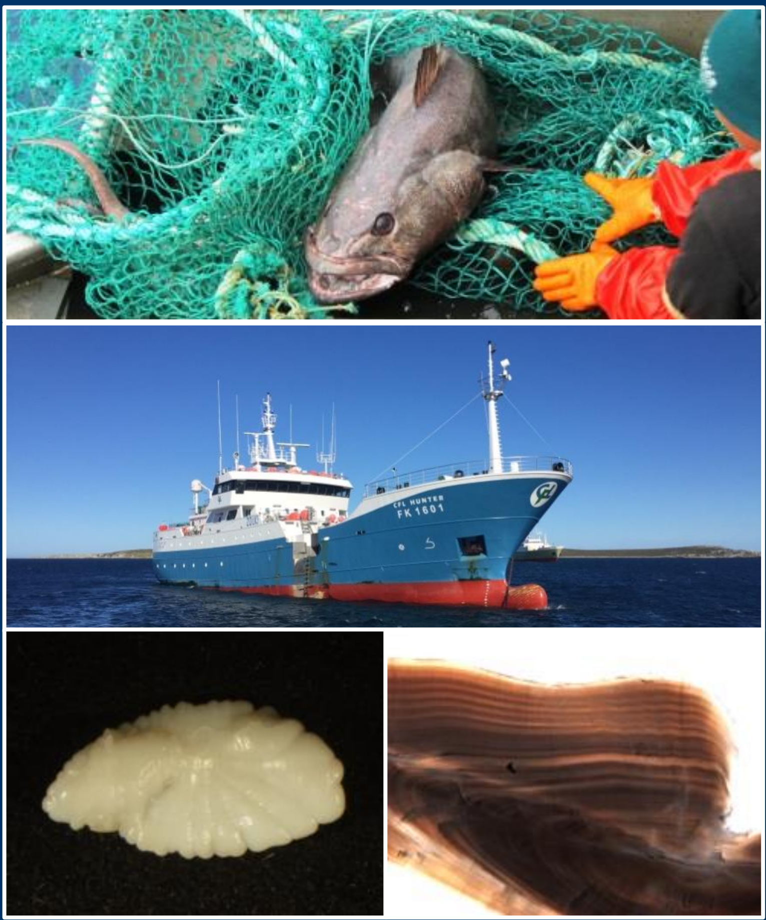
Stock assessment of Patagonian toothfish (*Dissostichus eleginoides*) in the Falkland Islands to 2025

SA – 2025 – TOO



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Summary

1. This report provides an updated integrated stock assessment of Patagonian toothfish *Dissostichus eleginoides* in Falkland Islands waters, using data up to the end of 2025.
2. The initial spawning stock biomass SSB_0 was estimated at 24,725 tonnes, and the current spawning stock biomass SSB_{2025} at 12,545 tonnes.
3. The ratio of current to initial spawning stock biomass (SSB_{2025}/SSB_0) was estimated at 0.507. According to the established harvest control rules (HCR), the SSB_{2025}/SSB_0 ratio places the stock in the *expansion range*.
4. Projections from the current model indicated that the SSB/SSB_0 ratio will drop and remain in the *target range* from 2032 to 2046.
5. Based on the HCR, the recommendation is to maintain the toothfish annual TAC in the longline fishery at its current level of 1,040 tonnes.

1. Introduction

Patagonian toothfish (*Dissostichus eleginoides*; hereafter, toothfish) is a long-lived, slow-growing species found on the shelves and slopes of South America and around the sub-Antarctic islands of the Southern Ocean. In Falkland Islands waters, toothfish spawn on the slopes of Burdwood Bank at ~1,000 m depth, with a minor spawning peak in May and a prominent peak in July-August (Laptikhovsky *et al.* 2006). The eggs, larvae, and small juveniles (<10 cm TL) develop and grow in epipelagic layers of the Falkland Current, with early juveniles of 10-12 cm TL (<1 year old; Lee 2017) occurring on the Patagonian Shelf at depths of ~100 m. Immature toothfish remain on the shelf for 3-4 years and then undertake a characteristic ontogenetic migration into deeper waters where adults reside and spawn (Arkhipkin and Laptikhovsky 2010).

The Falkland Islands toothfish longline fishery began in 1992 as an exploratory fishery and became an established fishery in 1994 (Laptikhovsky and Brickle 2005). The fishery used the 'Spanish' longlining system (with a few vessels using the Mustad Autoline system in the early years) until the 'umbrella' system was introduced in 2007 to reduce the loss of hooked toothfish to depredation. The umbrella system consists of hooks set in clusters, with an umbrella of buoyant netting attached above each cluster. The umbrella floats above the cluster whilst the gear is on the seabed but folds over the cluster and the hooked fish during hauling, preventing depredation (Brown *et al.* 2010). Following initial trials in 2007, all vessels operating in the Falkland Islands longline fishery adopted the umbrella system by 2008.

Besides the targeted longline fishery, toothfish are bycatch in the shelf-based (<400 m depth) finfish and calamari trawl fisheries. In the finfish fishery, toothfish is a commercially valuable bycatch; in the calamari fishery, toothfish are typically discarded due to the small size of the specimens (20-30 cm TL). These fisheries exploit different parts of the toothfish population in distinct areas: longlining occurs on the deep-water slope, finfish trawling on the shelf primarily north and west of the Falkland Islands, and calamari trawling on the shelf south and east of the Falkland Islands (Figure 1).

This report presents an updated Bayesian integrated stock assessment for toothfish in Falkland Islands waters, using data up to the end of 2025.

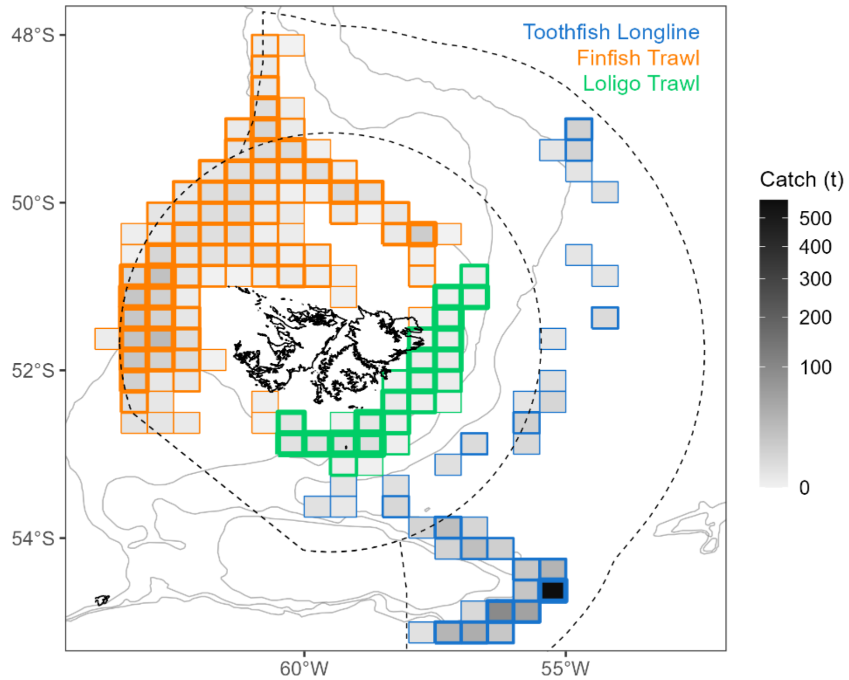

Figure 1. Distribution of toothfish catch and effort per fishery in 2025. The thickness of grid lines is proportional to vessel days, and the greyscale shading is proportional to toothfish catch biomass. Both variables were square-root transformed prior to plotting.

1.1. Stock structure and assumptions

A long-term research programme investigating the stock structure of toothfish on the Patagonian Shelf revealed complex patterns (Lee 2023). Research results indicate high levels of spatial-temporal variability in the extent of connectivity during the early life-history phases of egg and larval dispersal. Recruitment to the Falkland Islands Shelf arises from Burdwood Bank and southern Chile spawning areas. It is proposed that high recruitment pulses are dominated by input from the Burdwood Bank spawning contingent. These pulses show strong spatial-temporal variability. Stable recruitment at lower levels occurs from the southern Chile spawning contingent, where they are retained on the western shelf of the Falkland Islands. Further, evidence of connectivity across the region through the active migration of adults appears to occur on a relatively small scale. Current results demonstrate that the stock structure arising from the retention of mixed contingents across the Falklands Shelf remains discrete (within the Falkland Islands Conservation Zones) until the adult life-history stages. Therefore, considering the currently available information, for this assessment, we assumed that there is one discrete toothfish stock present in Falkland Islands waters.

2. Methods

The stock assessment was undertaken using an integrated age-structured model implemented in CASAL (Bull *et al.* 2012) version v2.30-2012-12-02 rev.4840. The model assumes a single homogenous area, but the spatial heterogeneity of the population is represented by three geographically distinct commercial fisheries (longline, calamari trawl, and finfish trawl) and their gear-specific selectivity and fish availability (i.e. fleets-as-areas approach). The longline fishery is further split into two distinct fisheries according to gear type (Spanish-system and umbrella-system longline) to accommodate for different catchability between the two.

2.1. Model updates

Compared to the previous assessment (Skeljo, 2025), this assessment was routinely updated with (a) catch and effort data for the umbrella-system longline fishery in 2025, (b) catch data for the finfish and calamari trawl fisheries in 2025, (c) biological data (size-structure and maturity) for all fisheries and research surveys in 2025, (d) additional age readings for 2024 and 2025, and e) tag release data in 2024 and tag recapture data in 2025.

2.2. Data

Several datasets were used to inform the assessment, either as observations or input parameters (Figure 2). CPUE, catch-at-age and tag-recaptures are observations, i.e. appear in the objective function and are used to fit the model. Parameters of the length-at-age relationship, length-weight relationship and maturity curve are estimated outside the model and then treated as fixed parameters within the model.

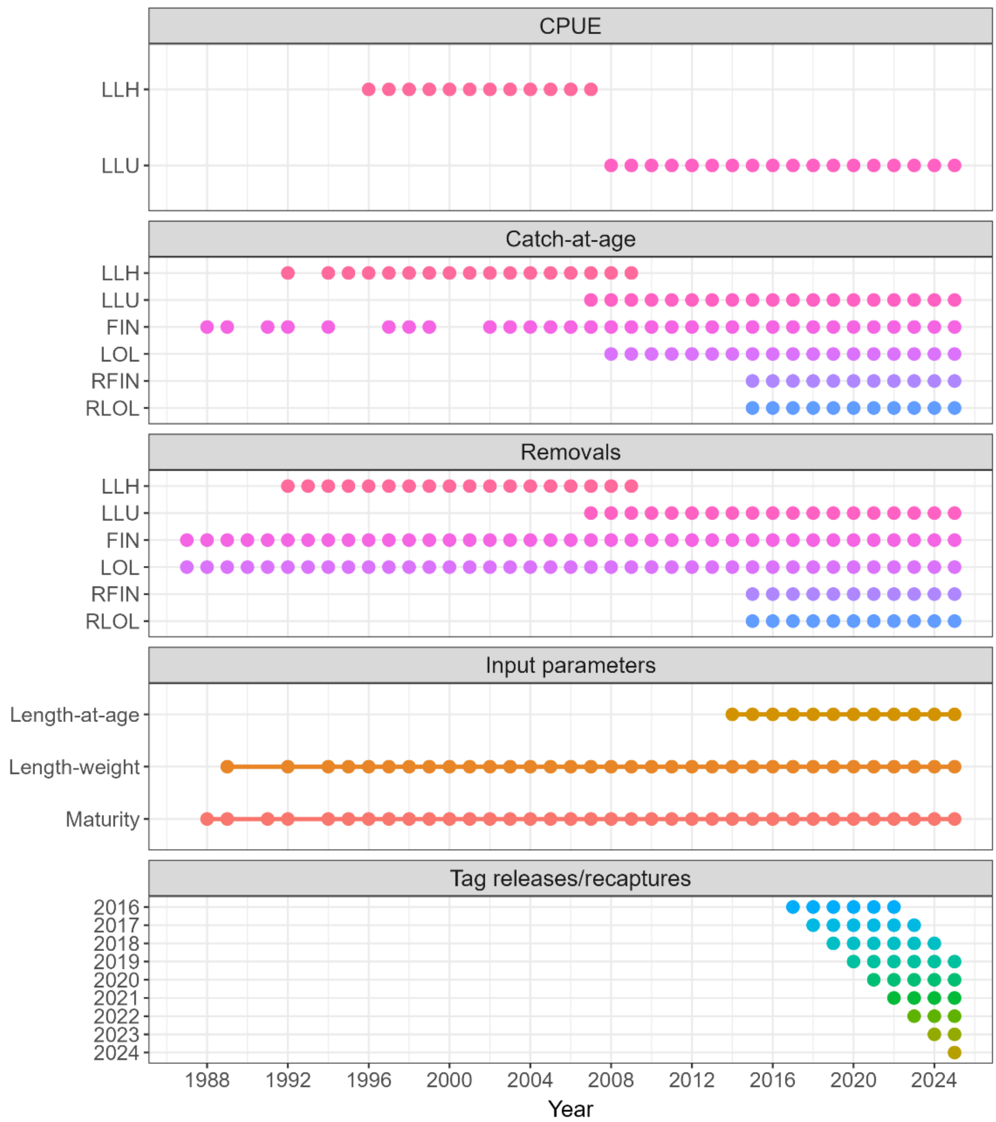

Figure 2. Data used to inform the assessment model. LLH – Spanish-system longline, LLU – umbrella-system longline, FIN – finfish trawl, LOL – calamari trawl, RFIN – groundfish survey, RLOL – calamari pre-season survey. Data used to calculate input parameters were pooled across years. Tag release years are on the y-axis, and tag recapture years are on the x-axis.

Catch-per-unit-effort (CPUE)

Although CPUE data were available for all four fisheries, only longline CPUE was used as a relative abundance index in the model; a decision motivated by the inconsistency of toothfish CPUE in trawl fisheries, where toothfish bycatch may change due to factors other than stock abundance (e.g. fisheries switching targets or areas). Longline CPUE data were divided between the Spanish and umbrella systems to allow for different catchability between the two, as was previously observed (Brown *et al.* 2010). The transition from the Spanish to the umbrella system occurred in 2007-2008.

For the Spanish-system longline fishery, the catch and effort data were available only aggregated per day (the fishery predates the use of electronic logbooks). 95 daily catch reports from remote areas (outside the region 47°W - 70°W and 40°S - 57°S) were excluded from the analysis. These records belong to the early years of the fishery (1998-2002) when presumably more exploratory fishing took place.

For the umbrella-system longline fishery, the catch and effort data were available per line (electronic logbook data). Since the onset of the umbrella system, the fishery was dominated by a Falkland Islands vessel (*CFL Gambler*, replaced by *CFL Hunter* in 2017), occasionally assisted by up to two chartered Chilean vessels. None of the chartered vessels has participated in the Falkland Islands fishery for more than two years since 2007, resulting in inconsistent CPUE data. Moreover, at least one of the chartered vessels had restrictions imposed on its fishing practice (e.g. a limit on the number of fishing days in the 'best' fishing grounds) that were not in place for the Falkland Islands vessel. Because of the above, only the Falkland Islands' vessels' CPUE was used as an index of abundance. With a similar goal, data from dedicated tagging trips and longlines set at depths <600 m were excluded from the analysis; tagging trips because part of the actual catch was unreported (released fish), and shallow-water sets because these were experimental fishing to collect brood stock for the toothfish rearing facility (commercial longlining is prohibited at depths <600 m).

CPUE was calculated from the cleaned data as reported toothfish catch in kg-per-hook per day (Spanish system) or kg-per-umbrella per line (umbrella system). Finally, CPUE was standardised using a generalised linear mixed modelling approach (GLMM), providing a time series of CPUE values as relative abundance indices (Appendix 1). The observation error of the CPUE indices was accounted for in the assessment model via the coefficient of variation (CV) estimates obtained directly from GLMM standardisation. To account for any additional variance on top of observation error, that may arise from the differences between model simplifications and real-world variation, a process error CV = 0.05 was assumed. The CPUE indices were assumed log-normally distributed about the model-predicted vulnerable biomass via a catchability parameter.

Catch-at-age (CAA)

Age readings used for the assessment were restricted to otoliths sampled in 2014-2025; these were processed and aged at the Falkland Islands Fisheries Department (FIFD) and were considered the most reliable toothfish age estimates available (Lee 2014, 2015, 2016, 2017, 2018, 2019, 2020; Lee and Le Luherne 2023; Le Luherne 2025a, 2025b, 2025c; Le Luherne 2026). Since the last assessment (Skeljo, 2025), an additional 496 age readings belonging to otoliths collected in 2024 and 483 readings belonging to otoliths collected in 2025 became available. In total, 4,417 toothfish age estimates belonging to longline fisheries and 3,761 age estimates belonging to trawl fisheries were used to construct two corresponding age-length keys: $ALK_{LONGLINE}$ and ALK_{TRAWL}. Next, the length-frequency distribution of 182,154 toothfish randomly sampled in 1988-2025 was split between the corresponding fisheries or surveys. Age was assigned to each fish by the conditional probability of the appropriate age-length key: $ALK_{LONGLINE}$ for longline fisheries and ALK_{TRAWL} for calamari fishery, finfish fishery, and trawl surveys. Ages ≥31 years were assigned to a plus group. Then, fish counts-at-age were catch-raised per haul (i.e. multiplied by the catch/sample weight ratio in each observed haul), aggregated per year and fishery, and converted to proportions-at-age. CAA data for the calamari trawl fishery up to 2008 were considered unrepresentative and thus excluded from the analysis (Skeljo and

Winter 2021). Ageing error was applied to the observed CAA by assuming that true ages are normally distributed around read ages with CV = 0.1, and accounted for in the model via a misclassification matrix. The CAA data were assumed to be independently multinomially distributed about the model-predicted CAA.

A consideration in integrated models is to ensure that the observations are given appropriate weights in the objective function. The CAA data were weighted via effective sample sizes, estimated by a two-stage weighting approach: in stage 1, the weights appropriate for the observation error are assigned outside the model, and in stage 2, those weights are adjusted within the model to allow for process error (Francis 2011). In our assessment, in stage 1, the effective sample sizes were given by the number of unique hauls sampled. The initial model fit was then run, and the information from that run was used in the stage 2 adjustment of the effective sample sizes, multiplying them by a weighting factor calculated according to *Method TA1.8* (Francis 2011):

$$w_f = \frac{1}{var\left[(\bar{O}_{fy} - \bar{E}_{fy})/\sqrt{(v_{fy}/N_{fy})}\right]}$$

Where w_f is the weighting factor for fishery (or survey) *f*, $\bar{O}_{fy}$ and $\bar{E}_{fy}$ are calculated from the observed and expected proportions-at-age for fishery *f* in year *y*, v_{fy} is the variance of the expected age distribution for fishery *f* in year *y*, and N_{fy} is the effective sample size for fishery *f* in year *y* defined in stage 1. The model was then re-run with the adjusted effective sample sizes (Table 2).

Removals

Removals accounted for the reported catches in Falkland Islands waters, IUU catches in Falkland Islands waters, and catches lost to undetected whale depredation.

