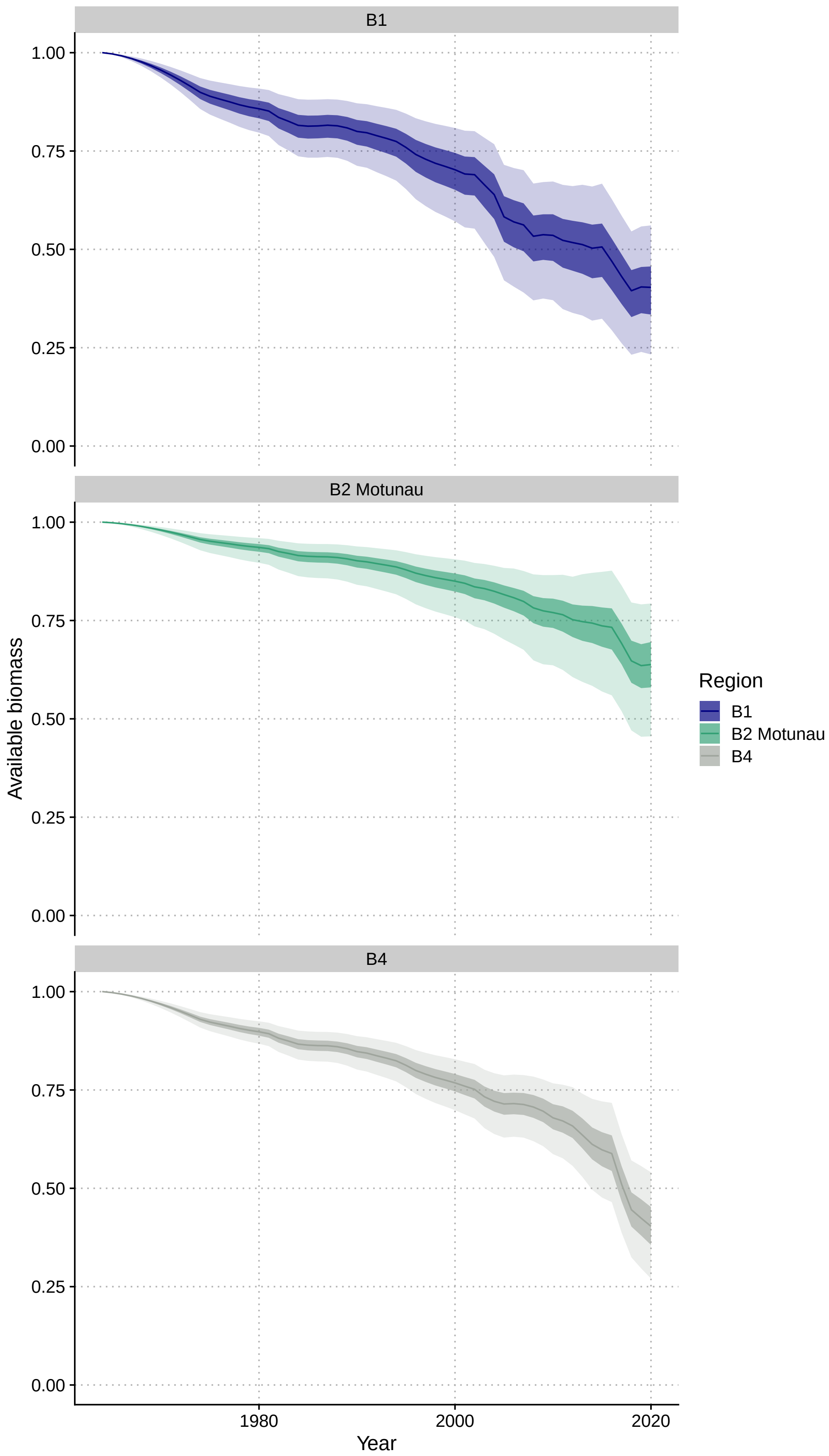

Figure A-7: Estimated relative available biomass trend for pāua for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

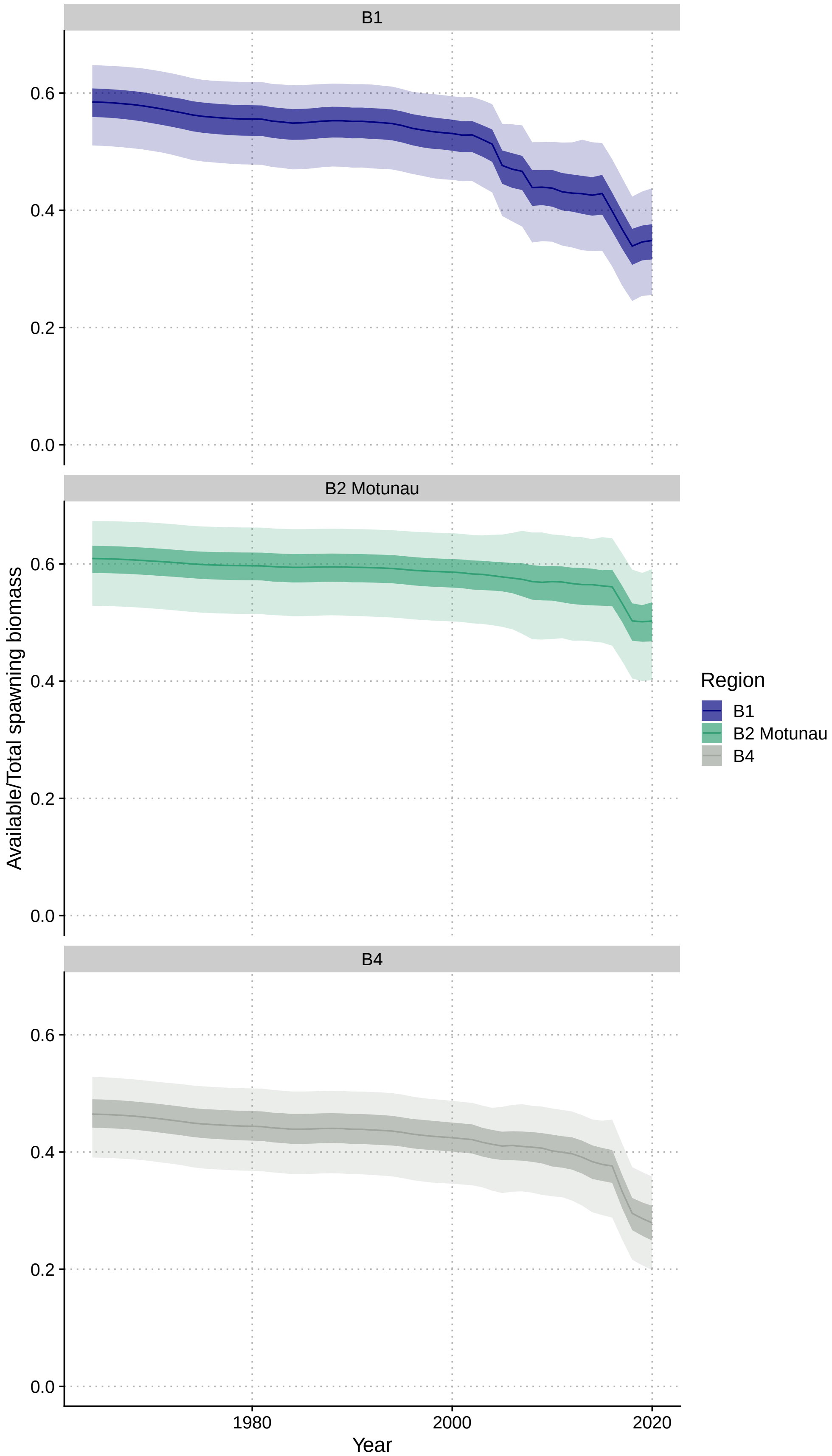

Figure A-8: Estimated relative available pāua biomass (relative to spawning stock) for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

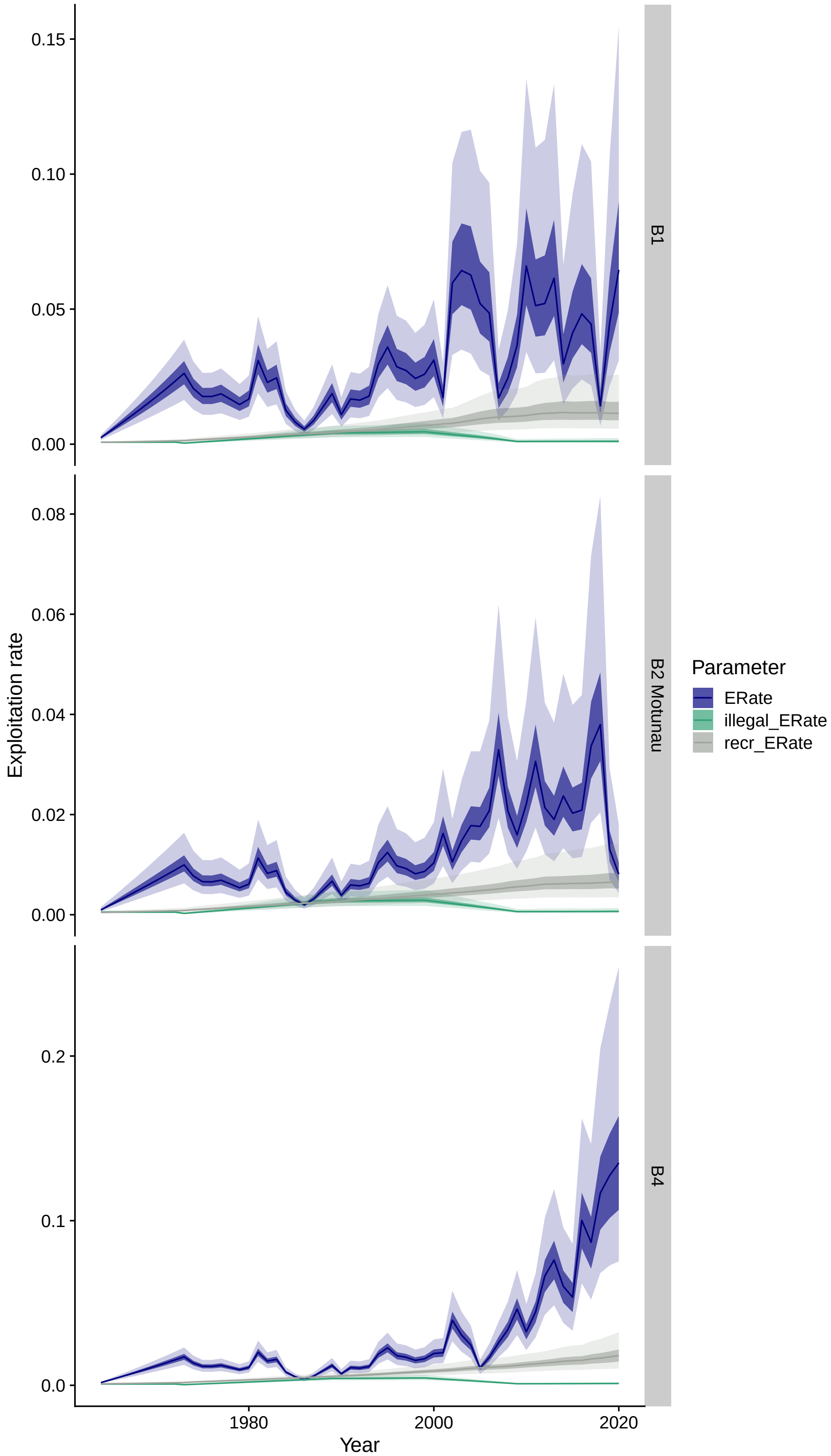

Figure A-9: Estimated exploitation rate (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)) for pāua for the attempted stock assessment model of zones B1, B2 Motunau and B4 within quota management area PAU 3B.