Catch reports from all available years for the four fisheries and two research surveys were used, starting in 1987. Trawl catch reports without licence information were considered calamari trawls if the dominant species in the catch was *Doryteuthis gahi,* and finfish trawls otherwise.

No information on IUU fishing within Falkland Islands waters was available; therefore, we utilised the data for the Antarctic region (Agnew *et al*. 2009), which gives estimates of IUU catches as a proportion of reported catches in 1980-2003. For later years, we took grey-literature estimations (e.g. CCAMLR Secretariat 2010) that IUU fishing decreased significantly in the southern oceans and assumed IUU catches equal to 5% of the reported catches in Falkland Islands waters.

Whale depredations are included in longline catch reports when they are evident as toothfish hauled up damaged or destroyed by bite marks. However, toothfish taken entirely by whales before hauling are not seen and accounted for in the catch reports. To quantify this cryptic depredation, Winter and Pompert (2016) developed a model-differencing algorithm between catches predicted from all observer-monitored longlines and catches predicted only from observer-monitored longlines without signs of whale depredation. Models included parameters: longline position, fishing depth, year, month, number of hooks, and soak time. The model-difference could then be projected onto all commercial longlines to estimate the amount of toothfish lost. The algorithm has recently been revised by modelling Spanish-system and umbrella-system longline fishing separately, as for the stock assessment, and by projecting the depredation ratios of the models rather than the models themselves, which improved the avoidance of outlier extrapolations.

Adding the reported catches, assumed IUU catches, and estimated whale depredation resulted in total removals used in the assessment model (Figure 3). The removals are treated as input parameters in CASAL and are assumed to be known without error.

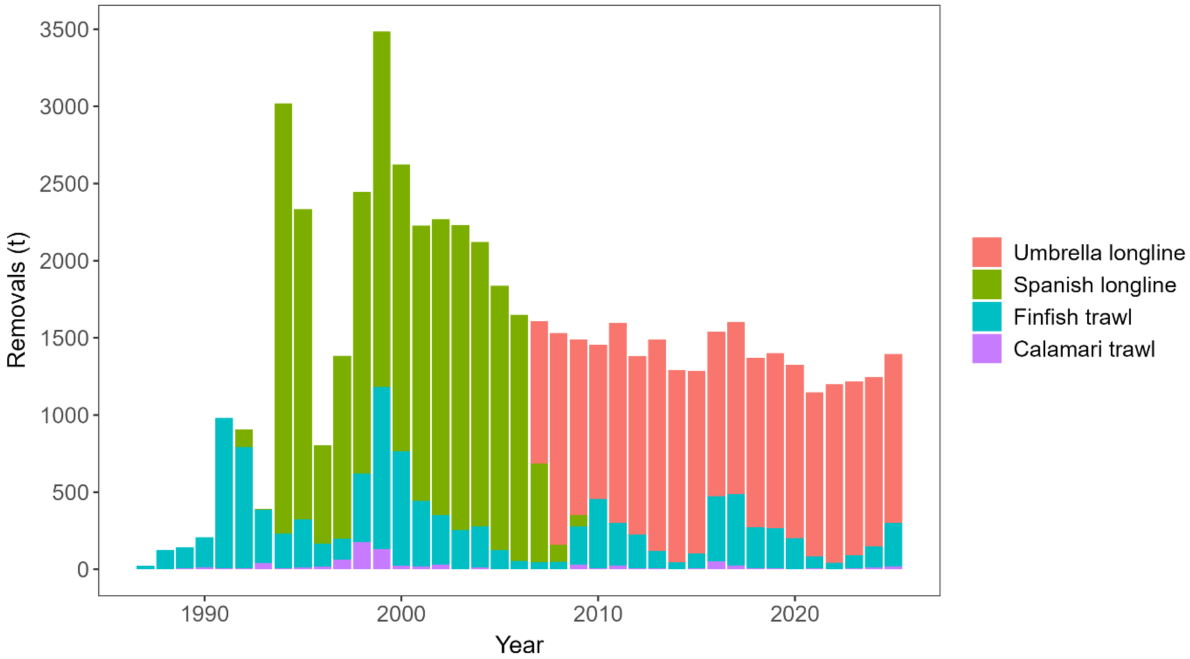

Figure 3. Toothfish removals in FCZ from 1987 to 2025, per fishery. Removals in trawl fisheries equal the reported catches. Removals in longline fisheries equal the sum of reported catches, assumed IUU catches and estimated depredation.

Length-weight relationship

The length-weight relationship was calculated as $W = aL^b$ based on the length and weight measurements of 47,607 toothfish sampled randomly by the observers from commercial catches in 1989-2025. Length-weight parameters are given in Table 3.

Von Bertalanffy growth

The length-at-age relationship was described by the von Bertalanffy growth model $L = L_{inf}\left(1 - e^{-k(age - t_o)}\right)$ based on age estimates and length measurements of 8,195 toothfish sampled randomly by observers from commercial catches in 2014-2025. Von Bertalanffy growth model parameters are given in Table 3.

Natural mortality

Natural mortality (M) was assumed to be 0.165 (Payne *et al.* 2005) and time- and age-invariant. Even though M would ideally be estimated within the model, there is not enough information in the available observations to do so reliably; all toothfish assessments done in CCAMLR waters assume a fixed M value (Earl and Readdy 2023; Readdy and Earl 2023; Masere and Ziegler 2023; Massiot-Granier *et al.* 2023a, 2023b; Mormede *et al.* 2023). Model sensitivity to different assumed M values was explored by Skeljo *et al.* (2022).

Maturity

A maturity-at-age vector was based on the maturity stage data estimated by observers for the 182,154 toothfish sampled randomly from commercial catches during 1988-2025. Maturity was scored on an 8-point scale, and toothfish are considered mature from stage 3 (Laptikhovsky *et al.* 2006). However, mature toothfish occasionally enter a ‘resting’ stage, and they can skip annual spawning (Collins *et al.* 2010, Boucher 2018). While in this resting stage, the gonads look very similar macroscopically to stage 2 gonads, which are considered immature. Analysis of the maturity data strongly indicated that some older fish were erroneously assigned immature (stage 2) when observed. To address this inaccuracy, a generalised additive model (GAM) was used to predict the expected number of older fish at stage 2, and maturity data were corrected accordingly (Farrugia and Winter, 2018). Finally, instead of the more typical logistic function, the maturity ogive was fitted using GAM, resulting in a maturity-at-age vector with the proportion of mature fish in each age class from 1 to 31+ (plus group). The maturity-at-age vector is given in Table 3.

Tag releases and recaptures

The tagging programme for Falkland Islands toothfish commenced in 2016, aiming to improve understanding of toothfish movement patterns within the region. The initial goal of tagging 3,000 fish was achieved during four tagging research surveys on board the longliner in 2016-2018. In addition to surveys, observers have been tasked to tag an average of 25 toothfish per week during their trips on board the longliner. However, the tagging programme largely relied on dedicated research surveys; in their absence, the number of tagged toothfish declined considerably in 2019-2020. In response, a 4-year extension of the tagging programme was recommended (Lee and Skeljo 2020) and followed up by renewed tagging efforts since 2021 (Skeljo and Pearman 2021, Nicholls and Raczyński 2023, Le Luherne and Peruzzo 2023, Le Luherne and Desmet 2025) with a goal of tagging ~1,000 longline-caught fish annually, i.e. one fish per tonne of TAC. Since 2016, 8,908 toothfish have been tagged and released within the FCZ, of which 595 have been recaptured (Table 1). A further 536 toothfish were tagged on the High Seas (North Scotia Ridge) in 2023 to improve our understanding of toothfish stock connectivity within the region (Raczynski *et al.* 2024). Under the current assumption of a discrete toothfish stock in Falkland Islands waters (Lee 2023), the recaptures of fish tagged on the High Seas were not used in the assessment. Ten fish tagged in 2024 within the FCZ were also excluded because they were mistakenly released by an observer while sperm whales were present around the vessel, making their survival unlikely.

Table 1. Numbers of tags released within FCZ and recaptured within and outside (in brackets) the FCZ. Grey shading denotes the numbers used in the assessment (i.e. within-year recaptures and recaptures after six years at liberty were excluded). Recaptures outside FCZ were used to calculate the tag emigration rate, but not to fit the assessment model. Tags deployed on the High Seas and their subsequent recaptures were excluded from the assessment and the table.

Releases		**Recaptures**										
Year	**Number**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**Total**
2016	437	14	15	3	7	8	6	8	1	4 (1)	0	66 (1)
2017	685	-	6	7 (3)	10 (1)	12 (2)	12 (1)	15 (1)	7	5	0 (1)	74 (9)
2018	2189	-	-	4 (1)	24 (2)	32 (7)	89 (1)	44 (6)	12 (6)	28 (1)	6 (6)	239 (30)
2019	127	-	-	-	1 (1)	4	6	1	4	1	1	18 (1)
2020	171	-	-	-	-	0	3 (2)	1	3	0	1	8 (2)
2021	866	-	-	-	-	-	13	22	7 (2)	13 (1)	7 (2)	62 (5)
2022	1072	-	-	-	-	-	-	5	14 (1)	22 (3)	7 (5)	48 (9)
2023	1146*	-	-	-	-	-	-	-	4	51 (2)	7 (1)	62 (3)
2024	1310	-	-	-	-	-	-	-	-	6	7 (2)	13 (2)
2025	905	-	-	-	-	-	-	-	-	-	5	5
Total	8908*	14	21	14 (4)	42 (4)	56 (9)	129 (4)	96 (7)	52 (9)	130 (8)	41	595 (62)

* An additional 536 toothfish were tagged on the High Seas in 2023.

The spatial distribution of toothfish tag releases, recaptures, and longline fishing effort is shown in Figure 4; it shows that (a) the spatial extent of longline fishing effort remained consistent between 2016 and 2025, (b) tag releases were well spread across the fishing area in high-release years (2017-2018 and 2021-2024) compared to a more localised spread in low-release years (2019, 2020), and (c) spatial overlap between tag releases and their subsequent recaptures was high.

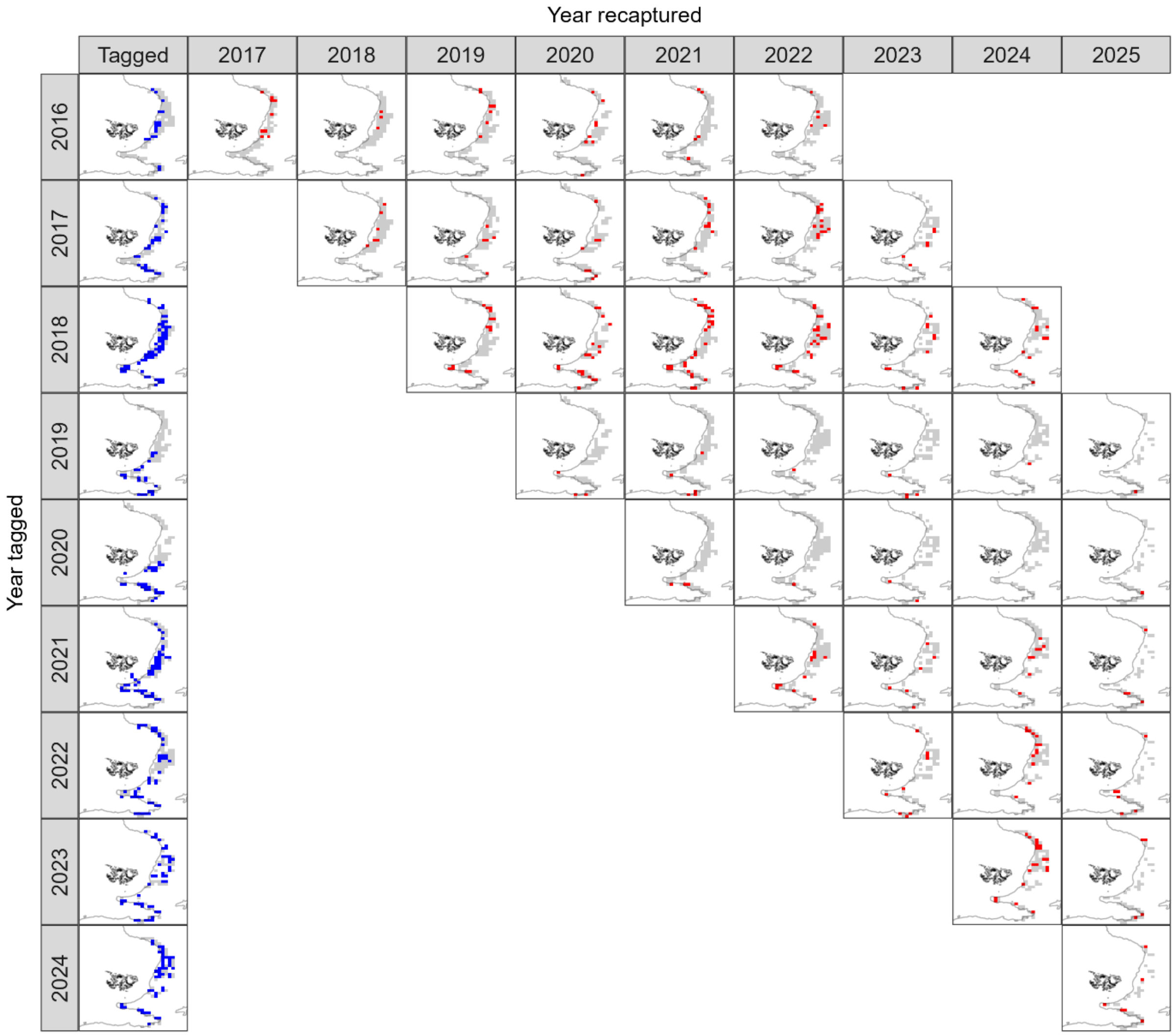

Figure 4. Spatial distributions of toothfish tag releases in FCZ in 2016-2024 (blue) and recaptures in FCZ in 2017-2025 (red); grey shading denotes the distribution of longline fishing effort for each year. Recaptures after six years at liberty were excluded from the model and the plot. Cells correspond to locations where at least one tagged fish was released (blue) or recaptured (red) or where at least one longline was hauled (grey).

The current assessment used the data on longline-caught toothfish tag releases within the FCZ in 2016-2024 and their subsequent recaptures by longline in 2017-2025 (Table 1). Within-year recaptures were excluded from the model to restrict recapture data to tagged fish that had sufficient time to mix with the untagged population, at least at a local population level. The CASAL modelling framework allowed the specification of several tag-related parameters, i.e. initial tag-release mortality, tag-related growth loss, tag detection rate, and tag shedding rate. These parameters were obtained from the literature or estimated outside of the stock assessment model and then used as fixed input values in the assessment.

Initial tag-release mortality was assumed to be 10% (Agnew *et al.* 2006), effectively reducing the number of tagged fish in the population at the time of tagging. Tagging was assumed to result in a retardation of growth in individual toothfish equivalent to half a year of zero growth immediately after tagging (Parker *et al.* 2013). The tag detection rate in the longline fishery was assumed to be 100% due to the high observer coverage (~50%), an excellent record of cooperation with a sole vessel operating in the fishery since 2017, and the fact that each fish is handled individually by several crew members while un-hooked and processed.

The first 6,500 tagged toothfish (2016-2023) were double-tagged, with a large and a small dart tag. By 2024, 55 double-tagged fish were recaptured with only large tags and 20 with only small tags remaining, allowing the estimation of tag-shedding rates. Tag shedding rates were calculated following the approach outlined by Dunn *et al.* (2011) and Ziegler (2017) but adapted here to accommodate non-identical tags. The instantaneous shedding rate of large tags was estimated at λ_1 = 0.0147 and of small tags λ_2 = 0.0315. Since the CASAL algorithm requires a tag shedding rate for a single-tagged fish only, tag shedding rates for double-tagged fish had to be approximated by a single-tag shedding rate, estimated as λ_S = 0.0017. However, the approximation proved adequate only when the available recapture data were restricted to fish recaptured after ≤6 years at liberty (for more details, see Dunn *et al.* 2011). Since our tagging programme is recent, the only recaptures after >6 years at liberty occurred in 2023 for fish tagged in 2016, in 2024 for fish tagged in 2016 and 2017, and in 2025 for fish tagged in 2017 and 2018 (16 recaptures inside, and 8 outside FCZ; see Table 1); these data were excluded from the model to allow for the above-mentioned approximation and do not appear in corresponding plots throughout the report.

Emigration of tagged fish from the assessed area can violate the assumptions of tag recapture models used in the assessment and result in overestimated biomass and overly optimistic stock status estimates. The emigration rate of toothfish from Falkland Islands waters was estimated based on the numbers of recaptures inside and outside the FCZ of the fish tagged within the FCZ, following the approach of Burch *et al.* (2017). For the recaptures outside the FCZ, we relied on the reporting by fishing fleets operating in these regions, specifically through collaborative work with Chile and the High Seas Korean fleet. The approach of Burch *et al.* (2017) requires the knowledge of annual harvest rates (i.e. catches and vulnerable biomass) both inside and outside the FCZ; given the lack of reliable information on overall harvest rates outside the FCZ, they were assumed equal to inside the FCZ. Tag reporting was assumed to be 50% outside the FCZ, compared to 100% within the FCZ. The tag emigration rate was estimated at λ_M = 0.0461; the tag shedding parameter supplied to CASAL (λ_S) was increased by the value of the emigration rate, providing a simple yet effective approach to correct for the effects of emigration (Burch *et al.* 2017).

The numbers-at-length of toothfish tagged each year, by 10 cm length bin, were used as fixed input in the assessment model. The numbers-at-length of toothfish recaptured each year for each release year, by 10 cm length bin, were used as observations to fit the model. Besides releases and recaptures, the model required the numbers scanned at length (i.e. numbers of fish caught and inspected for a possible tag) in each recapture year; as detection was assumed 100% this was derived by disaggregating the total annual catch in numbers into 10 cm length bins, using the random length-frequency samples from the fishery observer records. For each recapture year, the recaptures-at-length from each release year *t* were fitted, in 10 cm length bins, using a robust binomial log-likelihood:

$$-LL = \sum_i \left[\log(n_i!) - \log\big((n_i - m_i)!\big) - \log(m_i!) + m_i \log\left(Z\left(\frac{M_i}{N_i}, r\right)\right) + (n_i - m_i)\log\left(Z\left(1 - \frac{M_i}{N_i}, r\right)\right)\right]$$

Where n_i is the number of scanned fish in length bin *i*, m_i is the number of recaptured fish from release year *t* in length bin *i*, N_i is the expected number of fish in length bin *i* in the available population (tagged and untagged), M_i is the expected number of fish in length class *i* in the available population that have the tag from release year *t*, and *Z*(*x,r*) is a robustification function defined as:

$$Z(x,r) = \begin{cases} x \ where \ x \geq r \\ r/(2 - x/r) \ otherwise \end{cases}$$

Where *r* is a non-negative robustification constant; a default value of *r* = 1e-11 was used in the assessment.