APPENDIX B: CONDITIONED OPERATING MODEL: BASE MODEL

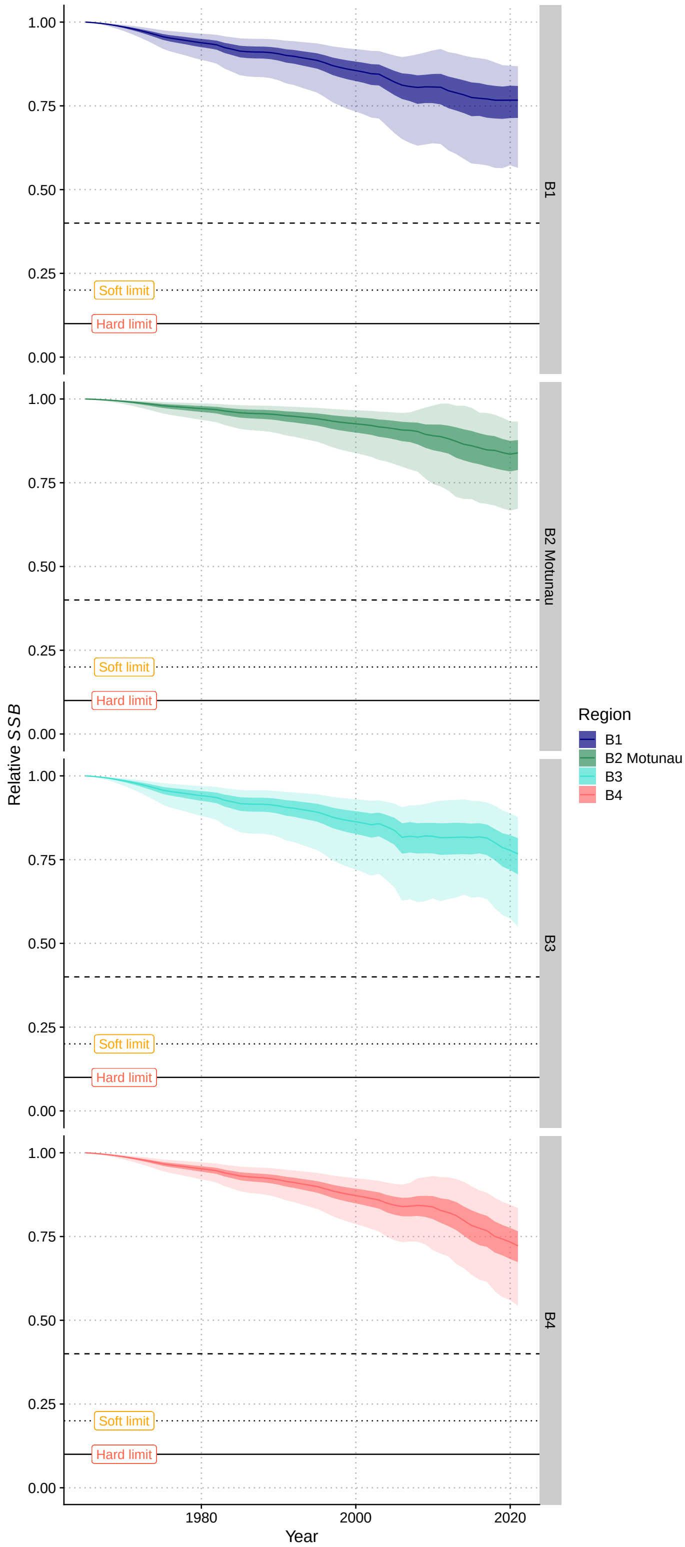

Figure B-1: Estimated relative spawning stock biomass (*SSB*) trend for pāua for the base operating model, with management according to the tested control rules for each zone represented in the stock assessment model for quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

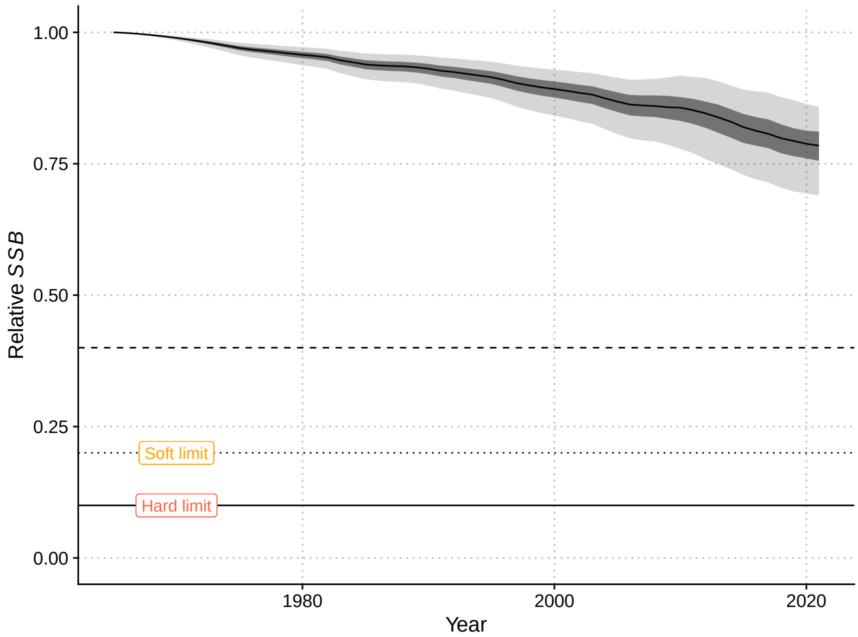

Figure B-2: Estimated relative spawning stock biomass (*SSB*) trend for pāua for the base operating model, with management according to the tested control rules for each zone represented in the stock assessment model for quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

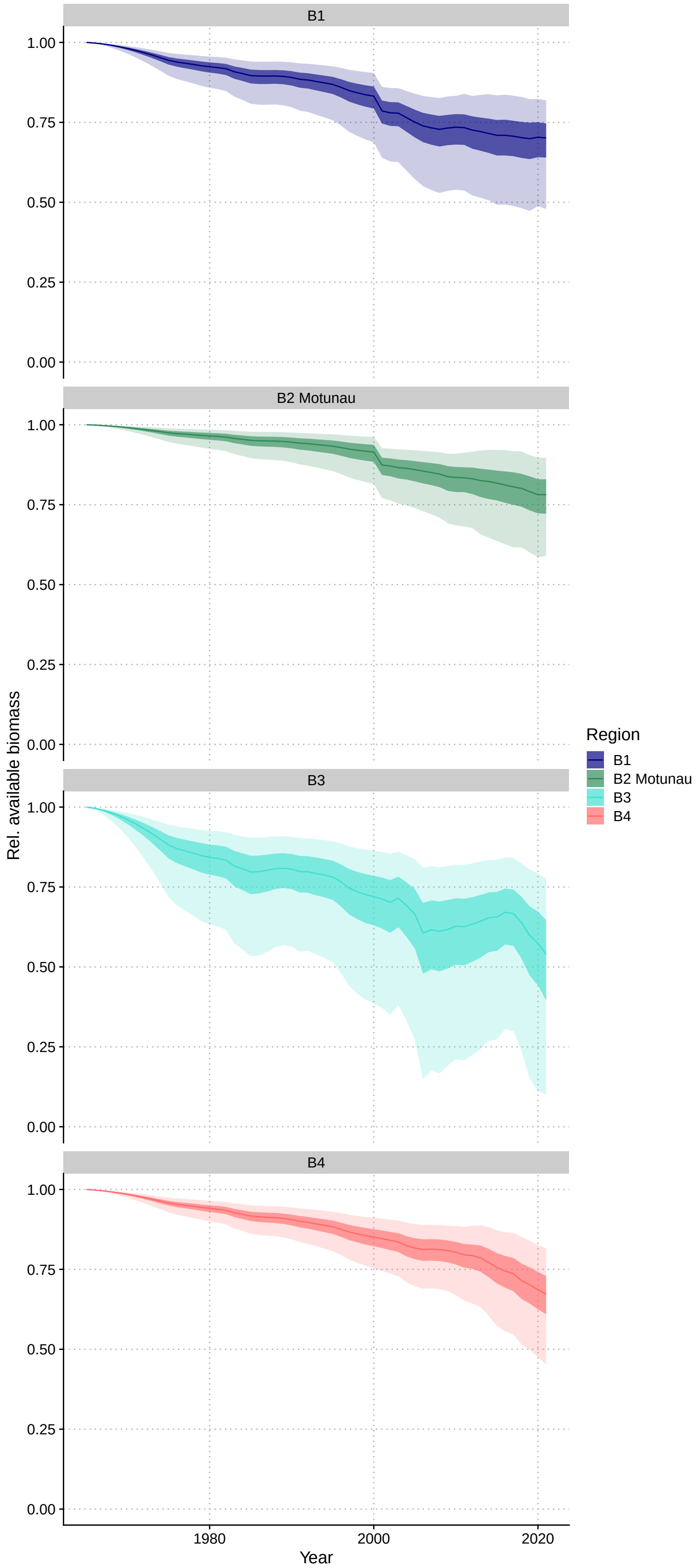

Figure B-3: Estimated relative available biomass trend for pāua for the base operating model, with management according to the tested control rules for each zone represented in the stock assessment model for quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)).

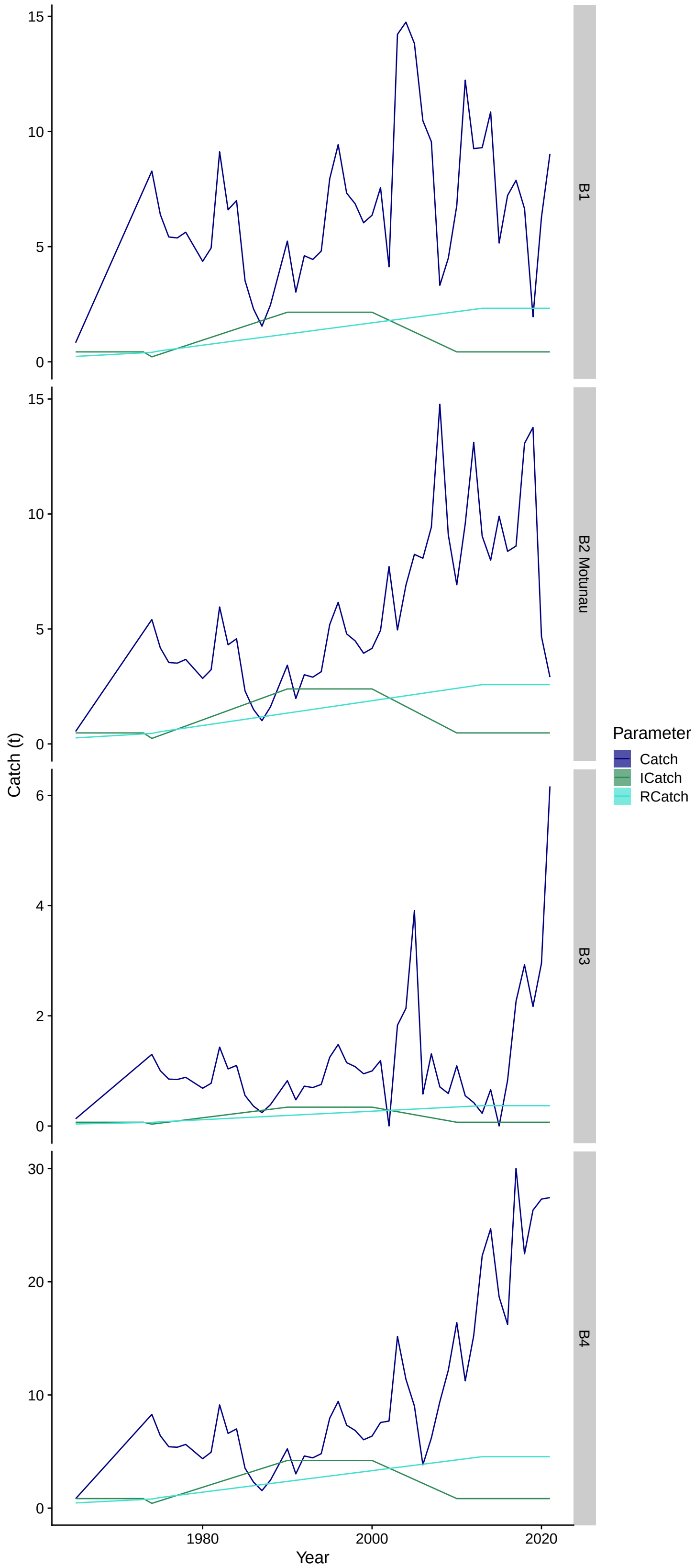

Figure B-4: Assumed catch for the base operating model, with management according to the tested control rules for each zone represented in each sector (I: illegal; R: recreational) in pāua quota management area PAU 3B.