The default assumption in the assessment is that the numbers of recaptures are independent between release years and between length bins and follow a robust binomial distribution. There is evidence that some (probably most) tag-recapture datasets are over-dispersed; they are more variable than expected from the above assumptions and thus should be down-weighted (Francis 2016). CASAL provides parameter ϕ as an informal means of allowing for over-dispersion, with the log-likelihood of tag-recapture data being divided by ϕ. The default is ϕ = 1; setting ϕ > 1 implies over-dispersion and down-weights the data (Francis 2016). In the current assessment, the procedure was to use the default ϕ = 1 in the initial model run and use the initial maximum posterior density (MPD) model fit to calculate over-dispersion ϕ_j for each tagging event *j* from its *i* recapture events as:

$$\Phi_j = var\left(\frac{O_{ij} - E_{ij}}{\sqrt{E_{ij}}}\right)$$

Where O_{ij} was the observed number of recaptures and E_{ij} was the estimated number of recaptures. Over-dispersion terms for all release years were then combined by taking the geometric mean, and the model was re-run with the log-likelihood of tag-recapture data modified by dividing by ϕ (Table 2).

As both CAA and tag-recapture data had to be reweighted, the reweighting was applied first to the CAA data and then to the tag-recapture data (i.e. in successive MPD model runs).

Table 2. Weighting factors (w), used to adjust the effective sample sizes of catch-at-age data, and the over-dispersion parameter (ϕ), used to weight the tag-recapture data.

w_{LLH}	w_{LLU}	w_{FIN}	w_{LOL}	w_{RFIN}	w_{RLOL}	ϕ
0.912	0.582	0.185	0.086	0.223	0.494	3.482

Table 3. Input parameters in the assessment model.

Component	Parameter	Value				
Length-weight	a ($t \cdot cm^{-1}$)	5.56e-9				
	b	3.138				
Von Bertalanffy growth	L_{inf} (cm)	185.30				
	k (y^{-1})	0.057				
	t_0 (y)	-2.593				
	CV	0.154				
Natural mortality	M (y^{-1})	0.165				
Maturity *(proportion mature at age)*	Age 1	0	Age 12	0.393	Age 23	0.569
	Age 2	0.001	Age 13	0.420	Age 24	0.585
	Age 3	0.028	Age 14	0.444	Age 25	0.604
	Age 4	0.061	Age 15	0.464	Age 26	0.626
	Age 5	0.103	Age 16	0.482	Age 27	0.649
	Age 6	0.150	Age 17	0.497	Age 28	0.670
	Age 7	0.199	Age 18	0.510	Age 29	0.689
	Age 8	0.247	Age 19	0.522	Age 30	0.706
	Age 9	0.291	Age 20	0.533	Age 31+	0.722
	Age 10	0.330	Age 21	0.544		
	Age 11	0.363	Age 22	0.555		
Steepness	h	0.75				
Future recruitment variability	σ_R	0.6				
Ageing error	CV	0.1				
Initial tag-release mortality		0.1				
Tag shedding rate	λ_S (y^{-1})	0.0017				
Tag emigration rate (added to the tag shedding rate in the model)	λ_M (y^{-1})	0.0461				
Tag detection rate		1				
Tag-related no-growth period	(y)	0.5				

2.3. Model setup

Population dynamics

Toothfish population dynamics were described by a Bayesian age-structured model, with age classes from 1 to 31+ years, the last being a plus group. It is a single-sex, single-area, multi-fishery model with an annual cycle divided into three time-steps (Table 4). Recruitment, fishing mortality from all concurrent fisheries, tag releases and recaptures, and the first half of the year's natural mortality occur in time step 1; spawning and the second half of natural mortality in step 2; and ageing in step 3. Since both fishing and natural mortality occur in time step 1, the process was to apply half the time step's natural mortality, then fishing mortality instantaneously, then the remaining half of the time step's natural mortality.

Table 4. Annual cycle of the current toothfish stock assessment model with three timesteps, and the processes in order of occurrence within each timestep.

Time-step	Period (approx.)	Sequence of processes	Observations
1	January - June	Recruitment	
		0.25 M	
		Fishing (removals by all fisheries and surveys instantaneously)	CPUE, LF (CAA), tag recaptures
		0.25 M	
		0.5 tag loss	
2	July - December	0.25 M	
		Spawning (SSB calculation)	
		0.25 M	
		0.5 tag loss	
3	Year-end (instant)	Age increment	

M – natural mortality, SSB – spawning stock biomass, CPUE – catch per unit of effort, LF – catch length frequencies, CAA – catch at age.

Recruitment to the population was calculated by multiplying average recruitment (R0) by estimated year class strength (YCS) and a stock-recruitment relationship. Stock recruitment was assumed to follow a Beverton-Holt relationship:

$$R = \frac{SSB}{SSB_0} \Big/ \left(1 - \frac{5h-1}{4h}\left(1 - \frac{SSB}{SSB_0}\right)\right)$$

Where R is the recruitment, SSB is the spawning stock biomass, SSB_0 is the pre-exploitation equilibrium spawning stock biomass, and h is the steepness parameter, defined as the fraction of recruitment from an unfished population when the spawning stock biomass declines to 20% of its unfished level. Steepness was fixed rather than estimated, as suggested for example by He *et al.* (2006) and Kenchington (2014) and the steepness parameter was assumed to be h = 0.75 (Myers *et al.* 1999, Punt *et al.* 2005, Dunn *et al.* 2006).

The initial year in the model was 1987, the first year of recorded data by the FIFD, and the model was run up to 2025. Projections from the model were extended for another 35 years, up to 2060. Conditions in the initial year were assumed to be an equilibrium age structure at an unexploited equilibrium biomass (i.e., a constant recruitment assumption).

Within the model, each year's tagging event was included as an additional partition, i.e. the model kept account of the numbers of fish tagged in each year separately. The numbers of fish in the tagged component were modified by initial tag-related mortality (as a proportion) followed by a subsequent ongoing annual tag loss (at a constant rate). The population processes (natural mortality, fishing mortality, ageing, etc.) were then applied collectively over the tagged and untagged components of the model. The proportions-at-age of tagged fish were determined within the model by multiplying the observed proportions-at-length of tagged fish by the proportions of fish at age by length assumed by the model for the overall population (Mormede *et al.* 2014).

Estimation method

Model parameters were estimated by minimising the total objective function, which is the sum of the negative log-likelihoods from the observations, the negative-log Bayesian priors, and the penalties applied to constrain the parameterisations (see below). The estimated parameter values presented in the report are MPD point estimates (Bull *et al.* 2012).

The posterior distribution of the parameters in a Bayesian analysis was estimated using the Monte-Carlo Markov Chain (MCMC) method. The starting point of each chain was the corresponding MPD estimate, the first 100,000 iterations were dismissed (burn-in), and every 1,000th value was taken from the following 1,000,000 iterations. The resulting 1,000 values represent a systematic sample from the Bayesian posterior distribution for the parameter of interest. Chains were investigated for evidence of non-convergence using trace plots, chain autocorrelation plots, the single-chain stationarity test of Geweke (1992) and the stationarity and half-width tests of Heidelberger and Welch (1983).

Estimated parameters

Parameters estimated by the model, their priors, starting values and bounds are given in Table 5. Annual year class strengths (YCS) were estimated for 1986-2024, with the *Haist parameterisation* used to make the YCS parameters average to 1 over 1986-2019 (for the Haist method description, see Bull *et al.* 2012). The catchability coefficient (q) was estimated separately for the two longline fisheries. Uniform-log priors were considered appropriate for SSB_0 (Mormede *et al.* 2014, Ziegler and Welsford 2015) and q (Hillary *et al.* 2006, Ziegler and Welsford 2015), lognormal for YCS (Candy and Constable 2008, Ziegler and Welsford 2015), and uniform for selectivity parameters (Dunn and Hanchet 2010, Mormede *et al.* 2014).

Table 5. Number of parameters (N), priors, start values and bounds for free parameters estimated in the assessment model.

Estimated parameter		N	Prior	Start value	Lower bound	Upper bound
SSB_0		1	uniform-log	40,000	10,000	100,000
YCS		39	lognormal	1	0.001	20
Selectivity $_{LLH}$	a_{50}	1	uniform	10	1	50
	a_{to95}	1	uniform	5	0.05	50
Selectivity $_{LLU}$	a_{50}	1	uniform	10	1	50
	a_{to95}	1	uniform	5	0.05	50
Selectivity $_{FIN}$	a_1	1	uniform	2	1	50
	S_L	1	uniform	1	0.05	50
	S_R	1	uniform	2	0.05	500
Selectivity $_{LOL}$	a_1	1	uniform	2	1	50
	S_L	1	uniform	1	0.05	50
	S_R	1	uniform	2	0.05	500
Selectivity $_{RFIN}$	a_1	1	uniform	2	1	50
	S_L	1	uniform	1	0.05	50
	S_R	1	uniform	2	0.05	500
Selectivity $_{RLOL}$	a_1	1	uniform	2	1	50
	S_L	1	uniform	1	0.05	50
	S_R	1	uniform	2	0.05	500
q_{LLH}		1	uniform-log	1e-5	1e-9	0.1
q_{LLU}		1	uniform-log	1e-5	1e-9	0.1

LLH – Spanish-system longline, LLU – umbrella-system longline, FIN – finfish trawl, LOL – calamari trawl, RFIN – groundfish survey, RLOL – calamari pre-season survey.

Time-invariant selectivity-at-age was estimated separately for each fishery and survey to reflect distinct age distributions of fish in the catch (i.e., assuming a fleets-as-areas approach). Logistic selectivity ogive was used for longline fisheries, and double-normal for trawl fisheries and both surveys. Logistic ogive is defined by two parameters: a_{50} (age at 50% selectivity) and a_{to95} (difference in age at 50% and 95% selectivity), where the value of selectivity at age *x* is given by

$$f(x) = 1/\left[1 + 19^{(a_{50}-x)/a_{to95}}\right].$$

Double-normal ogive is defined by three parameters: a_1 (the mode), S_L (increasing left-hand limb shape parameter) and S_R (decreasing right-hand limb shape parameter), where the value of selectivity at age *x* is given by

$$\begin{aligned} f(x) &= 2^{-[(x-a_1)/S_L]^2}, \quad (x \le a_1) \\ &= 2^{-[(x-a_1)/S_R]^2}, \quad (x > a_1). \end{aligned}$$

Penalties

Besides observations and priors, the final components of the objective function are penalties. The model included a catch limit penalty and a vector average penalty. A catch limit penalty was applied to each fishery to ensure that the model does not estimate abundances so low that the recorded removals could not have been taken. A vector average penalty was used to encourage YCS to average 1. Penalty multipliers were set to 100 for catch limits and 20 for the YCS vector average penalty (for details on penalty calculations, see Bull *et al.* 2012).

Projections

Projections were carried out by running the model for 35 years into the future, using randomised recruitments and hypothetical catches. A total of 1,000 simulations were run, each using the same (MPD) estimate of model parameters and the same hypothetical future catches (i.e. simulations differed only in terms of the randomised recruitments). The most recent (2023-2025) and future recruitments (2026-2060) were assumed log-normally distributed with standard deviation σ_R = 0.6. Future catch split between fisheries was assumed from catch history and the current longline catch quota: umbrella-system longline = 1,040 t, finfish trawl = 300 t, and calamari trawl = 30 t.

Deterministic yield calculations

Deterministic MSY is the maximum constant annual catch (using the specified catch split) that can be sustained under deterministic recruitment (i.e. YCS = 1). The corresponding mortality rate is F_{MSY}, and the corresponding SSB is B_{MSY}. Simulations are run for different values of mortality *F*, starting from an unfished equilibrium state and running until the total annual catch C_F and spawning stock biomass SSB_F stabilise. CASAL searches over mortality rates *F* to find F_{MSY}, the value that maximises C_F. Then *MSY* and B_{MSY} are C_F and SSB_F, respectively. The calculations are based on a single set of model parameters (i.e. MPD).

3. Results

3.1. Model fits

Diagnostics plots of model fit to observed data are in Appendix 2. The model fitted standardised CPUE data relatively well, i.e. it captured the declining overall trend for the Spanish system longline fishery and a more levelled trend for the umbrella-system longline fishery (Figure A.3). Corresponding trends in normalised residuals for both longline fisheries are shown in Figure A.4.

The model fit to catch-at-age data was good for all four fisheries and both research surveys (Figures A.5 - A.10). The corresponding residual bubble plots show no clear patterns, except in longline fisheries, where the model consistently overestimated the proportion of young (<4 years) and old (>27 years) fish (Figure A.11). The model fit to the observed mean toothfish age was fairly good in all cases except the Spanish system longline fishery (Figure A.12).

The model fit to tagging data was generally good (Figures A.13 - A.15). However, notable discrepancies occurred between the observed and expected recaptures of fish tagged in 2018 (the model overestimated the number of recaptures in 2019 and underestimated in 2021). That may be the result of (a) a comparatively large number of fish tagged in 2018 or (b) variation in the spatial overlap of tagging and fishing effort, in combination with low movement rates of fish.

Likelihood profiling was done by fixing SSB_0 over a range of plausible values (20,000 - 60,000 t) and estimating the remaining parameters. Umbrella-system CPUE and tag-recapture data of fish tagged in 2019, and 2023 favoured lower biomass estimates. CAA data for the Spanish system longline, calamari trawl fishery and the two surveys, and tag-recapture data of fish tagged in 2020, 2022 and 2024 found that higher biomass estimates were more likely. Spanish-system CPUE, CAA data for the umbrella system longline and finfish trawl fishery, and tag-recapture data of fish tagged in 2016, 2017, 2018, and 2021 were at, or close to, the MPD biomass estimate (Figures A.16, A.17).

MCMC trace plots showed no evident lack of convergence in estimated parameters, except for the left-hand limb shape parameter of double-normal selectivity curve for the calamari trawl fishery and both surveys (Figure A.18). The stationarity test of Geweke (1992) and the Heidelberger and Welch (1983) stationarity and half-width tests suggested failure to converge for the mentioned selectivity parameters (Table A.2) and autocorrelations in their MCMC samples were high, indicating slow mixing in MCMC chains (Figure A.19).

Contributions to the objective function of each dataset, prior and penalty, are provided in Appendix 3 (Table A.3).

3.2. Model estimates

MPD estimates (with MCMC 95% credible intervals) of initial spawning stock biomass (SSB_0), current spawning stock biomass (SSB_{2025}) and current spawning stock biomass relative to SSB_0 (SSB_{2025}/SSB_0) are provided in Table 6. These estimates are highly consistent with those from the previous assessment, with SSB_0 lower by only 0.4% and SSB_{2025} and SSB_{2025}/SSB_0 higher by 1.5% and 1.8%, respectively. MCMC posterior distributions of SSB_0 and SSB_{2025}/SSB_0 are shown in Figure 5. Since the inclusion of tag-recapture data into the model in the 2023 assessment, these posterior distributions were noticeably narrower and only slightly asymmetrical compared to the earlier years. Likelihood profiles suggest this is likely due to tag-recapture data being highly informative on the SSB_0. The estimated historical SSB trend up to 2025 is shown in Figure 6. Deterministic MSY was estimated at 1,678 t, which falls within the range of estimates from the last three assessments (1,653-1,720 t).

Table 6. MPD estimates (and MCMC 95% credible intervals) of SSB_0, SSB_{2025} and SSB_{2025}/SSB_0.

SSB_0	SSB_{2025}	SSB_{2025}/SSB_0
24,725 (22,944 – 27,528)	12,545 (10,845 – 15,726)	0.507 (0.471 - 0.570)

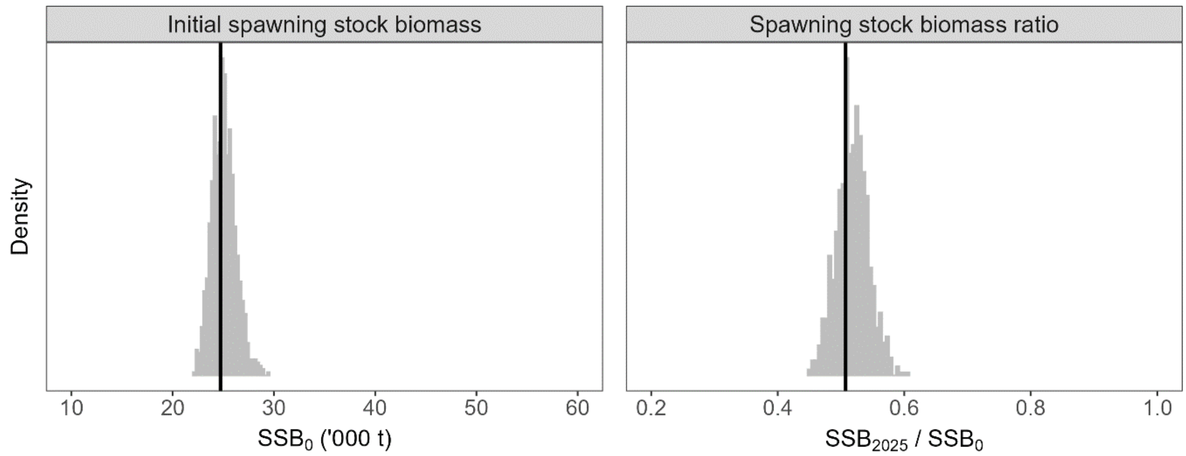

Figure 5. MCMC samples from the posterior distribution of SSB_0 and SSB_{2025}/SSB_0. Vertical black lines denote MPD point estimates.

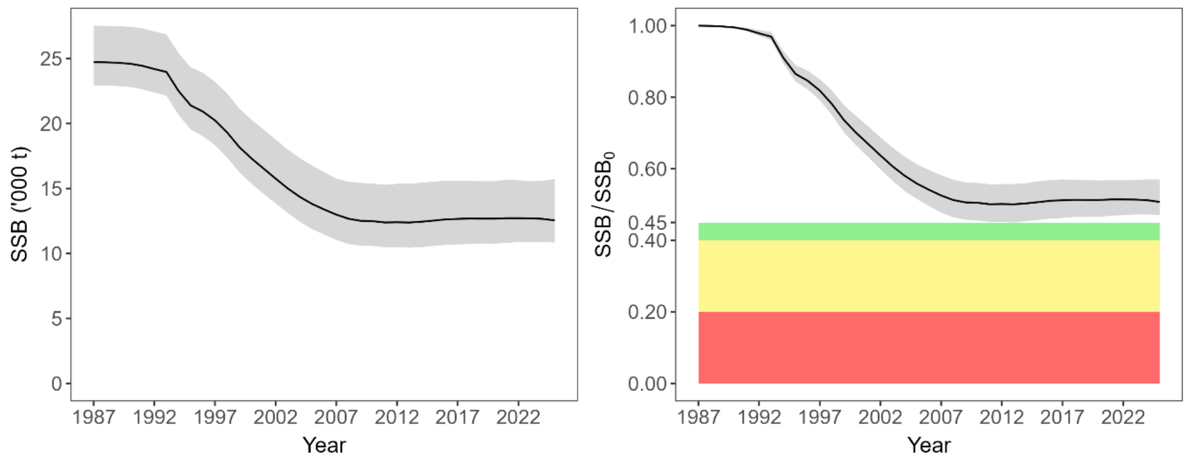

Figure 6. MPD estimate of the historical SSB trajectory; absolute on the left and relative to SSB_0 on the right (black line). Shaded areas denote MCMC 95% credible intervals of the model fit. Harvest control rule ranges are colour coded for reference: *target range* in green (SSB/SSB_0 = 0.45-0.40), *trigger range* in yellow (SSB/SSB_0 = 0.40-0.20) and *closure range* in red (SSB/SSB_0 < 0.20).