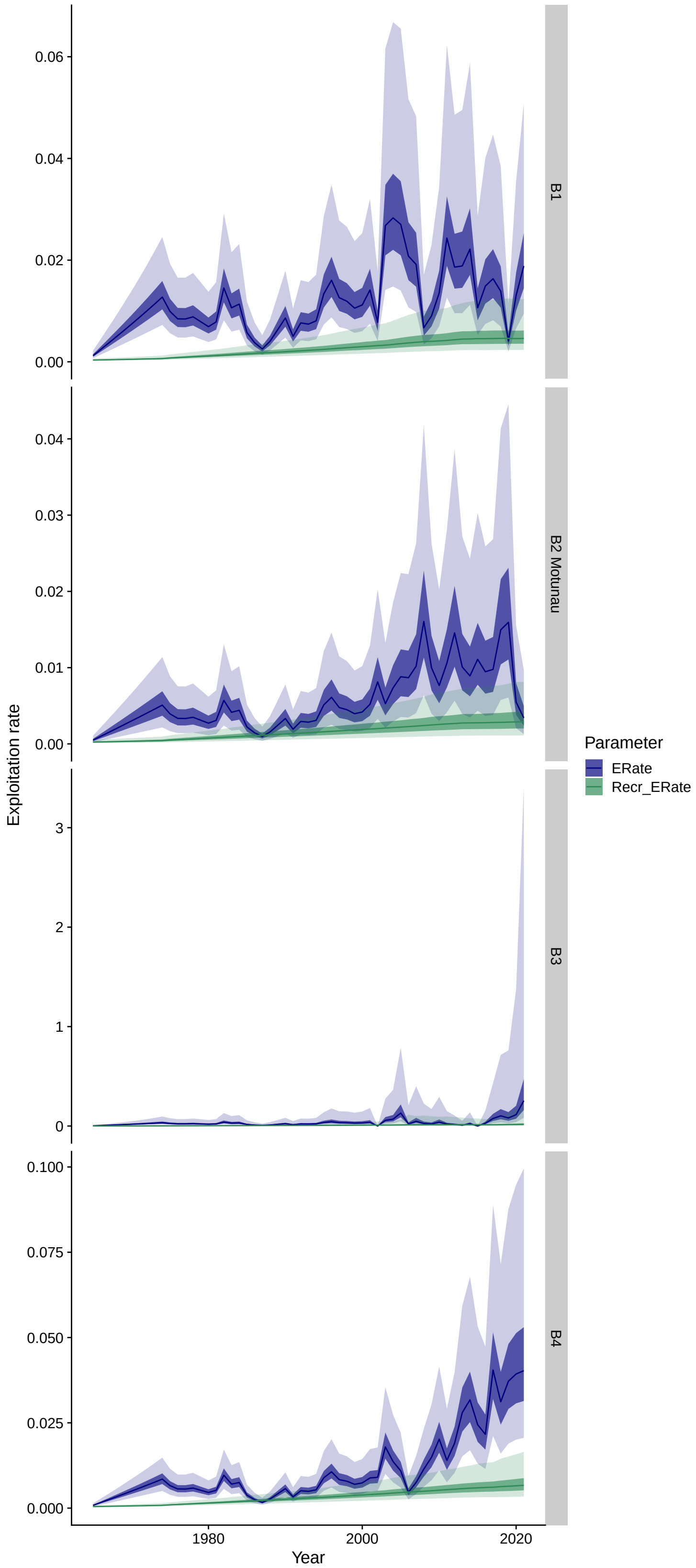

Figure B-5: Estimated exploitation rate (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)) for the base operating model, with management according to the tested control rules for each zone represented in the model (Recr: recreational).

APPENDIX C: MANAGEMENT PROCEDURE EVALUATION: BASE MODEL

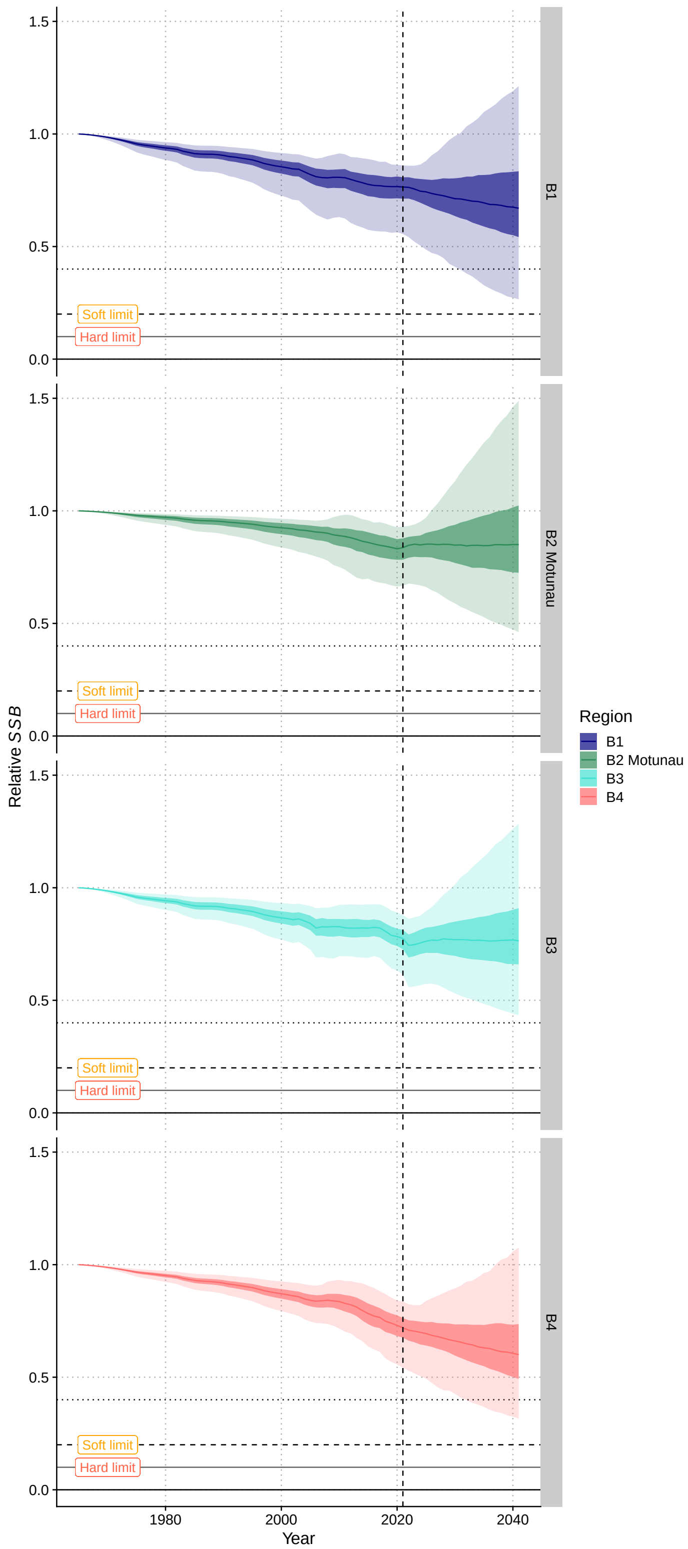

Figure C-1: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua for the base operating model, with management according to the tested control rules for each zone represented in quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)). Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. The final projection year was 2041.

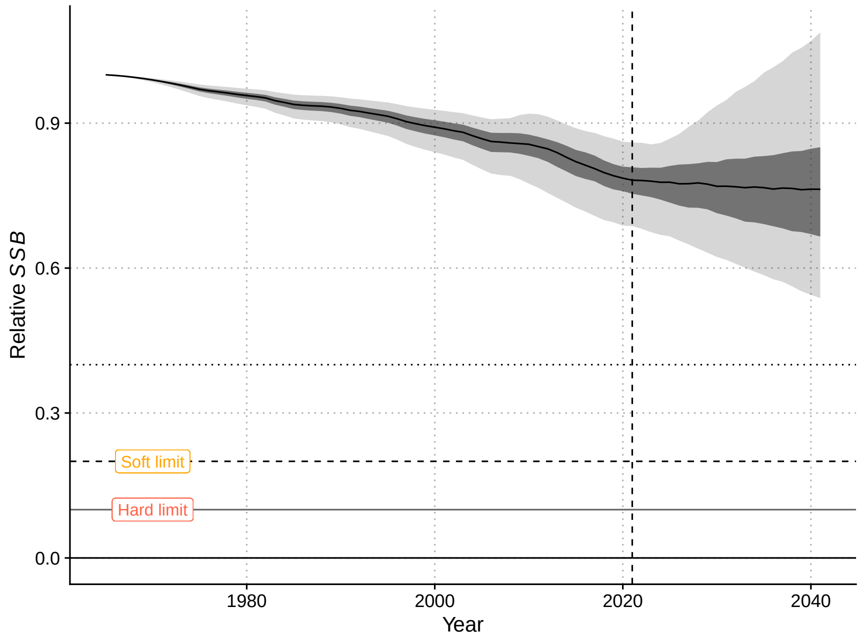

Figure C-2: Estimated and projected total (across zones) relative spawning stock biomass (*SSB*) trend for pāua for the base operating model, with management according to the tested control rules for each zone represented in quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)). Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. The final projection year was 2041.

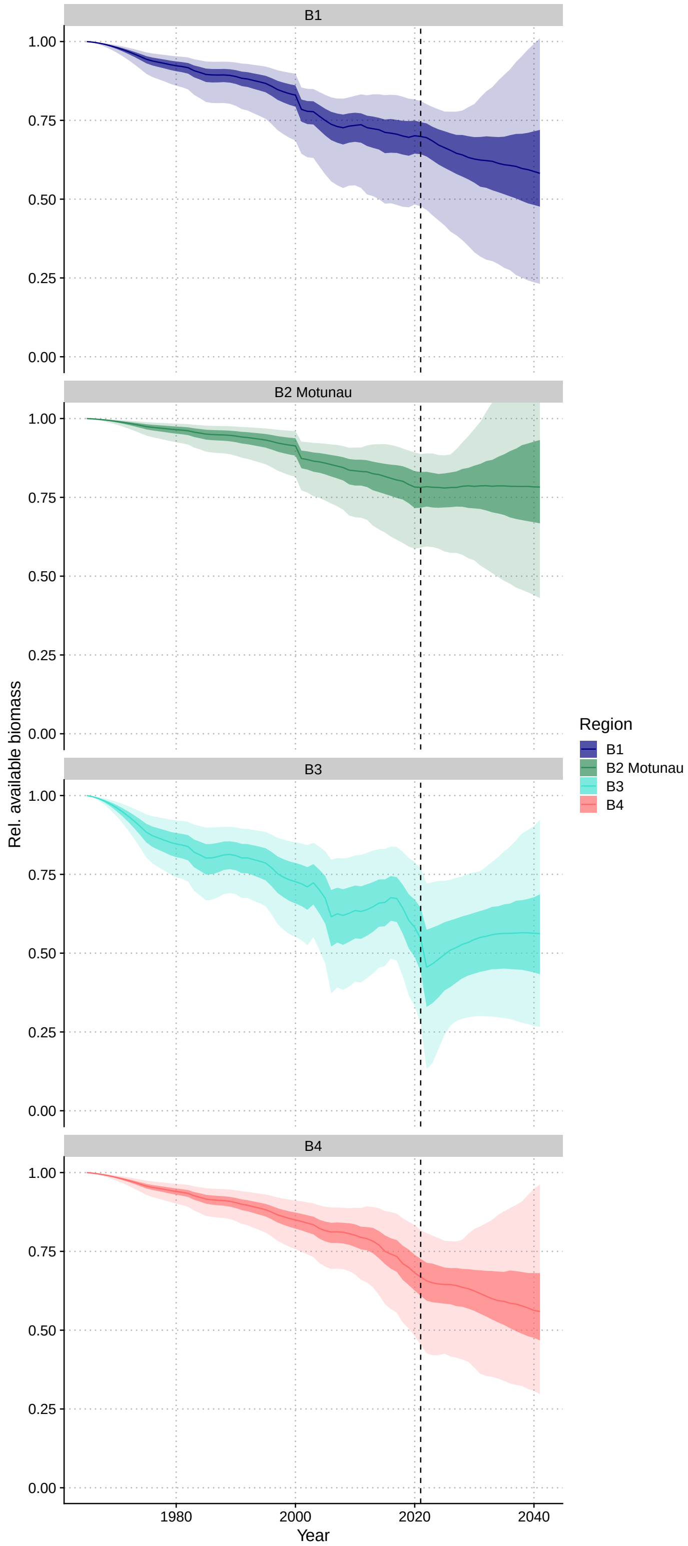

Figure C-3: Estimated and projected relative available biomass trend for pāua for the base operating model, with management according to the tested control rules for each zone represented in quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)). Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. The final projection year was 2041.

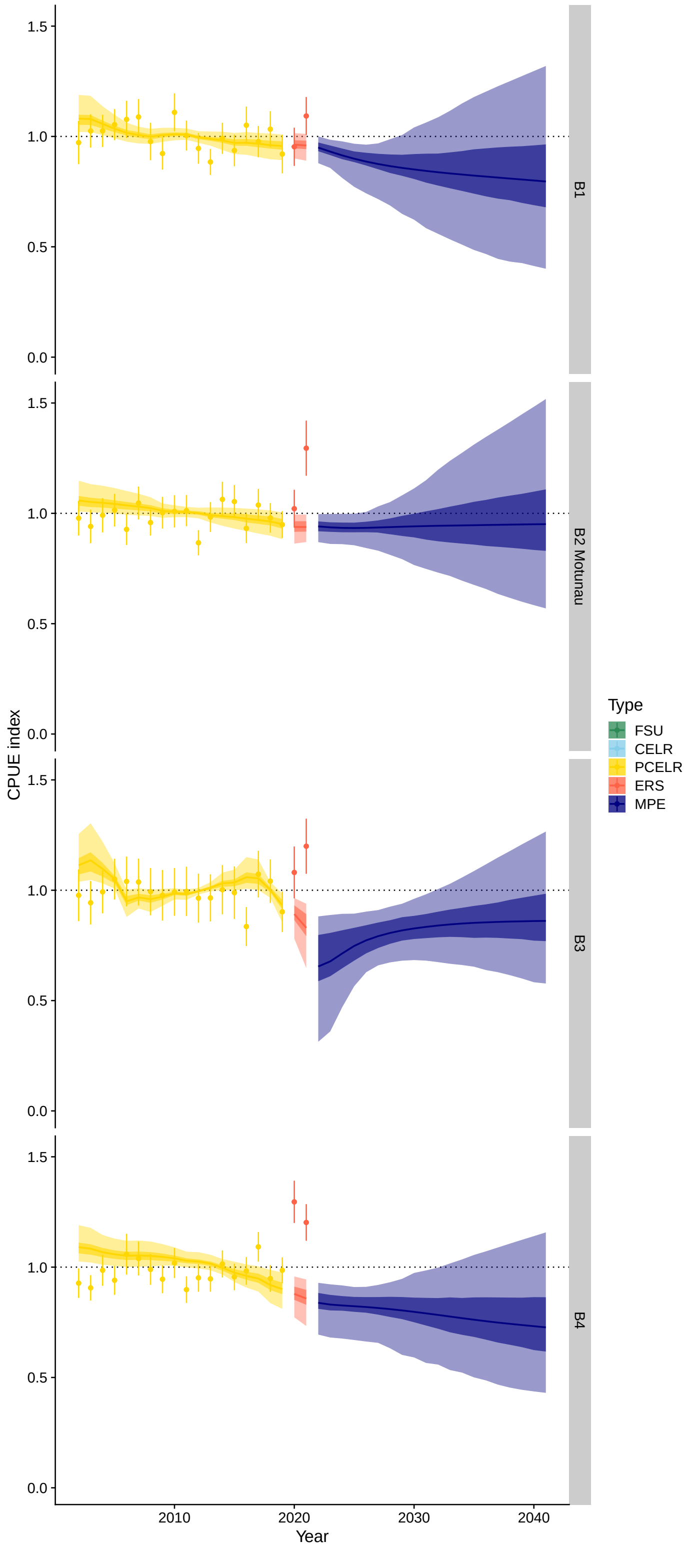

Figure C-4: Predicted CPUE trends for past and future fishery for pāua for the base operating model, with management according to the tested control rules for each zone represented in quota management area PAU 3B (median line, inter-quartile range (dark shaded area) and 95% confidence interval (lighter shading)). The final projection year was 2041. FSU, Fisheries Statistical Unit; (P)CELR, (Paua) Catch Effort Landing Return; ERS, Electronic Reporting System; MPE, management procedure evaluation.

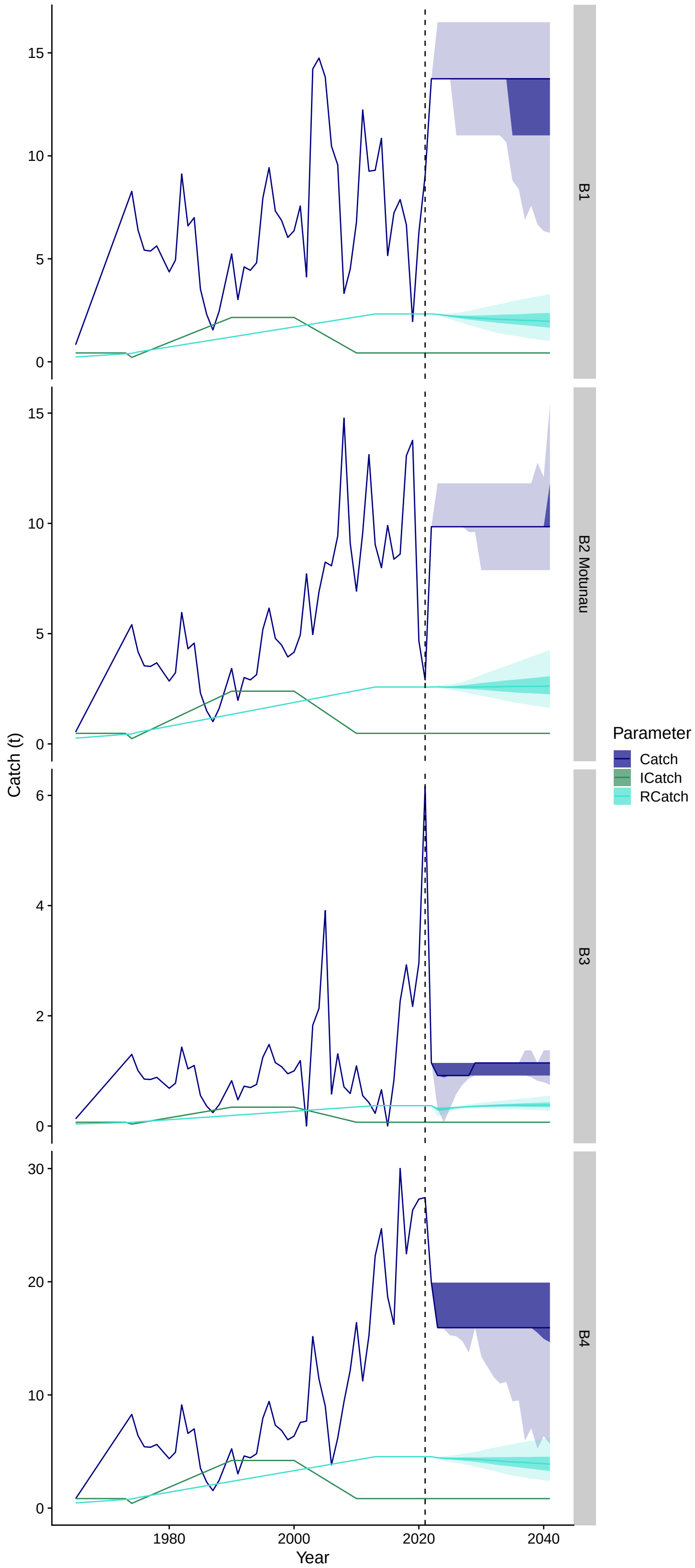

Figure C-5: Assumed and projected pāua catch by sector (I: illegal; R: recreational) for the base operating model, with management according to the tested control rules for each zone represented in quota management area PAU 3B. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. The final projection year was 2041.