Estimated selectivity ogives were biologically plausible and aligned with current understanding of toothfish ontogenetic movements and fishery interactions with the stock (Figure 7). The calamari trawl fishery captured the youngest fish because it operates in shallow waters—where only young fish are available—and uses a small mesh size, resulting in a selectivity pattern represented by the right limb of the assumed double-normal ogive. For the finfish trawl fishery (also assumed double-normal), the model estimated maximum retention at age 2, with lower retention of younger fish (escaping due to mesh selectivity or not yet present on trawl grounds) and older fish (which have migrated to deeper waters). The two longline fisheries showed similar logistic selectivity curves, reflecting their tendency to catch predominantly older fish available at depth. Selectivities for the trawl surveys were broadly similar to those of commercial trawl fisheries, consistent with their use of comparable gear and spatial coverage.

The estimated year class strength for 2015-2020 aligned well with model-independent recruitment estimates (Lee *et al.* 2021), indicating high recruitment in 2015-2017 and low in 2018-2020 (Figure 8). No model-independent recruitment estimates were available for the earlier or later years, making it challenging to confirm the YCS trend estimated in the model.

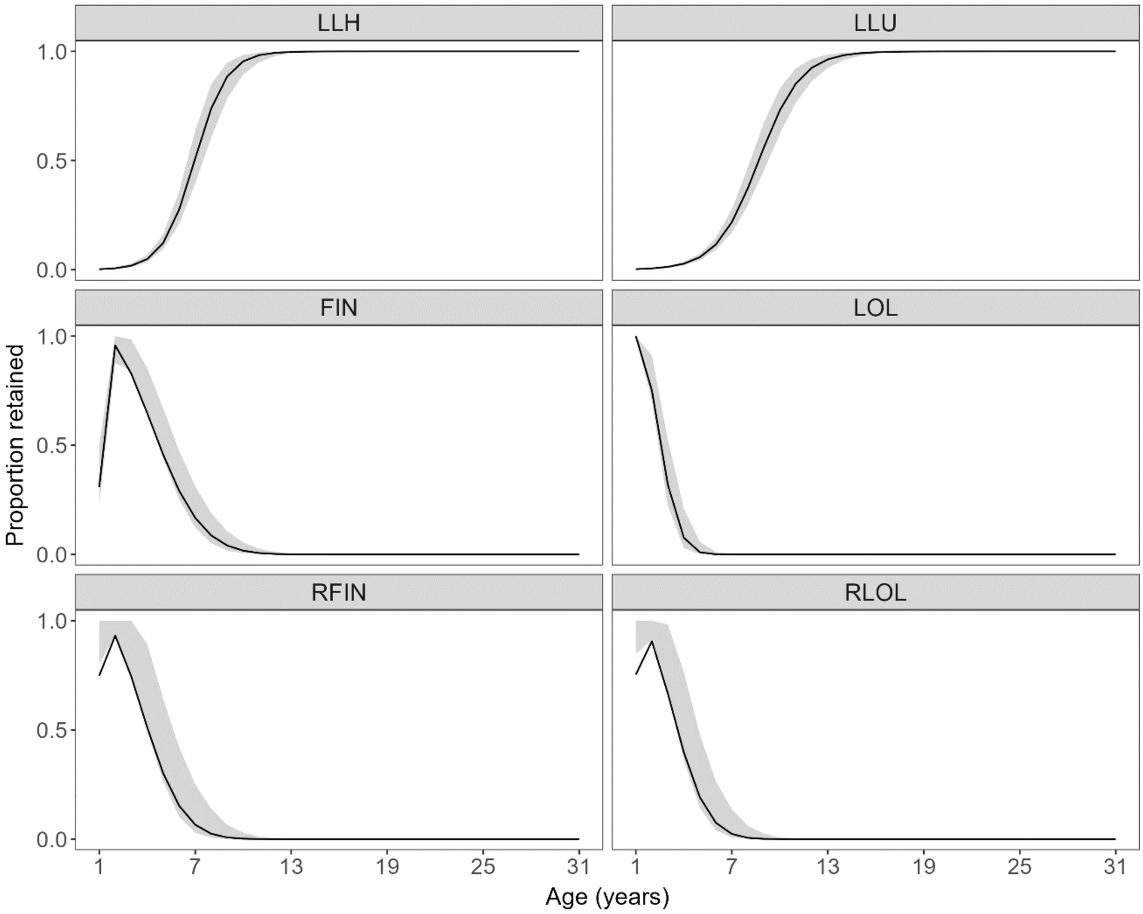

Figure 7. MPD estimate of selectivity ogives for four fisheries and two surveys (black lines). Shaded areas denote MCMC 95% credible intervals of the model fit.

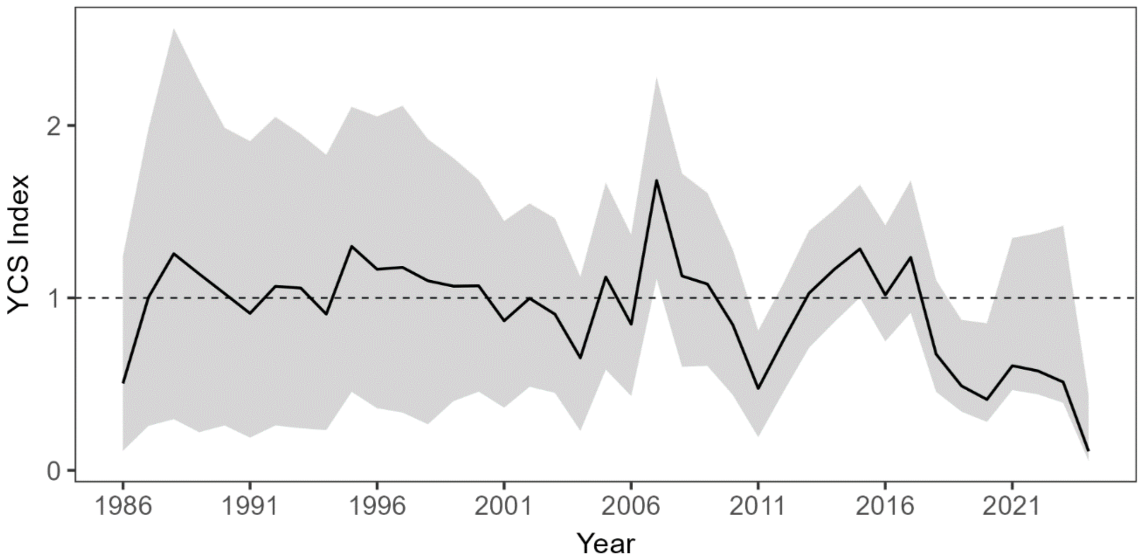

Figure 8. MPD estimate of year-class strengths in 1986-2023 (solid black line). The shaded area denotes MCMC 95% credible intervals of the model fit.

3.3. Model projections

Projections of SSB/SSB_0 under the assumption of random recruitments in 2023-2060 and constant annual catches in 2026-2060 are shown in Figure 9. The median SSB/SSB_0 is currently within the HCR *expansion range* but is projected to drop to the *target range* by 2032. Throughout the projection period, the median SSB/SSB_0 reaches a minimum of 0.44 in 2036, after which it remains within the target range until 2046. The probability of the SSB/SSB_0 ratio falling below existing management thresholds, corresponding to the upper bounds of HCR ranges, was calculated for each year of the projection period as the proportion of the 1000 simulations below the respective threshold (Figure 10). The highest probability of falling below 0.45, 0.40 and 0.20 thresholds during the projection period was estimated at 61%, 32% and 1%, respectively.

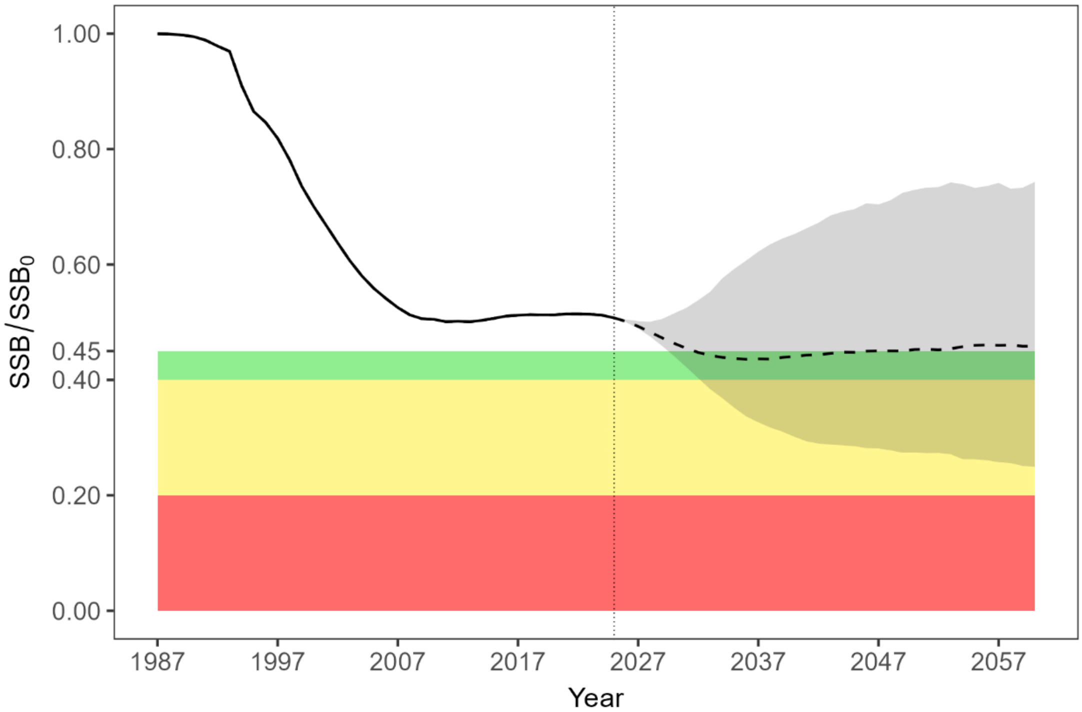

Figure 9. Future SSB/SSB_0 projections from the model MPD estimate. Shown are the MPD estimate (solid black line), and the median (dashed black line) and the 95% confidence intervals (shaded area) of the projections. The vertical dotted line denotes the boundary between MPD estimates (1987-2022) and projections (2023-2060) of SSB/SSB_0. Harvest control rule ranges are colour coded for reference: *target range* in green (SSB/SSB_0 = 0.45-0.40), *trigger range* in yellow (SSB/SSB_0 = 0.40-0.20) and *closure range* in red ($SSB/SSB_0 < 0.20$).

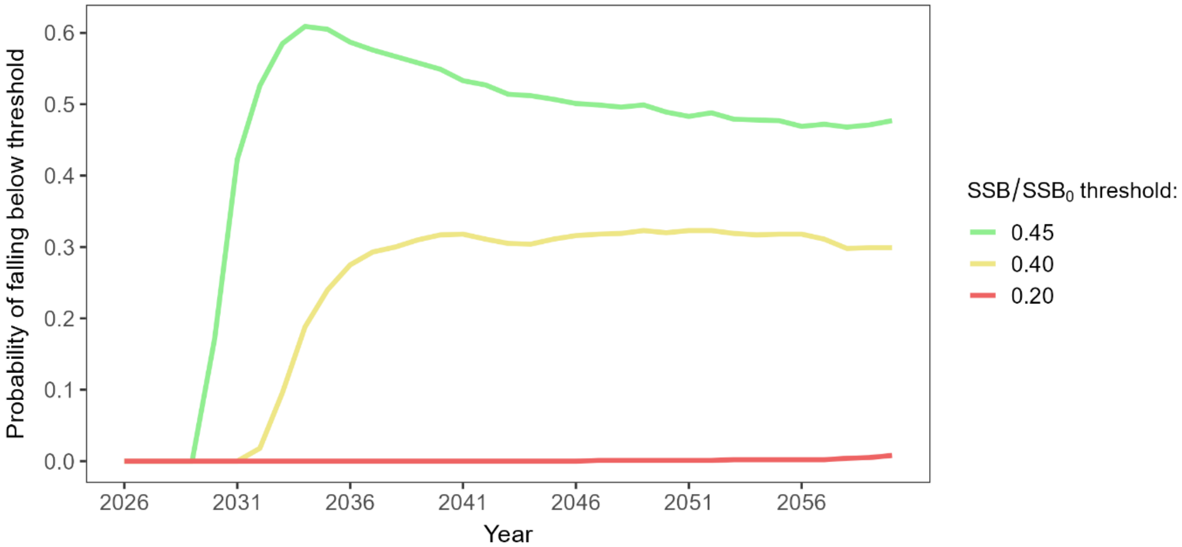

Figure 10. Probability of stock falling below designated SSB/SSB0 management thresholds, based on projections.

4. Discussion

This report presents an updated integrated stock assessment for toothfish in Falkland Islands waters, using data up to the end of 2025. It is the fourth consecutive assessment in which tag-recapture data have been used as an index of absolute abundance, thus reducing model reliance on commercial CPUE data. Although commercial CPUEs are widely used as an index of relative abundance in stock assessments, their shortcomings are well known (Harley *et al.* 2001; Maunder and Punt 2004; Ye and Dennis 2009; Thorson *et al.* 2017; Maunder *et al.* 2006, 2020). Tag-recapture data are routinely used in toothfish stock assessments across CCAMLR waters. For example, extensive long-term tag-recapture datasets underpin assessments in South Georgia, South Sandwich Islands, Heard and McDonald Islands, Kerguelen, Crozet Island, and Ross Sea (Earl and Readdy 2023; Readdy and Earl 2023; Masere and Ziegler 2023; Massiot-Granier *et al.* 2023a, 2023b; Mormede *et al.* 2023). In comparison, the Falkland Islands toothfish tagging programme is still relatively new. It began in 2016, and the tagging effort has varied widely between years. The initial goal of tagging 3,000 fish was achieved between 2016 and 2018, followed by a considerable decrease in tagging effort in 2019-2020. The programme was expanded and formalised as a long-term protocol in 2021, aiming to tag approximately 1,000 fish annually (one fish per tonne of TAC) to support the stock assessment. Since the extension, tagging has predominantly been conducted during dedicated surveys, aiming to cover the entire fishing area. In 2024, the tagging programme underwent further formalisation, with the fishing area delineated based on the distribution of fishing effort over the most recent five years and then divided into six geographically distinct sub-areas. The required number of tags was allocated among sub-areas in proportion to the fishing effort (Le Luherne and Desmet 2025). While this framework was retained in 2025, the actual number of fish tagged in each sub-area was generally lower than planned and only approximately proportional to fishing effort, owing to additional research protocols implemented during the survey (Le Luherne and Saulnier, 2026). The current stock assessment was informed by approximately 8,000 releases and 500 recaptures (excluding within-year and out-of-zone recaptures). These numbers remain low compared to some toothfish assessments (e.g. for South Georgia, with upwards of 58,000 releases and 7,800 recaptures by the end of 2022). Given its significance for the stock assessment, the tagging programme should be continued and established as a permanent requirement.

The estimated model parameters and derived quantities in the current assessment were highly consistent with those from the previous assessment (Skeljo, 2025), with annual estimates of absolute and relative SSB differing by only a few percent. In particular, the SBB ratio in the most recent year was nearly identical between the current (SSB_{2025}/SSB_0 = 0.507) and the previous (SSB_{2024}/SSB_0 = 0.498) assessment. This similarity was expected, as no major changes were made to the model structure or assumptions, and the data updates through 2025 did not indicate markedly different trends. Changes to input parameters—including Von Bertalanffy growth parameters, length-weight coefficients, the maturity vector, and tag-shedding and tag-emigration rates—were minimal and had a negligible effect on model outcomes.

Projections of SSB/SSB_0 in the current assessment were also highly similar to those from the previous assessment (Skeljo, 2025), showing an anticipated decline from the *expansion range* to the *target range* by 2032. The projected decline reflects a series of weak recruitments estimated by the model (below-average YCS in 2018-2020) and supported by an independent analysis (Lee *et al.* 2021). The current projections assumed random YCS for 2023 and 2024 instead of model-estimated values because limited information was available on the most recent recruitments (a common approach; see Masere and Ziegler 2023). For example, if a strong toothfish recruitment occurred in an area not covered by the calamari trawl fishery or surveys (e.g. on the west or southwest Falkland Islands Shelf), it could take several years before those fish appear in catches and become available to the model. Model estimates of YCS could potentially be improved by incorporating a survey biomass index in addition to the survey CAA data already used. Preliminary tests in 2025 indicated that sufficient data exist, but further work on survey-density standardisation, followed by model testing and sensitivity analysis, is required before this can be adopted in the base-case model. This work is planned for 2027. Given the influence of recent recruitment strength on projections, close monitoring of juvenile toothfish abundance during research surveys and commercial calamari fishing seasons needs to be emphasised. Protection of high recruitment age-0 cohorts while on the shelf via spatiotemporal management of calamari trawl fishery has also been proposed (Skeljo 2023), and a protocol was established in early 2024. However, no noticeable recruitment of age-0 toothfish into calamari fishery grounds has been observed since then, and the protocol has not yet been tested in practice.

Currently, FIFD is conducting a dedicated research project on toothfish reproductive traits in Falkland Islands waters, aiming to revise the current maturity-at-age data and provide insight into the prevalence of skipped spawning in females. However, sampling mature toothfish proved challenging. The only longliner fishing in Falkland Islands waters has been unavailable during the peak spawning time due to an established maintenance schedule (in Spain). In 2025, the vessel remained in the Falkland Islands, and an arrangement was made with CFL (taking into consideration vessel layover and crew change schedule) for survey during the July-October fishing trip. However, the fishing schedule changed, and the targeted fishing trip was cancelled following the announcement of tariffs on all imports to the US (a major toothfish market for CFL). Given that the maturity-at-age information currently used in the model needs to be revised sooner rather than later, existing samples have been processed and histological analyses began in May 2026. These analyses should be accompanied by a review of the maturity data presently used in the assessment, ideally including comparison with approaches applied in other toothfish stocks. Once available, the revised dataset will serve as an interim solution and will be incorporated into the stock assessment until more comprehensive sampling and analysis can be undertaken.

5. Management advice

Management advice is based on the harvest control rules (HCR) established for the Falkland Islands toothfish longline fishery (Farrugia and Winter 2018) (Appendix 4). The estimated SSB_{2025}/SSB_0 ratio of 0.507 was above the *upper target reference point* (0.45), i.e. in the *expansion range*. Projections from the current model indicated that the SSB/SSB_0 ratio will drop and remain in the *target range* from 2032 to 2046. The year 2025 was the sixth consecutive year with $SSB_{current}/SSB_0$ estimated to be in the *expansion range*. However, since SSB/SSB_0 projections under the current TAC showed a decrease below 0.45 within ten years, no alteration of TAC was anticipated by HCR at this point.

The recommendation is to maintain the toothfish annual TAC in the longline fishery at its current level of 1,040 tonnes.