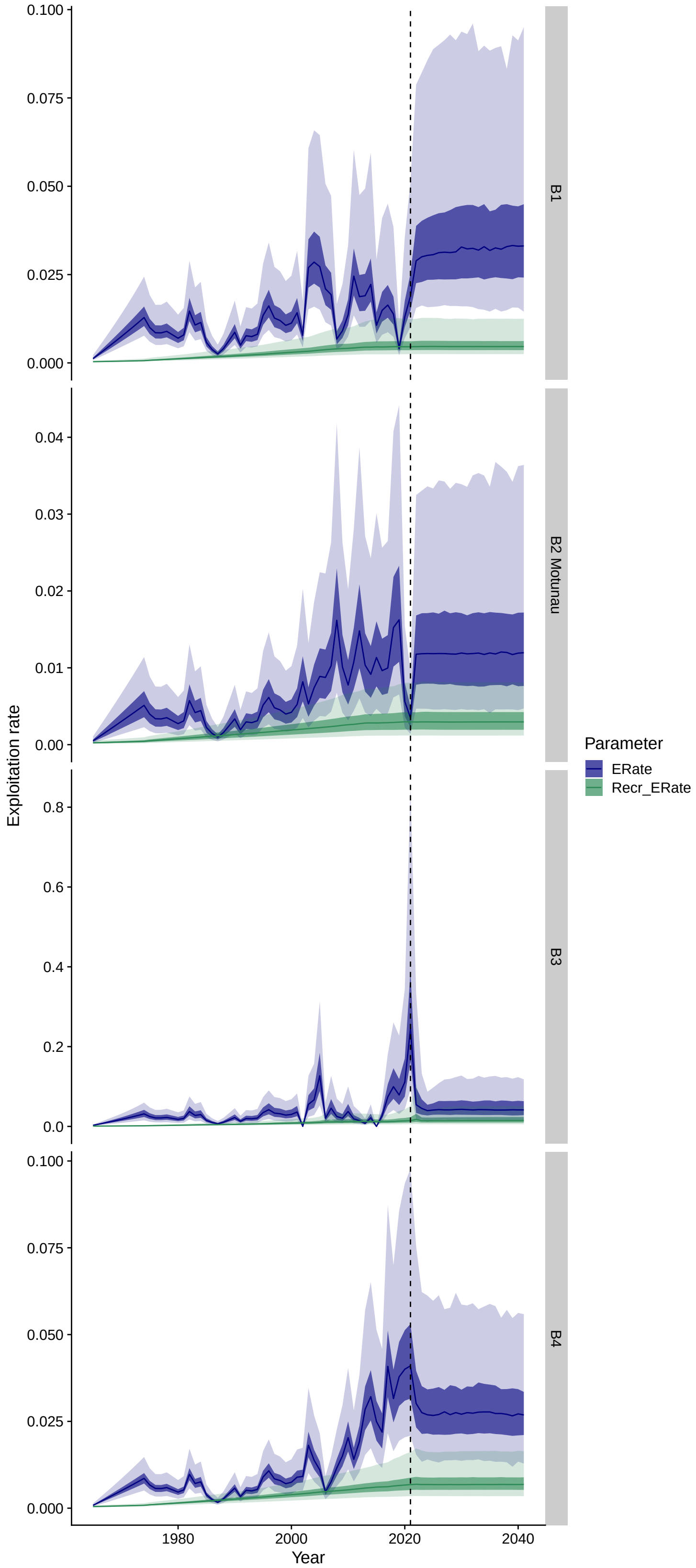

Figure C-6: Estimated and projected exploitation rate by sector (Recr: recreational; median line and 95% confidence interval) for the base operating model, with management according to the tested control rules for each zone represented in quota management area PAU 3B. Dashed vertical line shows the beginning of simulated trends based on the assessed harvest control rule. The final projection year was 2041.

APPENDIX D: MANAGEMENT PROCEDURE EVALUATION MODEL COMPARISON: CONDITIONING STATUS

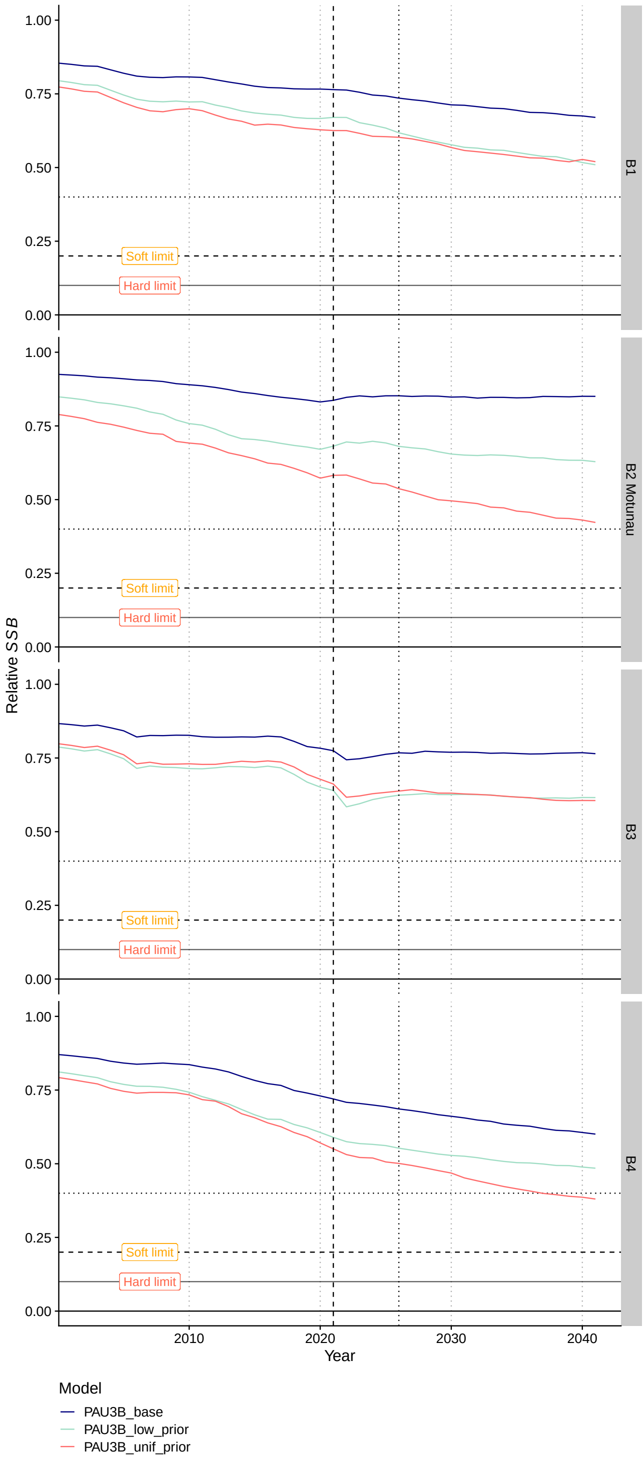

Figure D-1: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua, comparing models conditioned on different status assumptions, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical 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 2041.

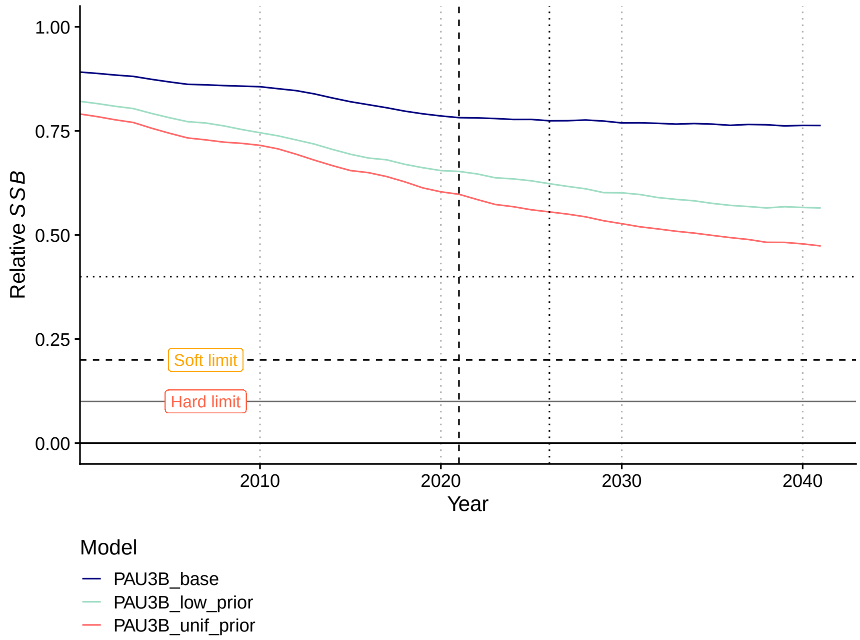

Figure D-2: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua, comparing models conditioned on different status assumptions, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical 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 2041.

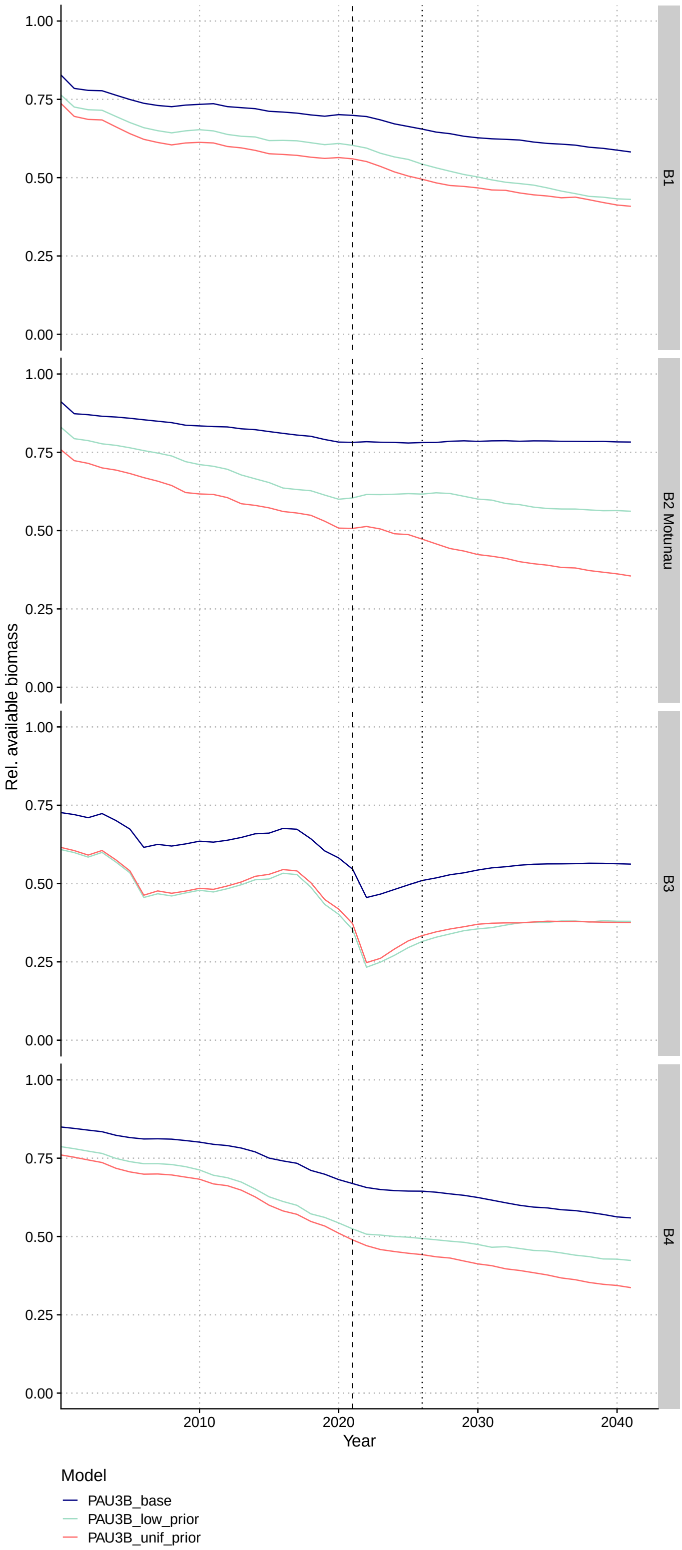

Figure D-3: Estimated and projected relative available biomass trend for pāua, comparing models conditioned on different status assumptions, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line shows the 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 2041.

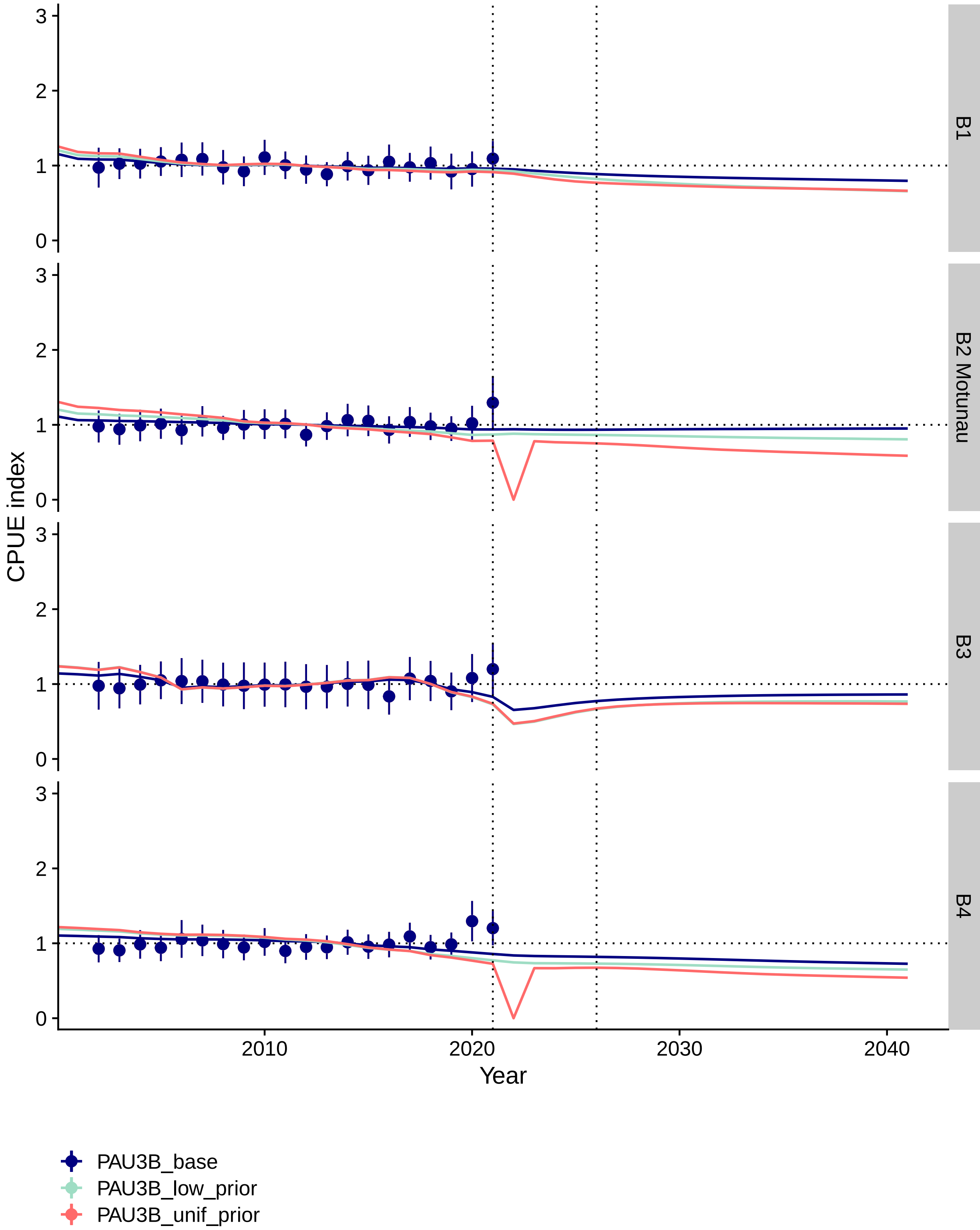

Figure D-4: Estimated relative spawning stock biomass (*SSB*) trend for pāua, comparing models conditioned on different status assumptions, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line shows the 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 2041.

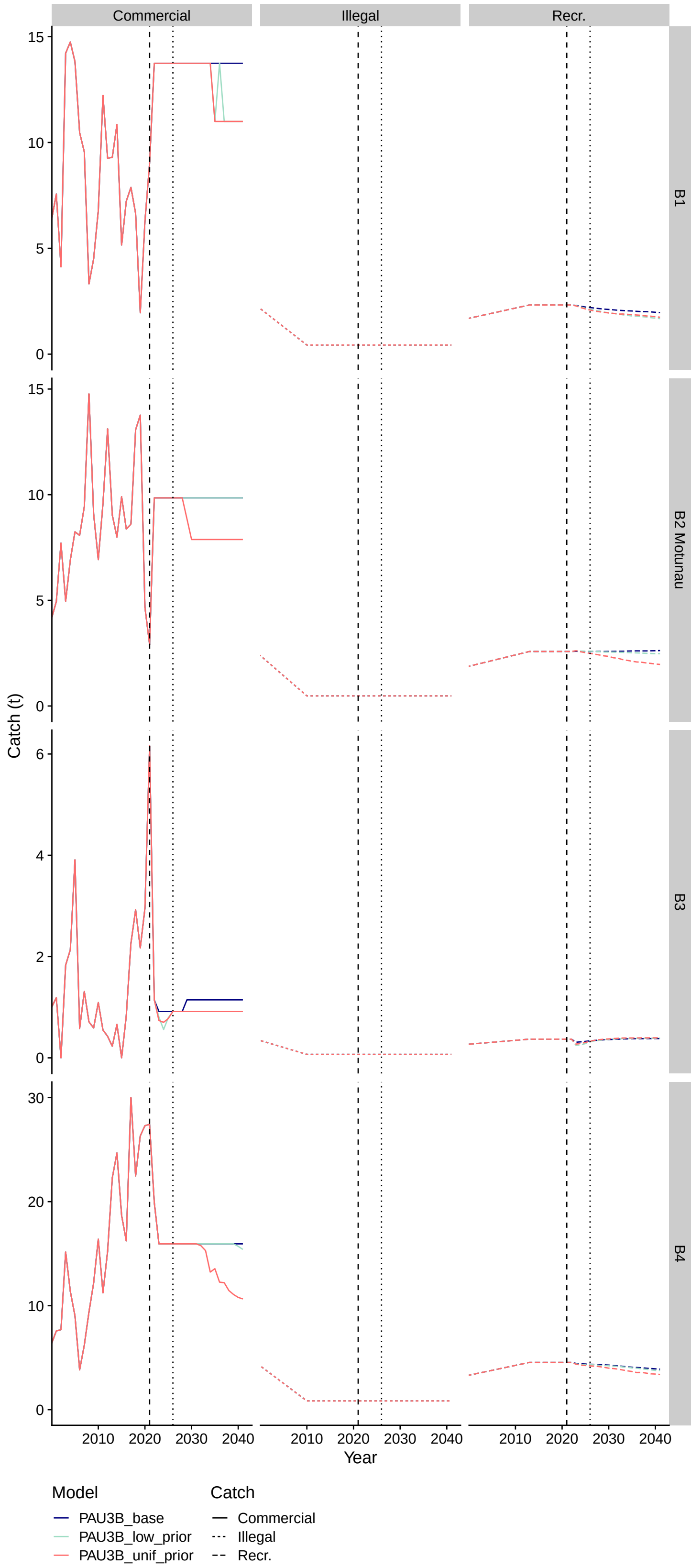

Figure D-5: Assumed and projected and simulated catch by sector, comparing models conditioned on different status assumptions, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line shows the beginning of 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 2041.

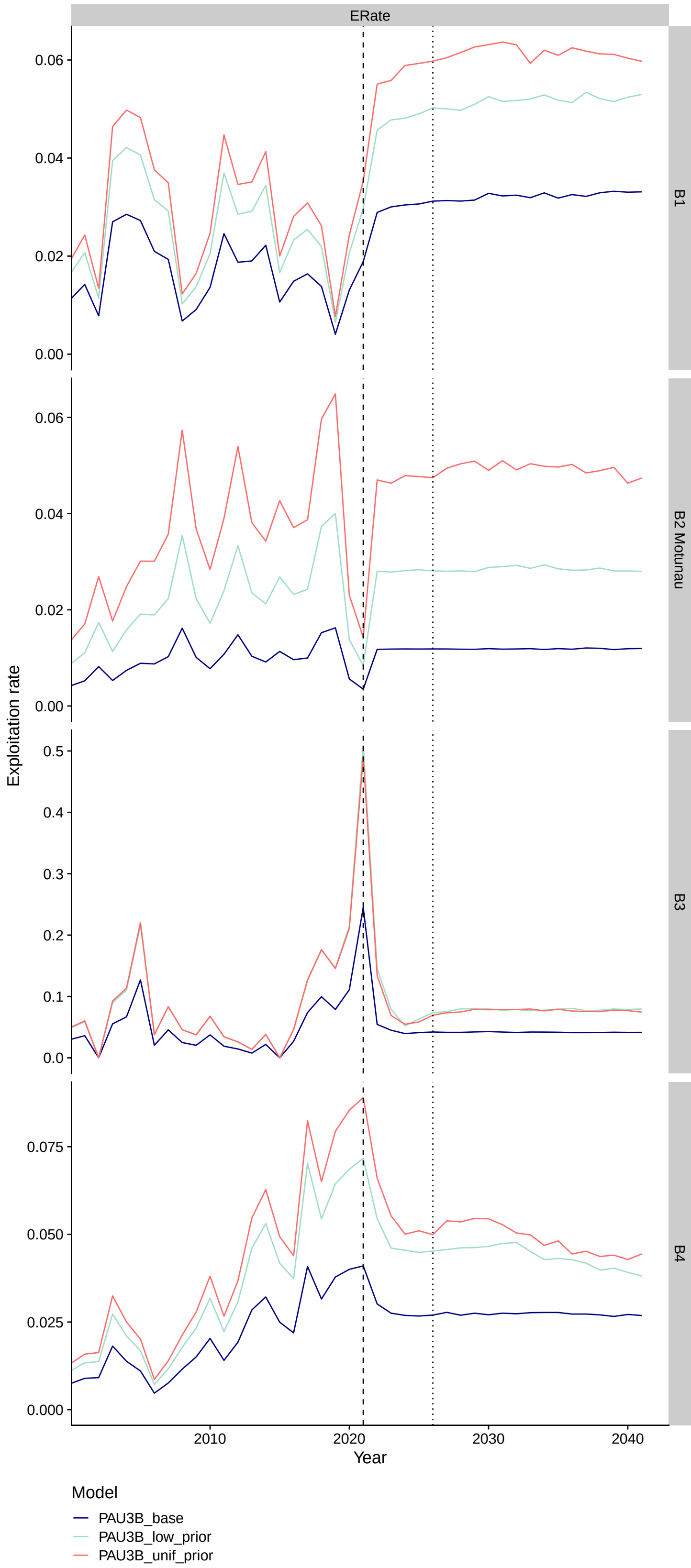

Figure D-6: Estimated and projected exploitation rate for the commercial pāua fishery (median line), comparing models conditioned on different status assumptions, with management according to the tested control rules in quota management area PAU 3B. Dashed vertical line shows the beginning of simulated 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 2041.

Table D-1: Performance of tested management procedures, comparing models conditioned on different status assumptions, with management according to the tested control rules in quota management area PAU 3B, by individual management zones and across the overall QMA. *SSB*, spawning stock biomass; CPUE, catch-per-unit-effort.