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Appendix 1. CPUE standardisation

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CPUE was standardised using Generalized Linear Mixed Models (GLMMs; Pinheiro and Bates 2000). GLMMs were fitted using the package glmmTMB (Brooks *et al.* 2017, Magnusson *et al.* 2017) implemented in R version 4.5.0 (R Core Team, 2025). Before modelling, raw CPUE data were explored following the protocol described by Zuur *et al.* (2010). Explanatory variables were inspected for outliers and collinearity. Continuous explanatory variables were scaled by subtracting the mean and dividing by the standard deviation. Reports with zero toothfish catch were presumed to represent erroneous entries or broken sets and were excluded from the analysis (1.2% of days for the Spanish system and 0.01% of lines for the umbrella system fishery).

The response variable was defined as toothfish CPUE expressed in kg-per-hook per day (Spanish system) or kg-per-umbrella per line (umbrella system) and modelled using a Gamma distribution with a log link function. The explanatory variables considered in the model as either fixed or random effects are given in Table A.1.

Table A.1. Explanatory variables considered in the CPUE standardisation.

Explanatory variables		Variable type	Effect
Spanish-system	umbrella-system		
Year*	Year*	Categorical	Fixed
Month*	Month*	Categorical	Fixed
Area*	Area*	Categorical	Fixed
Depth	Depth*	Continuous	Fixed
-	Soak-time*	Continuous	Fixed
Vessel ID*	-	Categorical	Random
Year:Area*	Year:Area*	Interaction	Random

* Variables included in the final model.

The *Year* effect is the quantity of interest and was included as a categorical variable in all models. The *Vessel ID* was included as a random effect in the Spanish-system CPUE standardisation to account for the dependency among CPUE values from the same vessel. Conversely, it was excluded from the umbrella-system CPUE standardisation because the dataset included only two vessels which never fished concurrently during the same year, making the *Vessel* and *Year* effects indistinguishable. The remaining explanatory variables were added by forward stepwise selection and retained in the final model only if they increased pseudo-R^2 by at least 0.5% (Maunder and Punt 2004). Pseudo-R^2 was calculated based on the likelihood-ratio test, as implemented in the R package MuMIn (Barton 2009). The *Month* variable aimed to capture seasonal patterns in effort concentration. The *Area* variable aimed to account for spatial heterogeneity in stock density. *Areas* were defined as 1° Lon x 1° Lat grid squares; these were considered sufficiently small and numerous to accommodate spatial patterns in CPUE, while avoiding overfitting. Only grid squares with at least 10 catch reports across the time series were kept for the analysis, resulting in the removal of 20 daily catch reports for the Spanish system, and 9 line catch reports for the umbrella system. The *Depth* variable was the average fishing depth of each line (umbrella system) or the average fishing depth of multiple lines set in a day (Spanish system). The *Soak-time* variable was defined only for the umbrella system, where it represented the soak time of individual lines. For the Spanish system, Soak-time was not available in a suitable format because it was reported as the sum of the soak times of multiple lines set on the same day. As the number and size of individual lines were unknown, soaking a single 10,000-hook line for 10 hours would have been recorded as a 10-hour soak time, whereas soaking two 5,000-hook lines for 10 hours would have been recorded as 20 hours—even though the same number of hooks was deployed for the same length of time in both cases. Finally, the *Year:Area* interaction was included as a random effect in the CPUE standardisation following the selection of main effects to account for potentially different interannual trends between areas.

The final GLMM fitted to the Spanish-system data included *Year*, *Month*, *Area*, *Vessel*, and *Year:Area* interaction (Table A.1); the model explained 23.1% of the overall variation in CPUE. The final GLMM fitted to the umbrella-system data included *Year*, *Month*, *Area*, *Depth*, *Soak-time*, and *Year:Area* interaction; the model explained 28.4% of the overall variation in CPUE.

Marginal predictions from GLMMs were used to generate the standardised annual CPUE indices, setting continuous covariates and random effects to their mean (zero) and marginalising over the *Month* and *Area* covariates using equal weights for each factor level (e.g., Candy 2004; Chang et al. 2026). Marginal predictions were adjusted for bias-correction when back-transformed to the response scale using the ggeffects package (Lüdecke 2018). These standardised CPUE indices were compared with those obtained by predicting CPUE separately for each area and then aggregating the results (the "predict-then-aggregate" approach; Hoyle et al. 2024). Both approaches produced standardised CPUE indices that were nearly identical.

Standardised and unstandardised CPUE time series for the Spanish system and the umbrella system are shown in Figures A.1 and A.2, respectively.

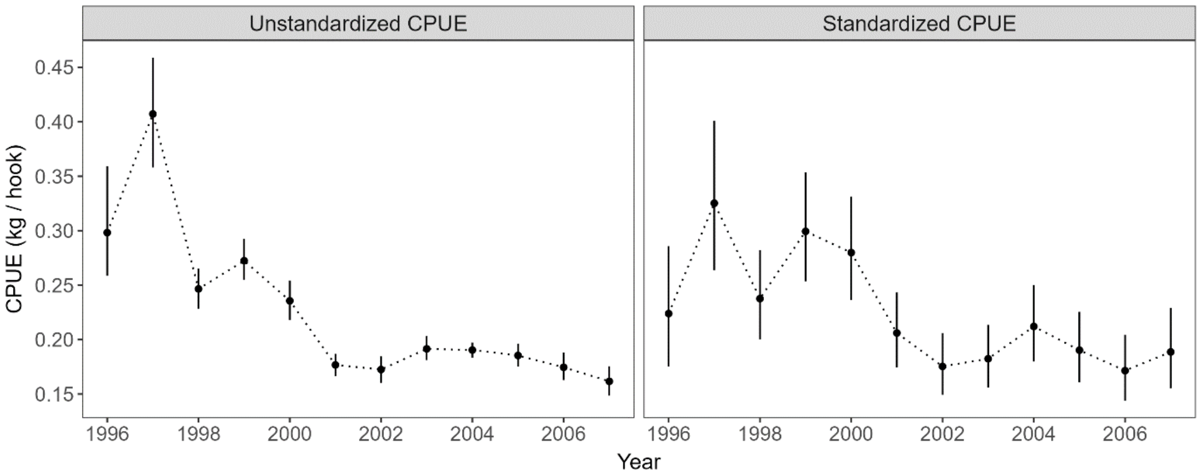

Figure A.1. Spanish-system longline fishery unstandardised and standardised CPUE time series. Black vertical lines denote 95% confidence intervals.

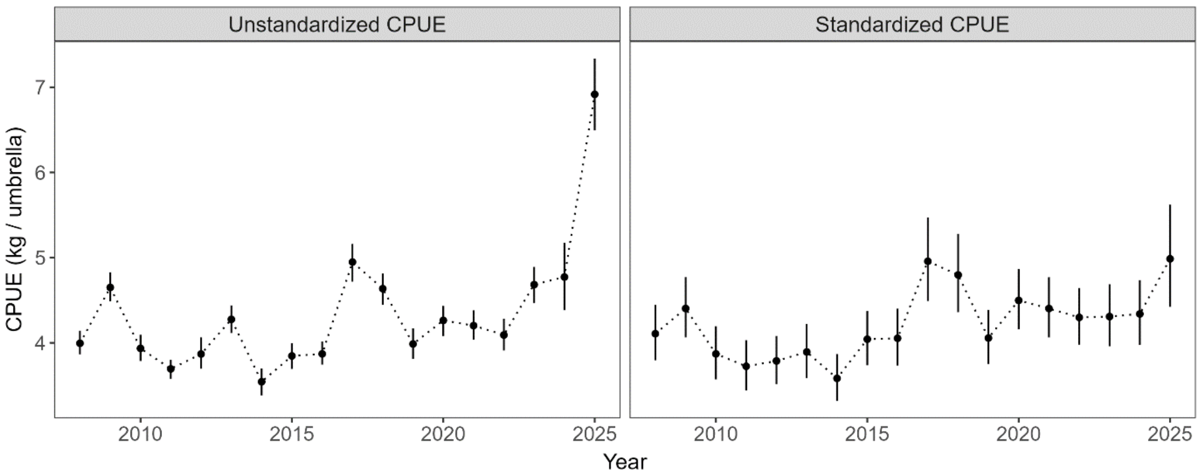

Figure A.2. Umbrella-system longline fishery unstandardised and standardised CPUE time series. Black vertical lines denote 95% confidence intervals.

Appendix 2. Diagnostics plots

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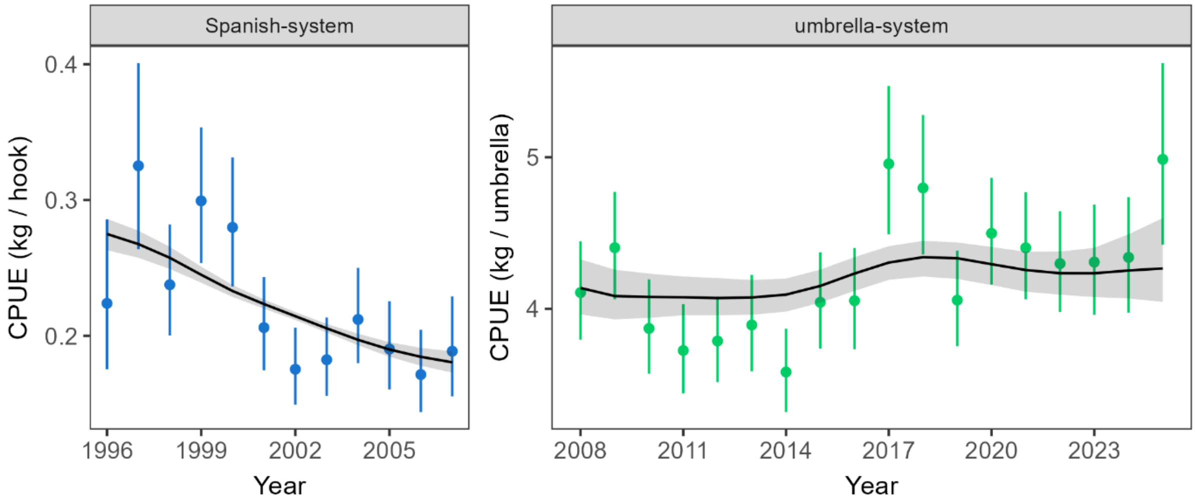


Figure A.3. MPD model fit (black line) to standardised CPUE indices for Spanish-system (blue dots) and umbrella-system (green dots) longline. Vertical blue and green lines denote 95% confidence intervals of standardised CPUE indices, while shaded areas denote MCMC 95% credible intervals of model fit.

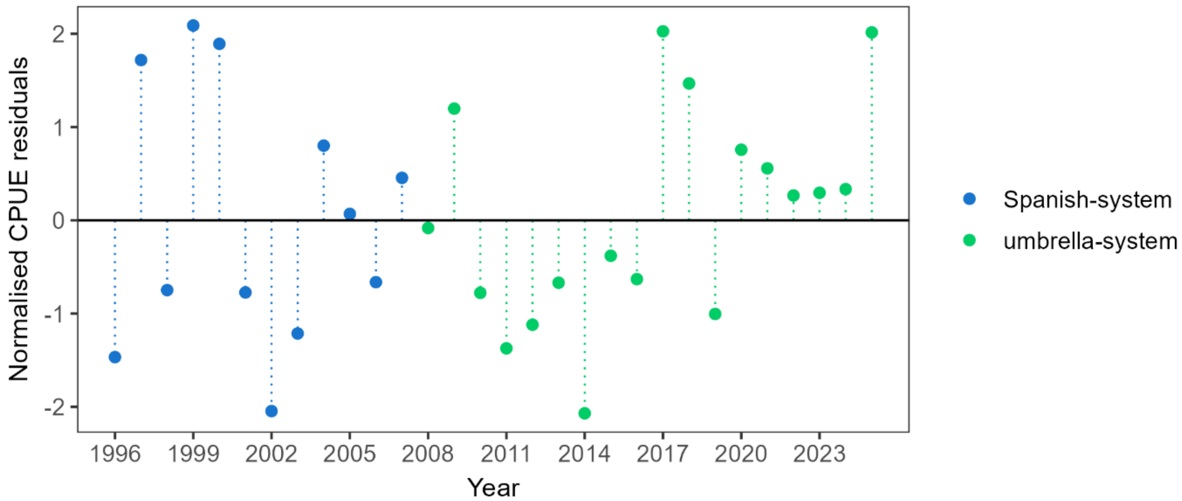


Figure A.4. Normalised residuals from model fit to standardised CPUE time series for Spanish-system (blue) and umbrella-system (green) longline.

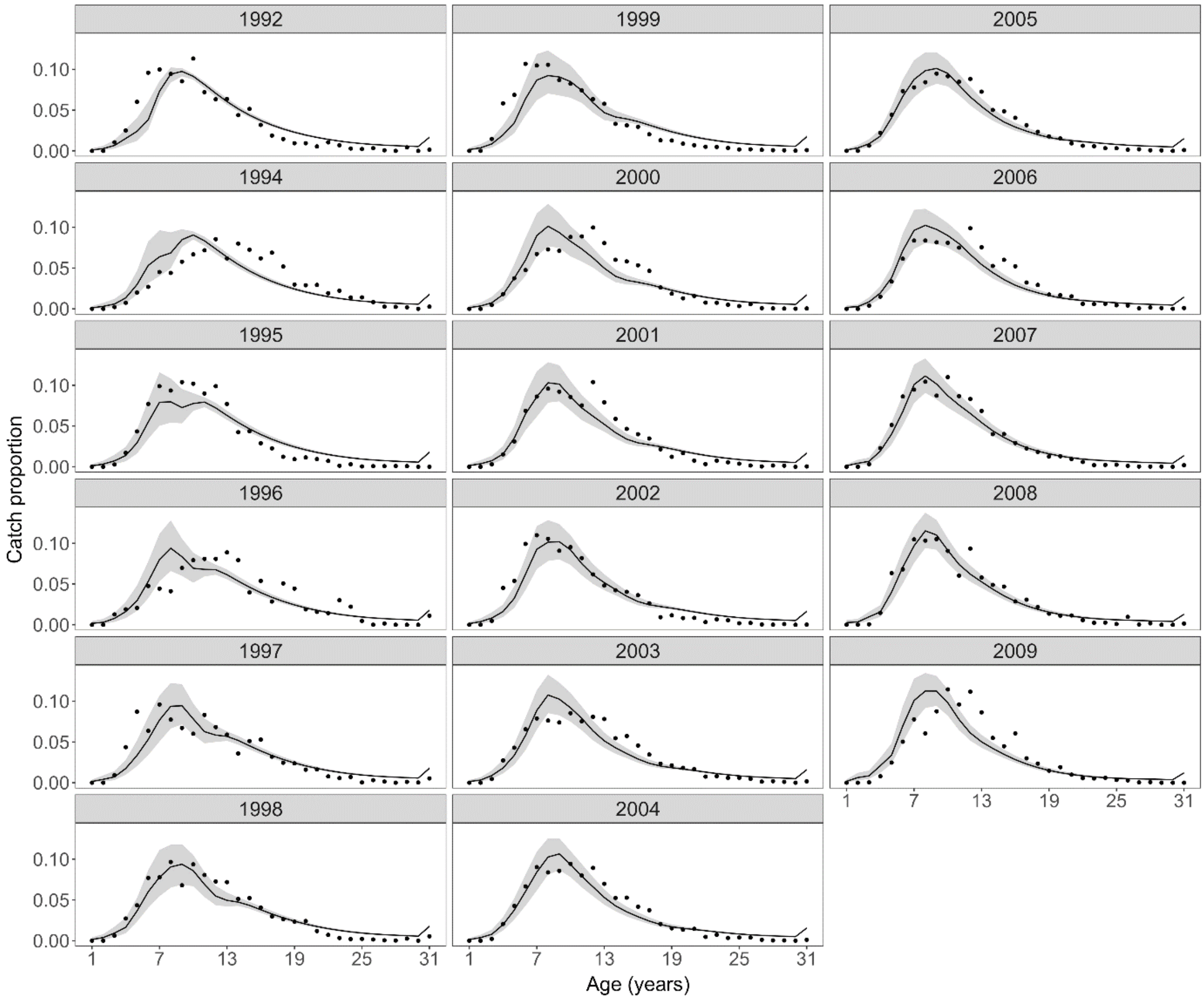


Figure A.5. MPD model fit (solid lines) to observed catch-at-age for the Spanish-system longline fishery (dots). Shaded areas denote MCMC 95% credible intervals of the fit.

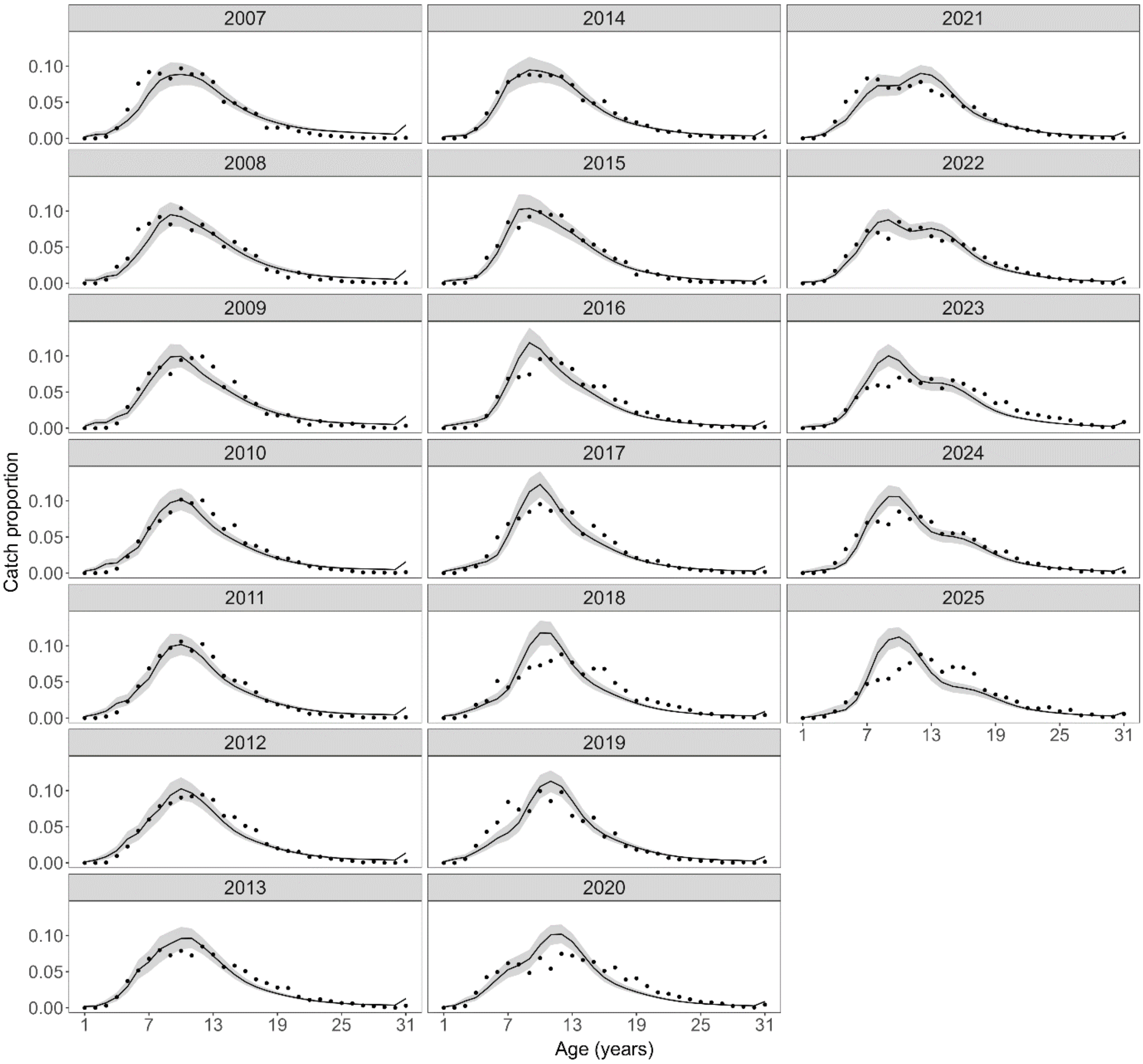


Figure A.6. MPD model fit (solid lines) to observed catch-at-age for the umbrella-system longline fishery (dots). Shaded areas denote MCMC 95% credible intervals of the fit.