Model	Zone	Mean rel. *SSB* (2026)	Mean rel. *SSB* (2041)	P(rel. *SSB* (2026) > 0.4)	P(rel. *SSB* (2041) > 0.4)	P(rel*SSB* (2026) < 0.2)	P(rel*SSB* (2041) < 0.2)	P(rel. *SSB* (2026) < 0.1)	P(rel. *SSB* (2041) < 0.1)	Mean rel. *SSB* (2021–2041)	Mean catch (kg)	Mean CPUE (kg/h)
Base	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.77	41443.82	44.14
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.72	13405.59	47.48
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.86	10028.15	51.69
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.77	1033.04	41.13
	B4	0.68	0.00	0.99	0.00	0.00	1.00	0.00	1.00	0.66	16977.03	37.22
Low status	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.61	38258.22	39.68
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.58	12549.64	42.38
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.66	9522.71	46.29
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.63	928.32	35.86
	B4	0.55	0.00	0.92	0.00	0.00	1.00	0.00	1.00	0.54	15257.55	33.57
Uniform status	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.52	35027.15	35.96
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.55	12326.48	41.32
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.49	8311.70	38.29
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.63	912.40	35.50
	B4	0.50	0.00	0.81	0.00	0.01	1.00	0.00	1.00	0.46	13476.57	29.65

APPENDIX E: MANAGEMENT PROCEDURE EVALUATION MODEL COMPARISON: PRODUCTIVITY ASSUMPTIONS

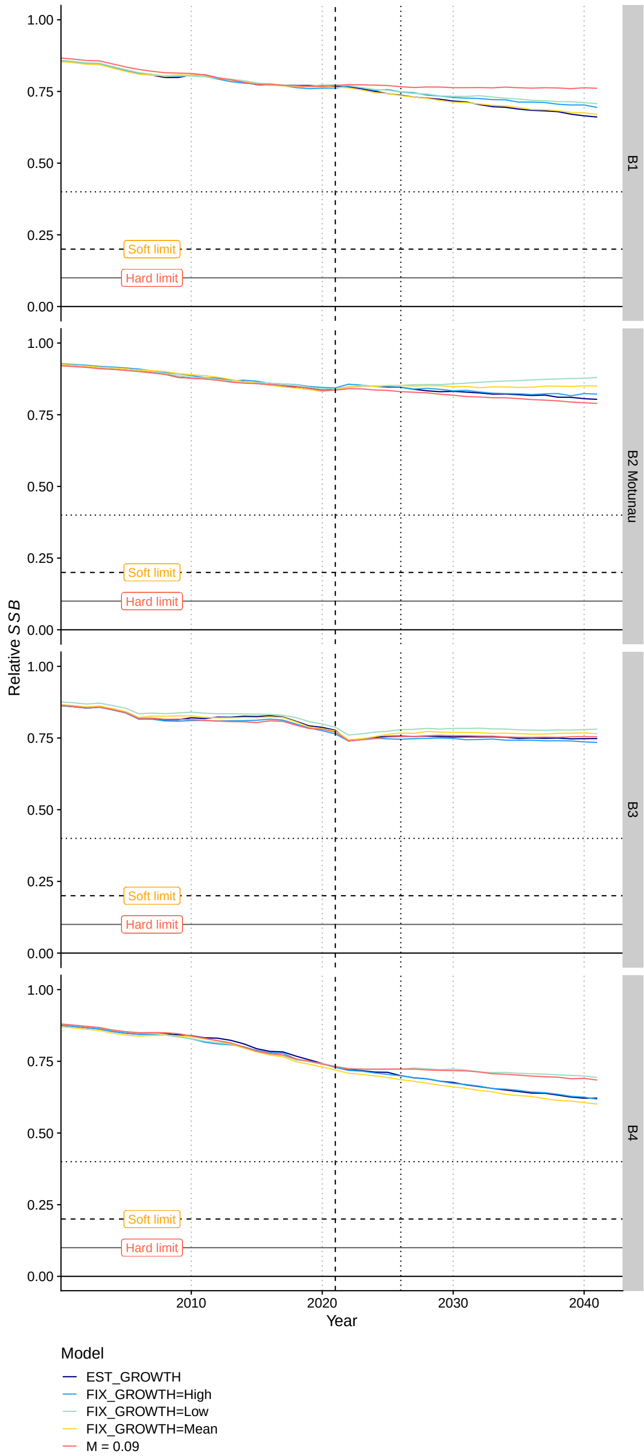

Figure E-1: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua, comparing models assuming different productivity parameters, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line 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 2041.

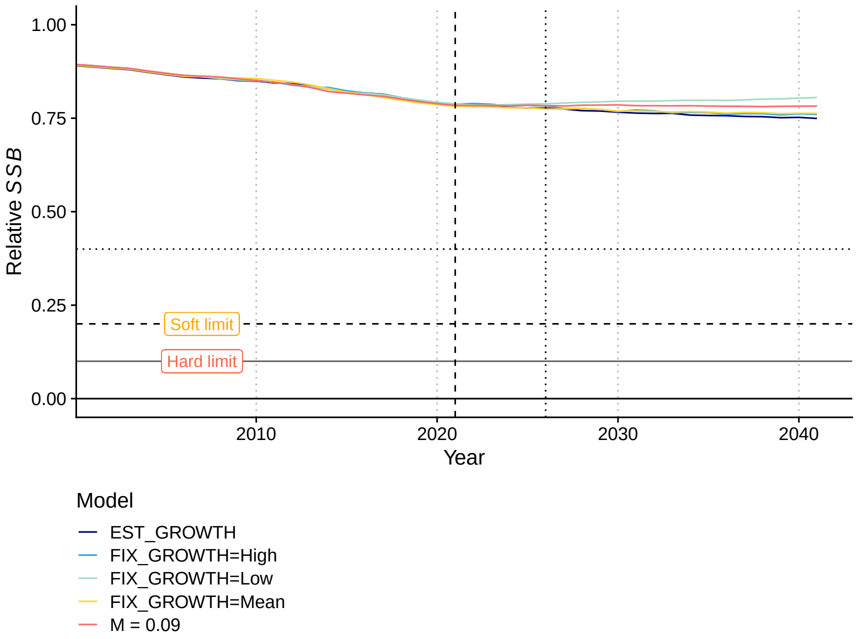

Figure E-2: Estimated and projected relative spawning stock biomass (*SSB*) trend for pāua, comparing models assuming different productivity parameters, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line 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 2041.

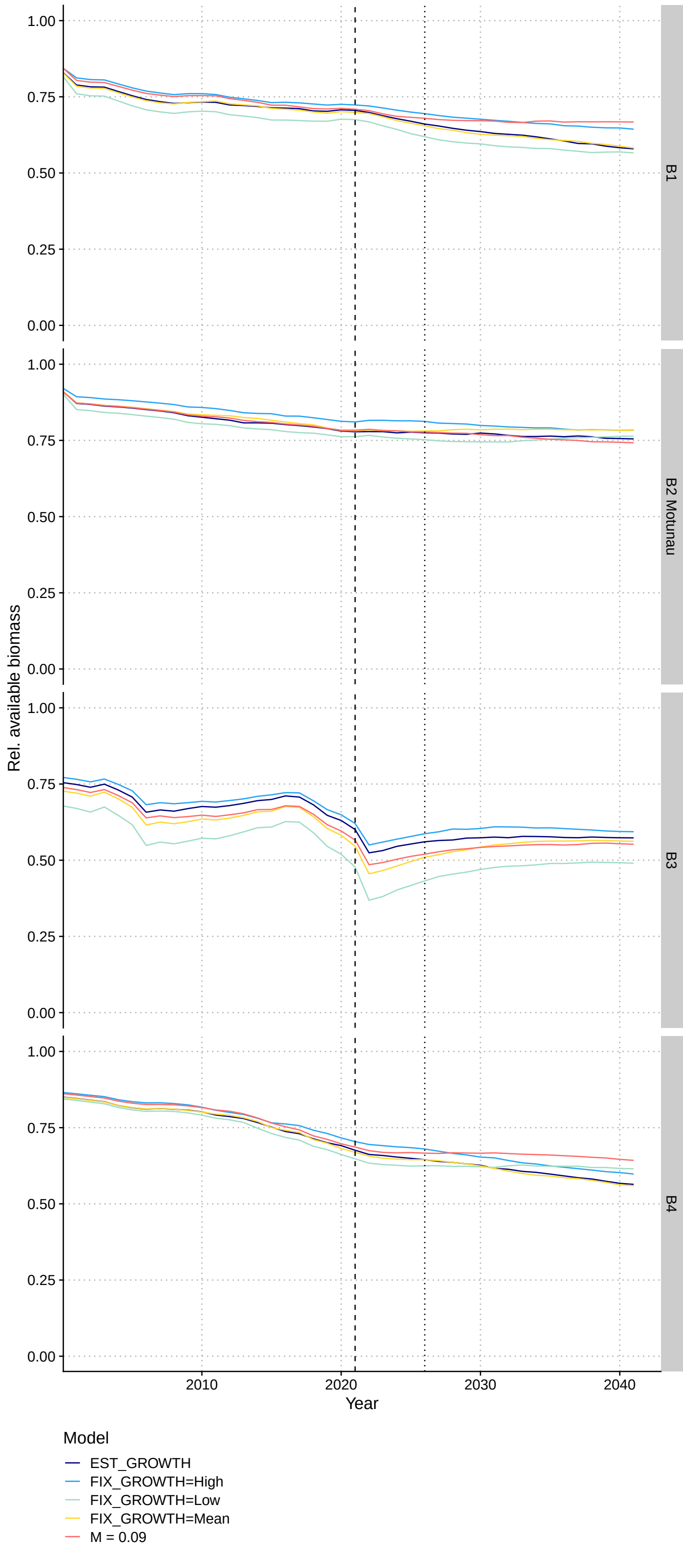

Figure E-3: Estimated and projected relative available biomass trend for pāua, comparing models assuming different productivity parameters, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line shows the 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 2041.

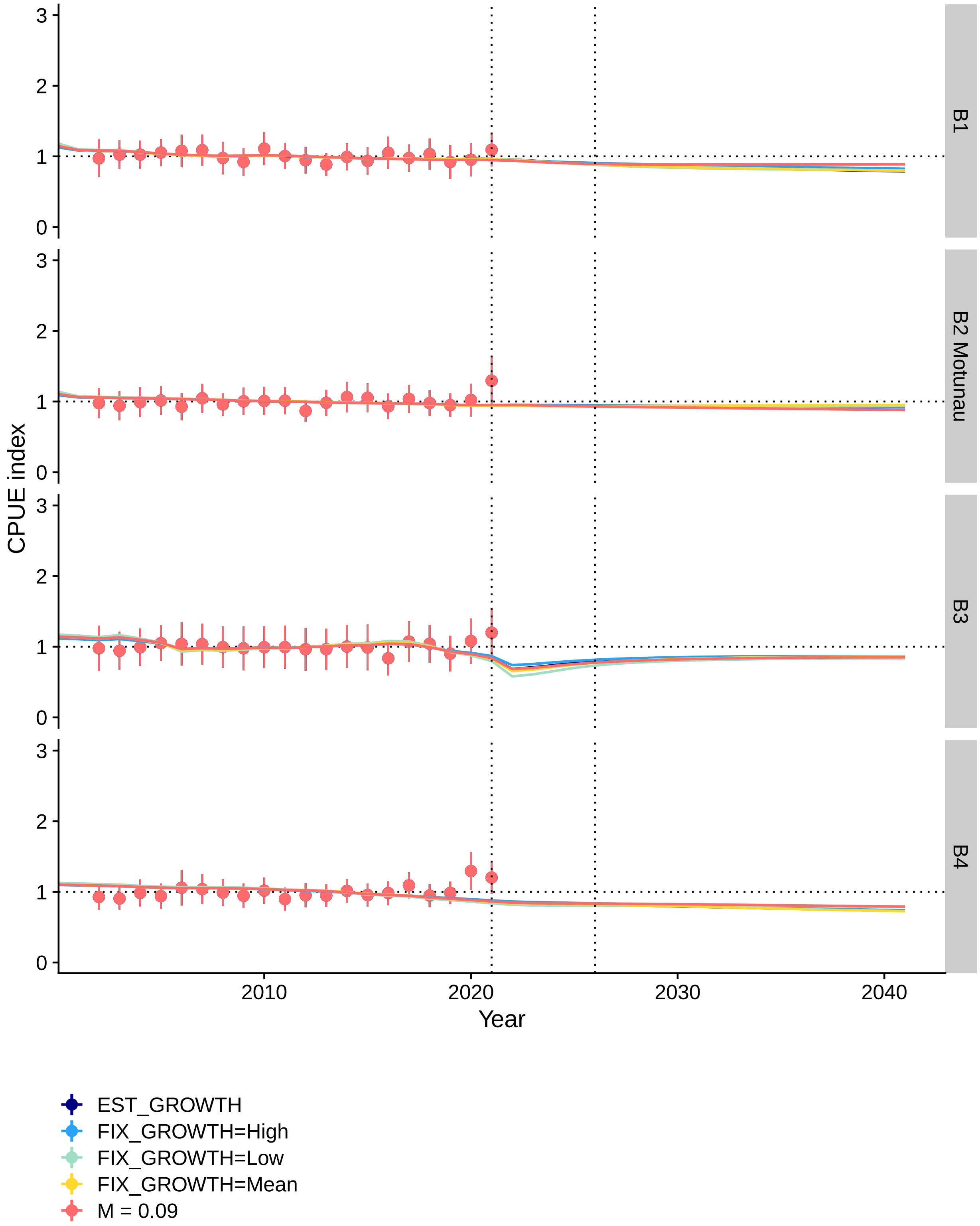

Figure E-4: Estimated relative spawning stock biomass (*SSB*) trend for pāua, comparing models assuming different productivity parameters, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line shows the 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 2041.

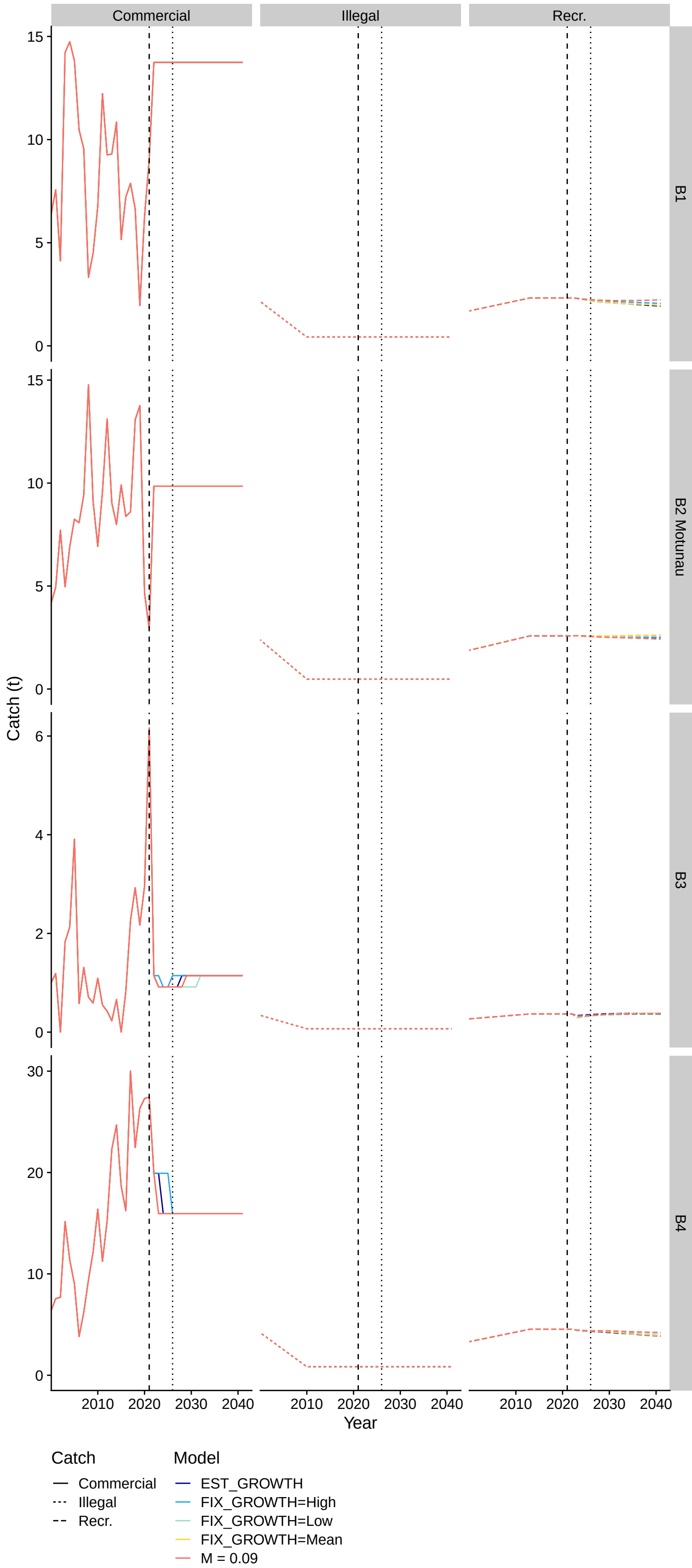

Figure E-5: Assumed and projected and simulated catch by sector, comparing models assuming different productivity parameters, with management according to the tested control rules in quota management area PAU 3B. Only medians from simulations are compared. Dashed vertical line shows the beginning of 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 2041.

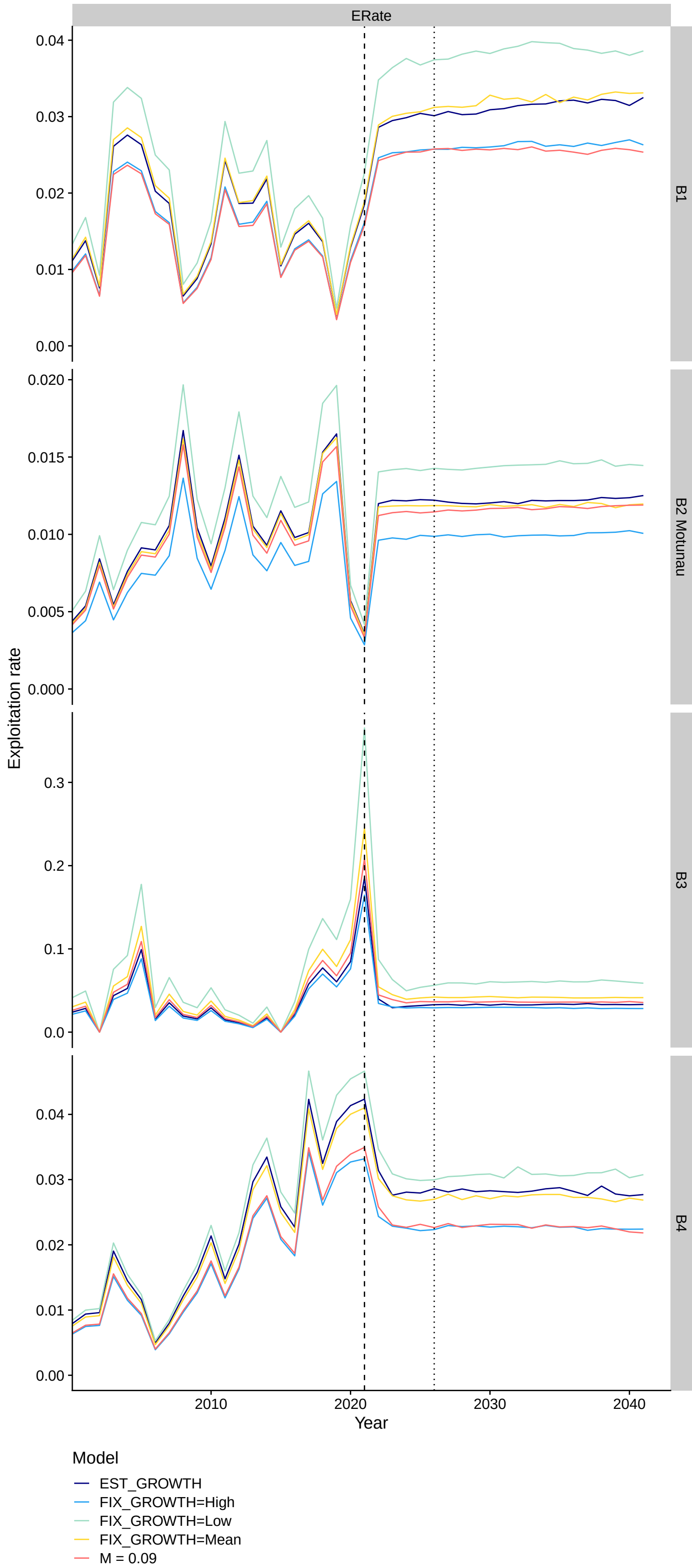

Figure E-6: Estimated and projected exploitation rate for the commercial pāua fishery (median line), comparing models assuming different productivity parameters, with management according to the tested control rules in quota management area PAU 3B. Dashed vertical line shows the beginning of simulated 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 2041.

Table E-1: Performance of tested management procedures, comparing models assuming different productivity parameters, with management according to the tested control rules in quota management area PAU 3B, by individual management zones and across the overall QMA. *SSB*, spawning stock biomass; CPUE, catch-per-unit-effort.

Model	Zone	Mean rel. *SSB* (2026)	Mean rel. *SSB* (2041)	P(rel. *SSB* (2026) > 0.4)	P(rel. *SSB* (2041) > 0.4)	P(rel*SSB* (2026) < 0.2)	P(rel*SSB* (2041) < 0.2)	P(rel. *SSB* (2026) < 0.1)	P(rel. *SSB* (2041) < 0.1)	Mean rel. *SSB* (2021–2041)	Mean catch (kg)	Mean CPUE (kg/h)
Fix mean growth	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.77	41443.82	44.14
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.72	13405.59	47.48
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.86	10028.15	51.69
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.77	1033.04	41.13
	B4	0.68	0.00	0.99	0.00	0.00	1.00	0.00	1.00	0.66	16977.03	37.22
Fix low growth	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.79	41495.58	43.96
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.74	13394.30	46.98
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.85	9911.30	50.66
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.78	997.75	39.30
	B4	0.71	0.00	0.99	0.00	0.00	1.00	0.00	1.00	0.71	17192.23	38.02
Fix high growth	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.77	41823.51	44.98
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.73	13579.81	49.07
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.84	10009.43	51.59
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.75	1062.35	42.85
	B4	0.69	0.00	0.99	0.00	0.00	1.00	0.00	1.00	0.66	17171.92	38.02
Est. growth	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.77	41511.83	44.04
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.71	13462.67	47.59
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.84	9988.40	51.14
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.76	1033.64	41.43
	B4	0.69	0.00	1.00	0.00	0.00	1.00	0.00	1.00	0.67	17027.12	37.22
M = 0.09	All	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.78	42048.28	45.12
	B1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.77	13721.84	49.86
	B2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.81	9854.44	49.82
	B3	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.76	1033.88	40.99
	B4	0.71	0.00	0.99	0.00	0.00	1.00	0.00	1.00	0.70	17438.11	38.99