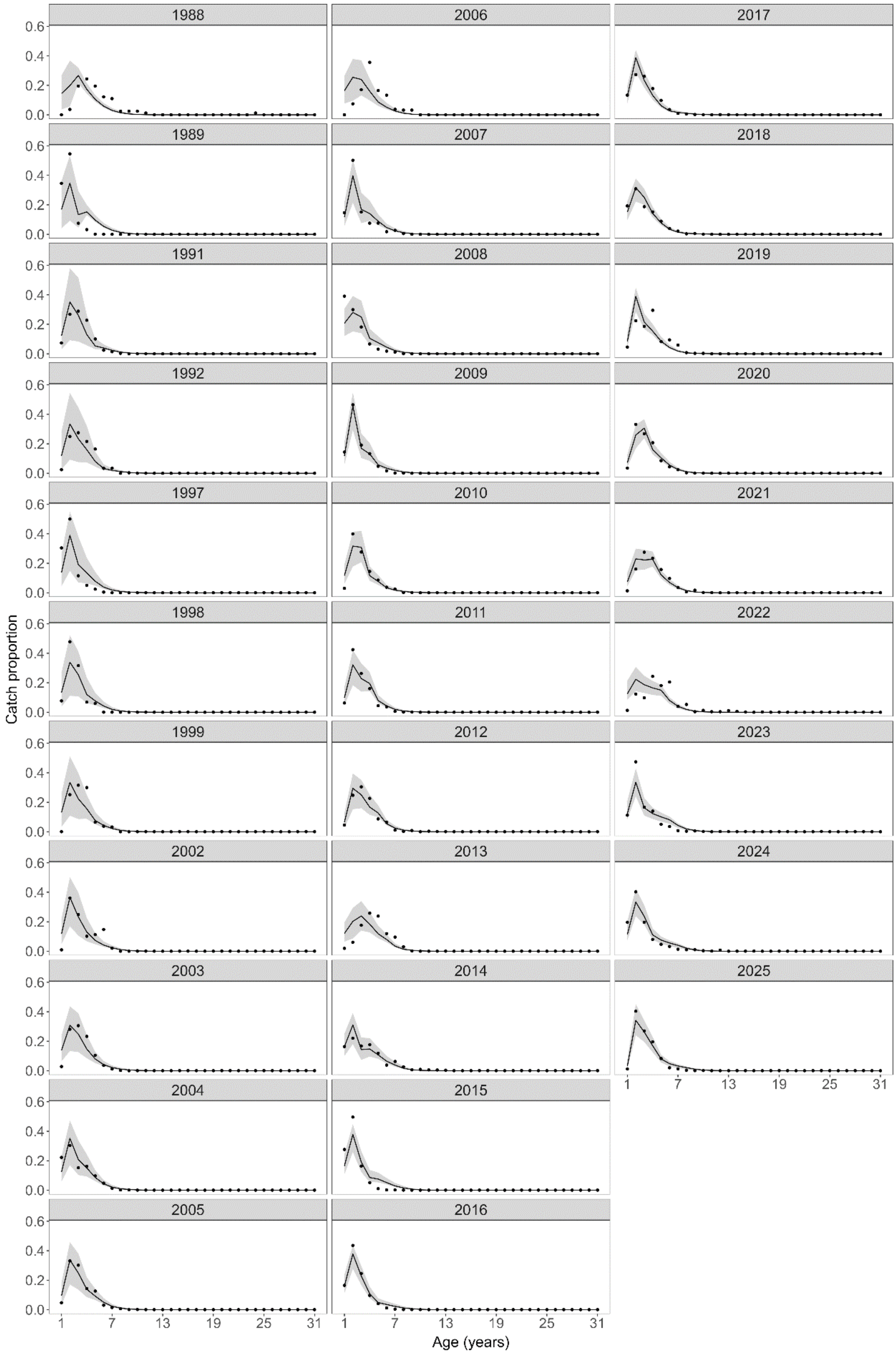


Figure A.7. MPD model fit (solid lines) to observed catch-at-age for the finfish trawl fishery (dots). Shaded areas denote MCMC 95% credible intervals of the fit.

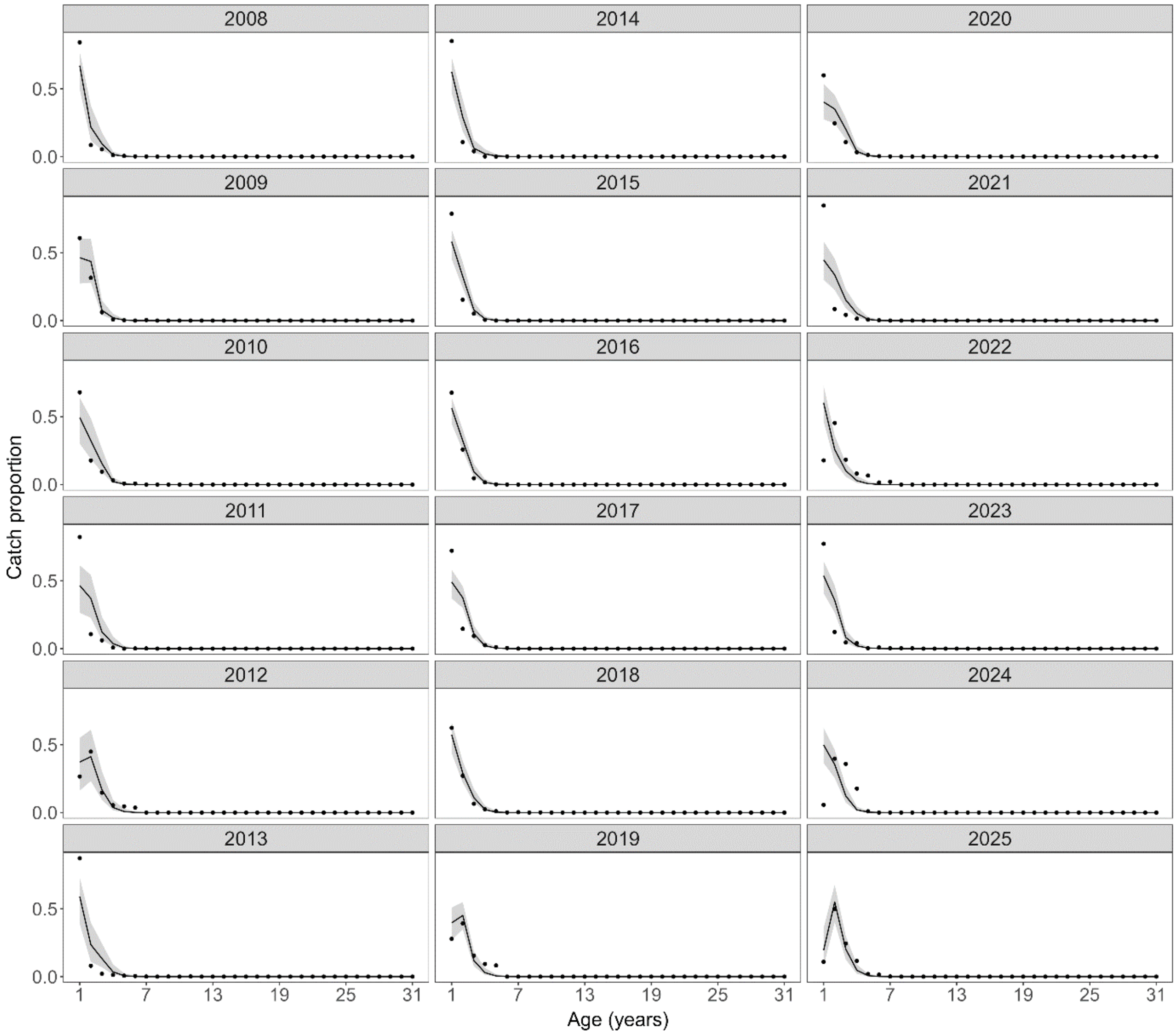


Figure A.8. MPD model fit (solid lines) to observed catch-at-age for calamari trawl fishery (dots). Shaded areas denote MCMC 95% credible intervals of the fit.

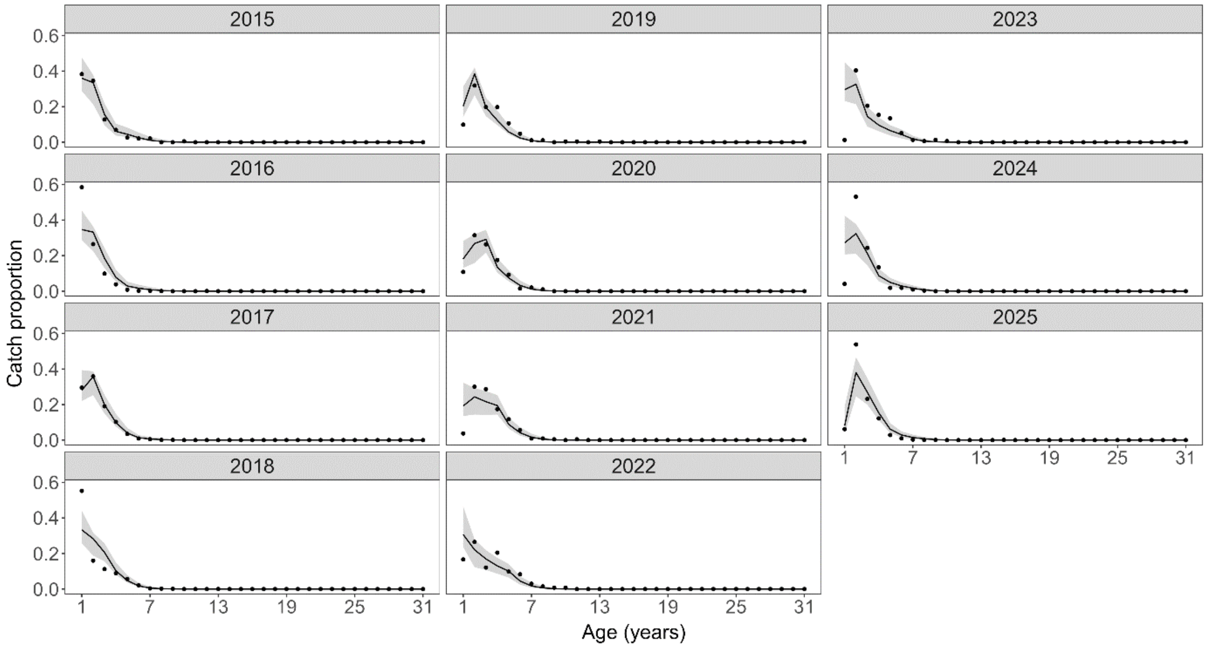


Figure A.9. MPD model fit (solid lines) to observed catch-at-age for groundfish survey (dots). Shaded areas denote MCMC 95% credible intervals of the fit.

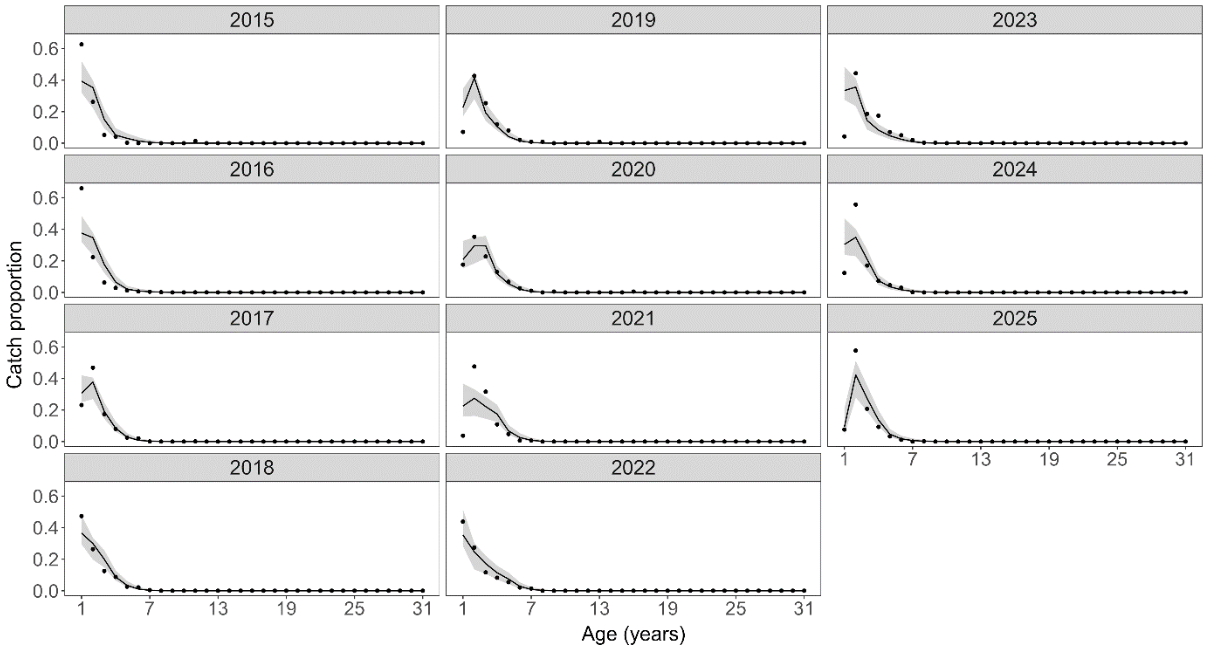


Figure A.10. MPD model fit (solid lines) to observed catch-at-age for calamari pre-season survey (dots). Shaded areas denote MCMC 95% credible intervals of the fit.

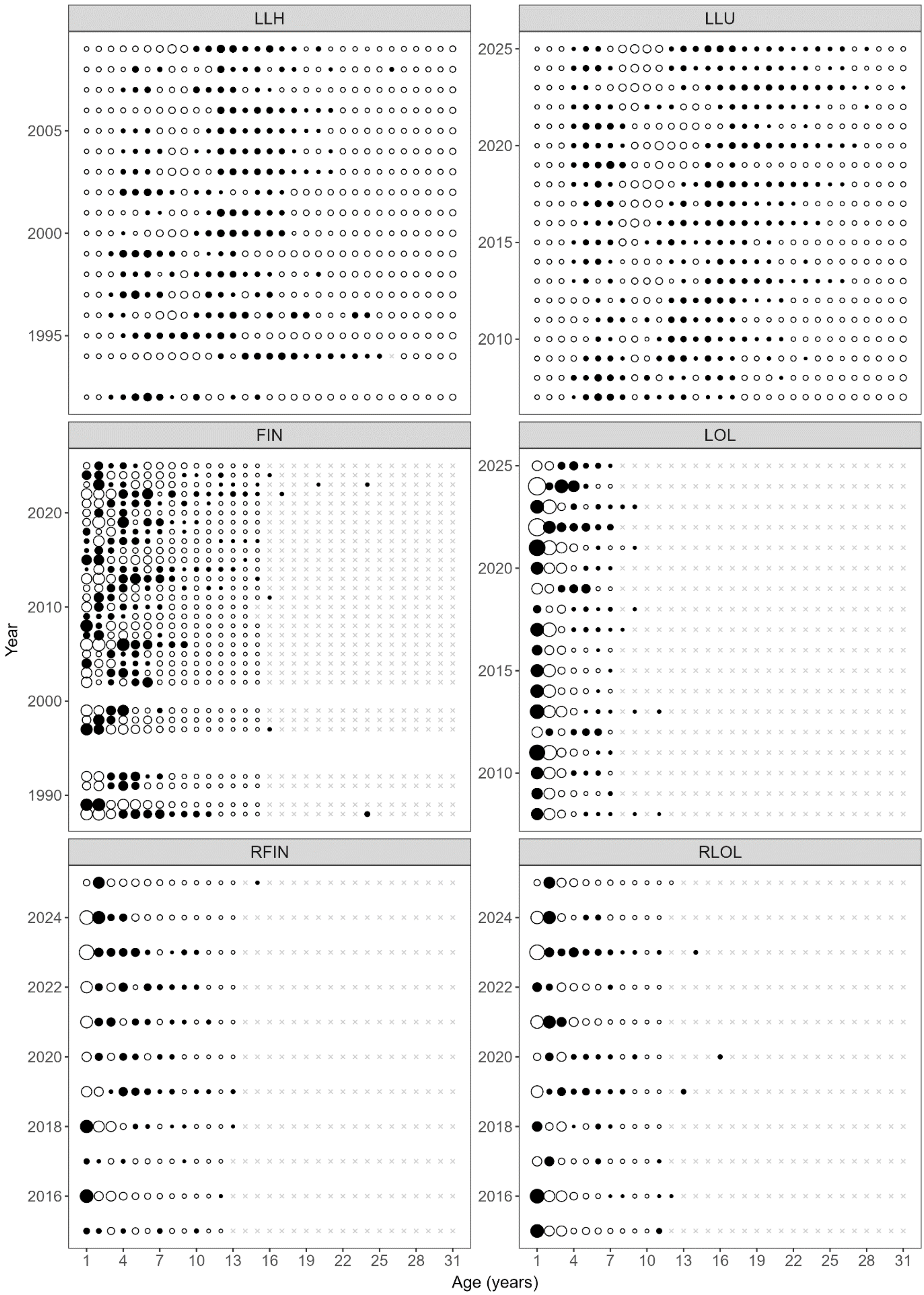


Figure A.11. Residuals from the model fit to observed catch-at-age for four fisheries and two research surveys. Bubble size is relative to the absolute residual value; positive residuals are denoted by full circles, and negative by empty circles.

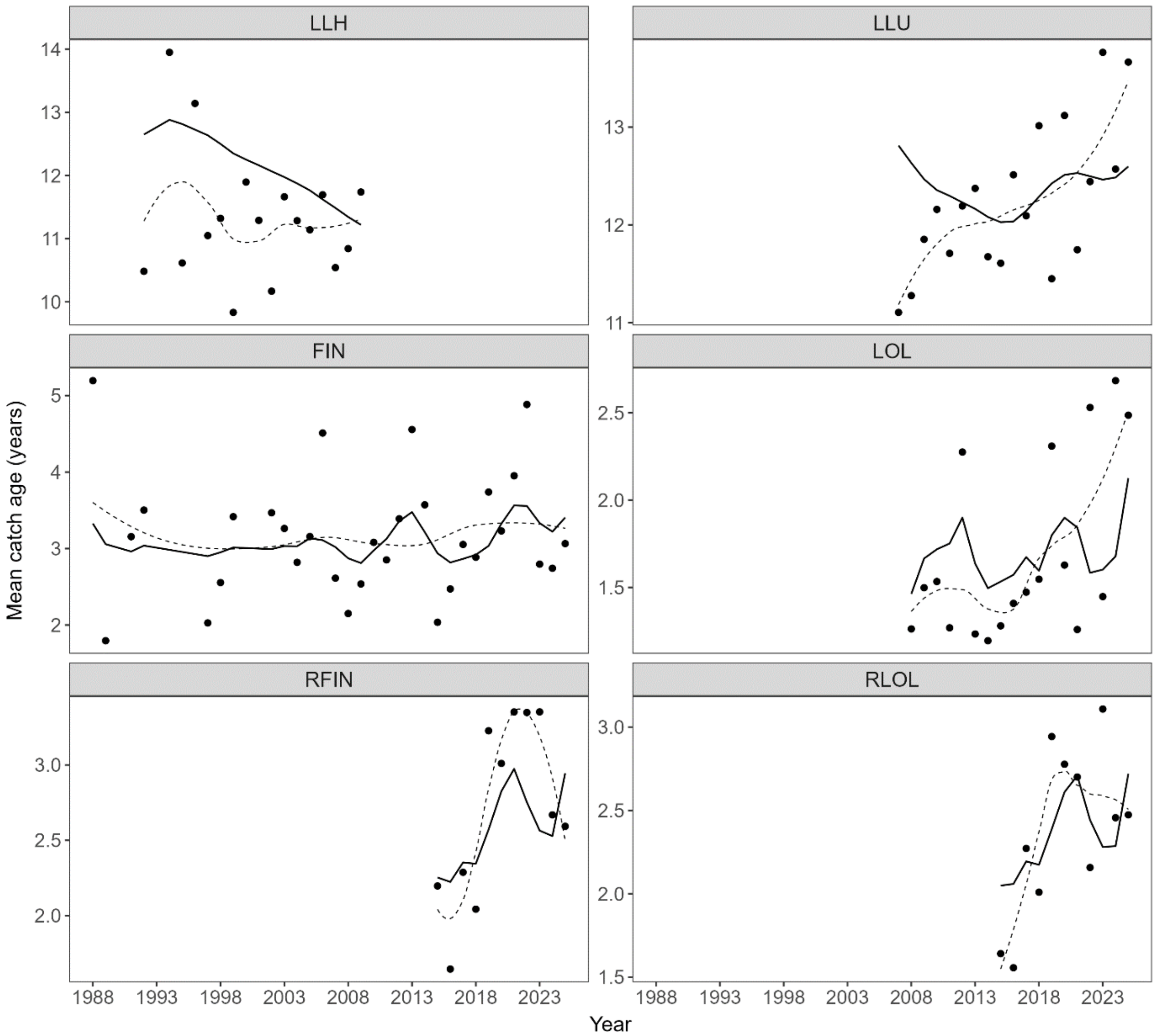
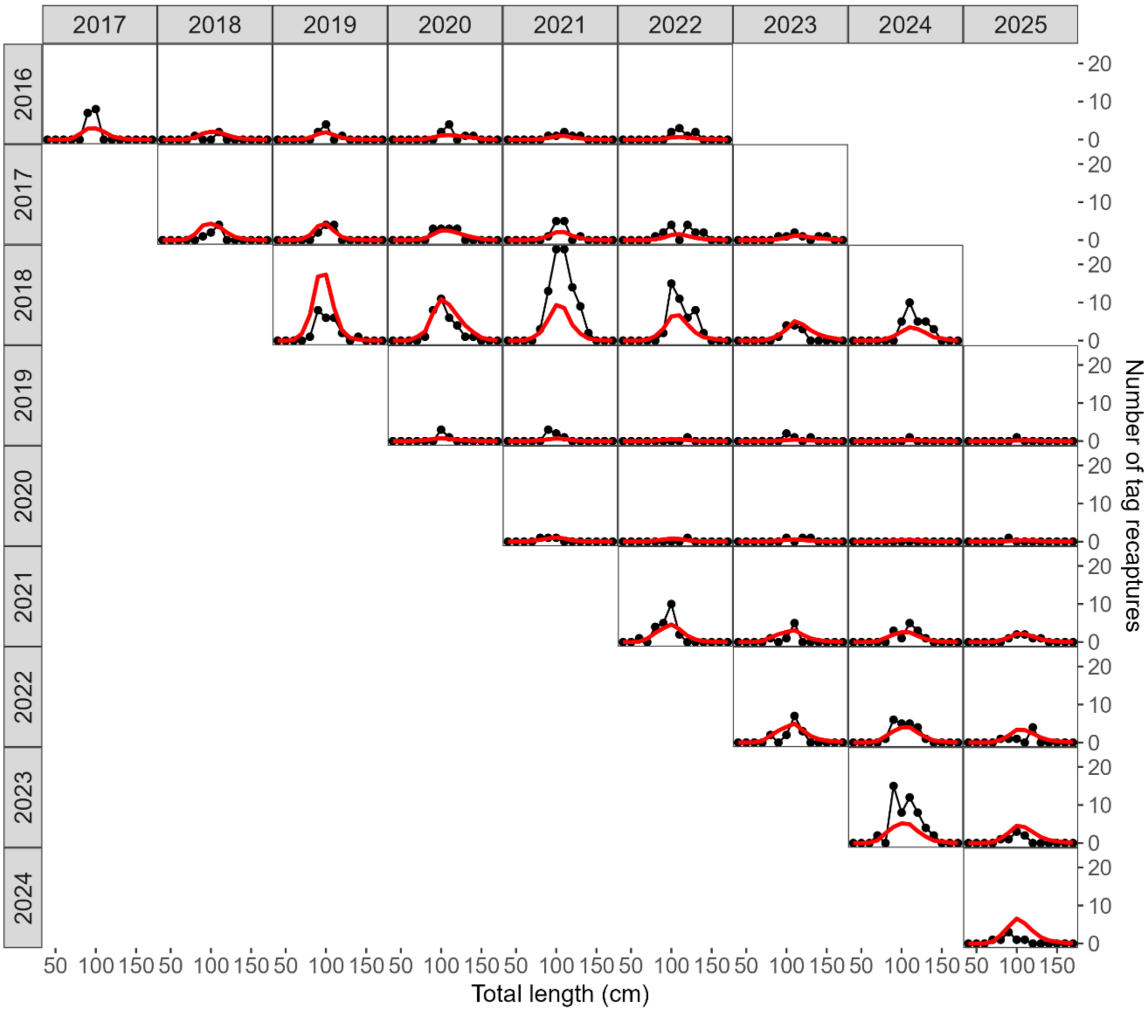
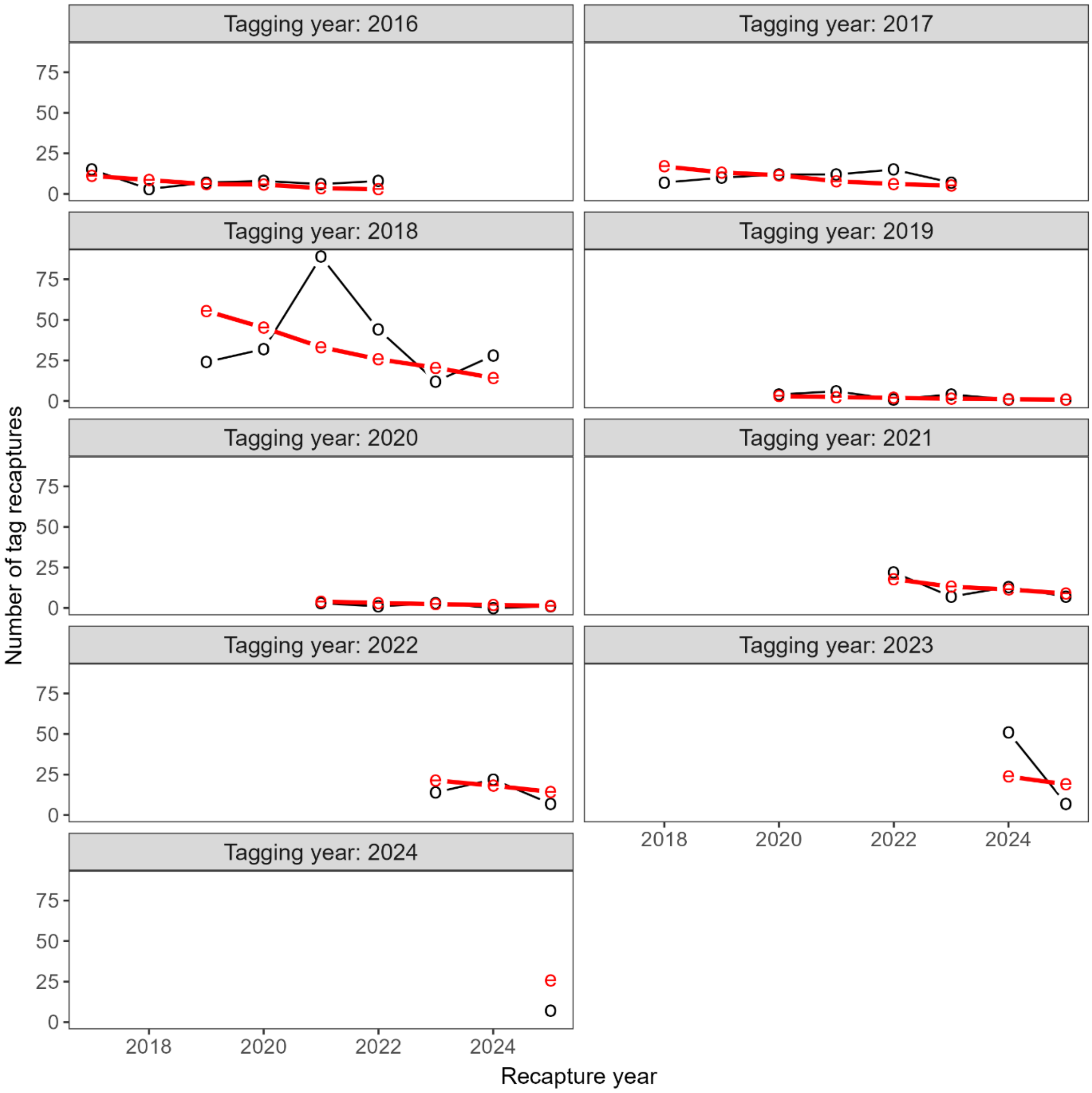


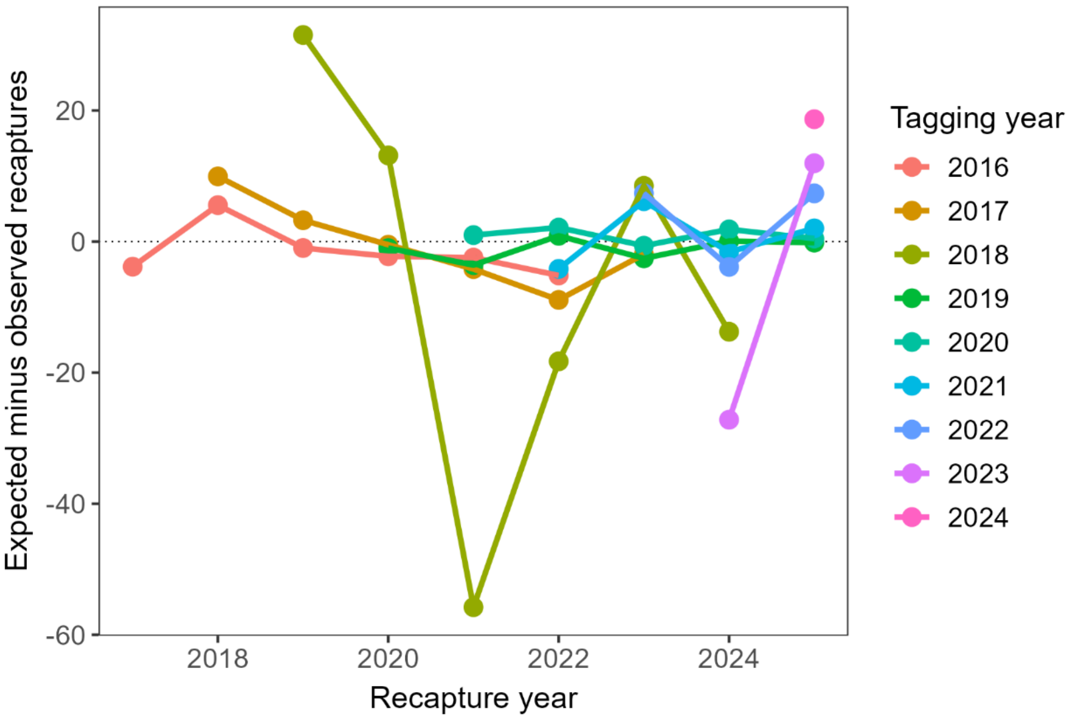
Figure A.12. Model fit (solid lines) to observed mean age-at-capture for four fisheries and two research surveys (black dots). Loess smoothers with span = 0.75 (dashed lines) are added to aid visual interpretation of trends in the observed data.



A.13. Model fit (red lines) to observed tag recapture numbers by 10 cm length bins (black dots) for tag releases in 2016-2024 and tag recaptures in 2017-2025. Recaptures after six years at liberty were excluded from the model and the plot.



A.14. Model fit (red lines) to observed tag recapture numbers (black dots) for tag releases in 2016-2024 and tag recaptures in 2017-2025. Recaptures after six years at liberty were excluded from the model and the plot.



A.15. Differences between fitted and observed tag recapture numbers for tag releases in 2016-2024 and tag recaptures in 2017-2025. Recaptures after six years at liberty were excluded from the model and the plot.

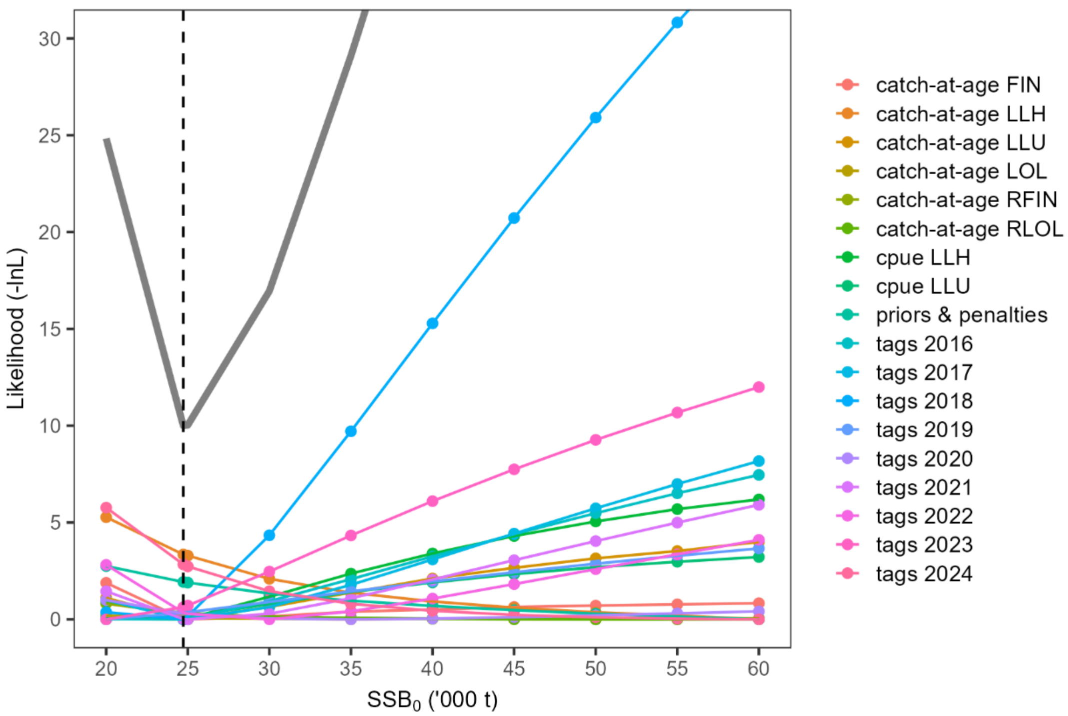


Figure A.16. Likelihood profiles for SSB_0. Negative log-likelihood values for individual datasets were rescaled to a minimum of zero, while the total objective function was rescaled to a minimum of 10 for easier visualisation (solid grey line). The dashed vertical line denotes the MPD estimate of SSB_0. LLH – Spanish-system longline, LLU – umbrella-system longline, FIN – finfish trawl, LOL – calamari trawl, RFIN – groundfish survey, RLOL – calamari pre-season survey.

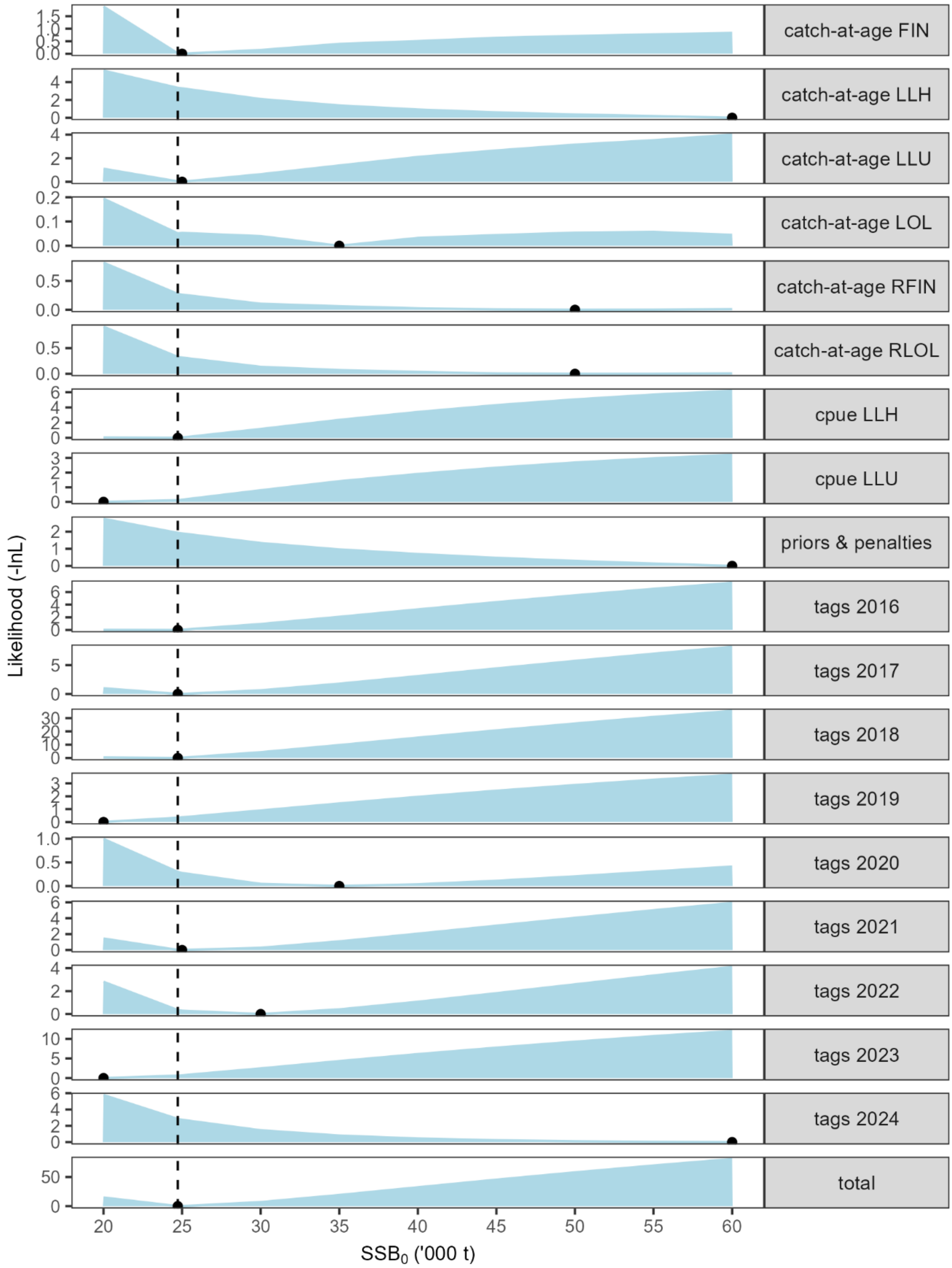


Figure A.17. Likelihood profiles for SSB_0. Negative log-likelihood values for individual datasets and the total objective function were rescaled to a minimum of zero. The dashed vertical line denotes the MPD estimate of SSB_0; dots denote SSB_0 values with the minimum negative log-likelihood value for each dataset. LLH – Spanish-system longline, LLU – umbrella-system longline, FIN – finfish trawl, LOL – calamari trawl, RFIN – groundfish survey, RLOL – calamari pre-season survey.

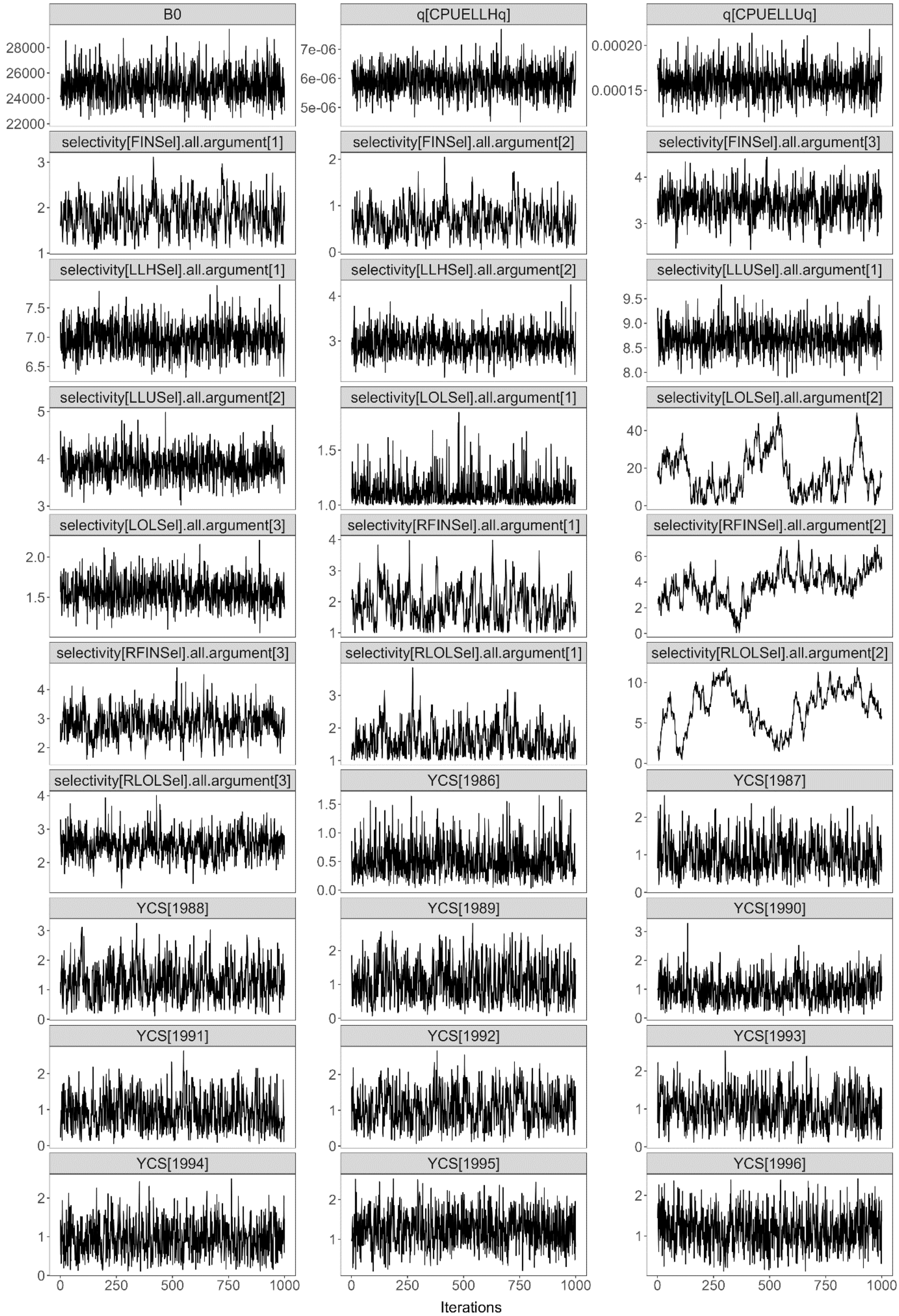


Figure A.18. MCMC posterior trace plots for all estimated parameters (figure 1 of 2).

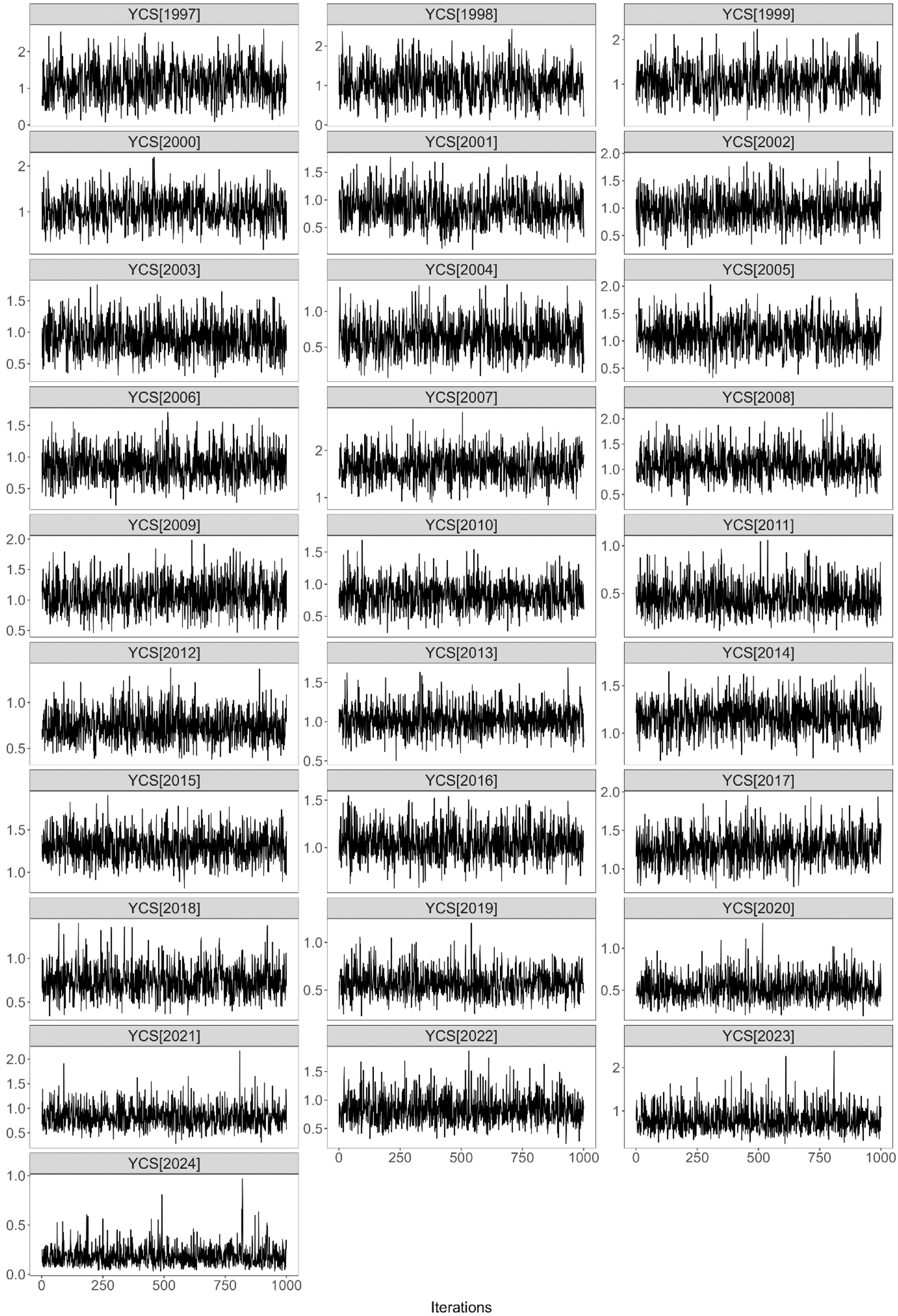


Figure A.18. Continued (figure 2 of 2).

Table A.2. MCMC convergence diagnostic results: Geweke's single-chain stationarity test and Heidelberger and Welch's stationarity and half-width tests.

Parameter	Geweke's stationarity test		Heidelberger and Welch's stationarity test		Heidelberger and Welch's halfwidth test		
	p-value	outcome	p-value	outcome	mean	halfwidth	outcome
B0	0.747	passed	0.667	passed	25050.8	73.137	passed
q[CPUELLHq]	0.593	passed	0.97	passed	0	0	passed
q[CPUELLUq]	0.811	passed	0.997	passed	0	0	passed
selectivity[FINSel].all.argument[1]	0.407	passed	0.287	passed	1.828	0.051	passed
selectivity[FINSel].all.argument[2]	0.387	passed	0.305	passed	0.68	0.042	passed
selectivity[FINSel].all.argument[3]	0.866	passed	0.756	passed	3.43	0.033	passed
selectivity[LLHSel].all.argument[1]	0.042	failed	0.543	passed	6.978	0.016	passed
selectivity[LLHSel].all.argument[2]	0.05	failed	0.468	passed	2.953	0.017	passed
selectivity[LLUSel].all.argument[1]	0.512	passed	0.598	passed	8.688	0.017	passed
selectivity[LLUSel].all.argument[2]	0.495	passed	0.792	passed	3.855	0.018	passed
selectivity[LOLSel].all.argument[1]	0.404	passed	0.841	passed	1.123	0.008	passed
selectivity[LOLSel].all.argument[2]	0.176	passed	0.903	passed	16.85	5.565	failed
selectivity[LOLSel].all.argument[3]	0.784	passed	0.201	passed	1.565	0.011	passed
selectivity[RFINSel].all.argument[1]	0.698	passed	0.494	passed	1.896	0.099	passed
selectivity[RFINSel].all.argument[2]	0	failed	0.04	failed	-	-	-
selectivity[RFINSel].all.argument[3]	0.751	passed	0.558	passed	2.82	0.058	passed
selectivity[RLOLSel].all.argument[1]	0.144	passed	0.679	passed	1.623	0.073	passed
selectivity[RLOLSel].all.argument[2]	0.274	passed	0.533	passed	6.823	1.773	failed
selectivity[RLOLSel].all.argument[3]	0.234	passed	0.348	passed	2.526	0.038	passed
YCS[1986]	0.249	passed	0.522	passed	0.532	0.021	passed
YCS[1987]	0.584	passed	0.408	passed	0.972	0.046	passed
YCS[1988]	0.542	passed	0.917	passed	1.278	0.063	passed
YCS[1989]	0.172	passed	0.674	passed	1.097	0.056	passed
YCS[1990]	0.373	passed	0.099	passed	1.002	0.04	passed
YCS[1991]	0.559	passed	0.3	passed	0.923	0.046	passed
YCS[1992]	0.04	failed	0.347	passed	1.072	0.053	passed
YCS[1993]	0.005	failed	0.104	passed	1.023	0.049	passed
YCS[1994]	0.249	passed	0.359	passed	0.949	0.035	passed
YCS[1995]	0.555	passed	0.596	passed	1.267	0.034	passed
YCS[1996]	0.041	failed	0.214	passed	1.147	0.035	passed
YCS[1997]	0.344	passed	0.47	passed	1.163	0.041	passed
YCS[1998]	0.658	passed	0.155	passed	1.047	0.035	passed
YCS[1999]	0.979	passed	0.17	passed	1.07	0.028	passed
YCS[2000]	0.084	passed	0.179	passed	1.061	0.026	passed
YCS[2001]	0.188	passed	0.068	passed	0.857	0.021	passed
YCS[2002]	0.841	passed	0.63	passed	0.985	0.019	passed
YCS[2003]	0.108	passed	0.206	passed	0.919	0.018	passed
YCS[2004]	0.56	passed	0.592	passed	0.637	0.017	passed
YCS[2005]	0.993	passed	0.582	passed	1.109	0.019	passed
YCS[2006]	0.944	passed	0.905	passed	0.866	0.016	passed

YCS[2007]	0.927	passed	0.814	passed	1.666	0.02	passed
YCS[2008]	0.783	passed	0.497	passed	1.106	0.018	passed
YCS[2009]	0.134	passed	0.065	passed	1.081	0.018	passed
YCS[2010]	0.721	passed	0.769	passed	0.829	0.013	passed
YCS[2011]	0.793	passed	0.746	passed	0.456	0.01	passed
YCS[2012]	0.787	passed	0.562	passed	0.741	0.01	passed
YCS[2013]	0.819	passed	0.555	passed	1.023	0.01	passed
YCS[2014]	0.912	passed	0.369	passed	1.174	0.01	passed
YCS[2015]	0.377	passed	0.623	passed	1.304	0.01	passed
YCS[2016]	0.416	passed	0.767	passed	1.052	0.012	passed
YCS[2017]	0.001	failed	0.138	passed	1.286	0.015	passed
YCS[2018]	0.633	passed	0.988	passed	0.742	0.012	passed
YCS[2019]	0.566	passed	0.878	passed	0.574	0.01	passed
YCS[2020]	0.481	passed	0.448	passed	0.523	0.009	passed
YCS[2021]	0.79	passed	0.896	passed	0.829	0.014	passed
YCS[2022]	0.842	passed	0.911	passed	0.831	0.015	passed
YCS[2023]	0.424	passed	0.978	passed	0.79	0.017	passed
YCS[2024]	0.82	passed	0.967	passed	0.186	0.007	passed

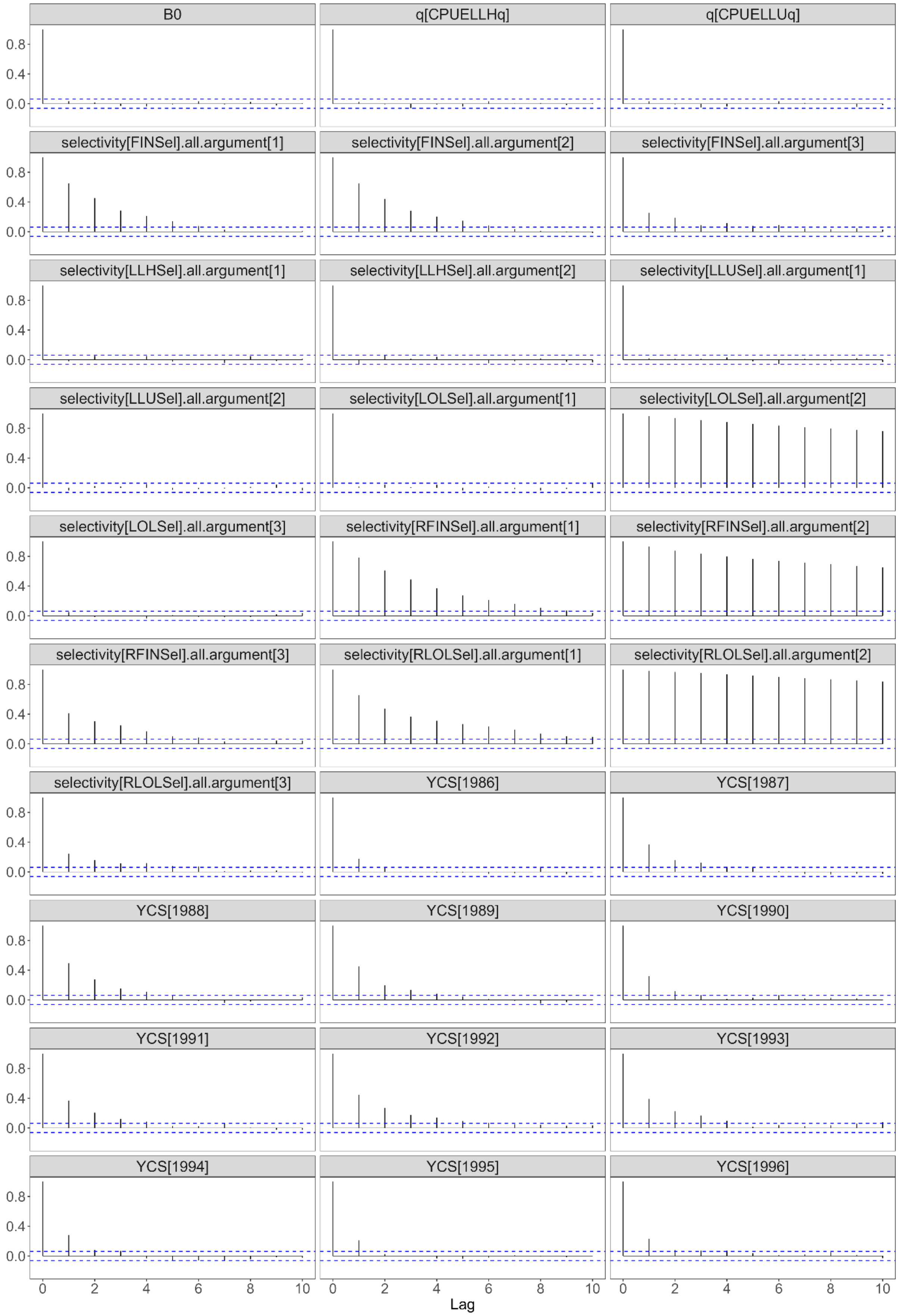


Figure A.19. MCMC autocorrelation lag plots for all estimated parameters (figure 1 of 2).

Figure A.19. Continued (figure 2 of 2).

Appendix 3. Objective function contributions

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Table A.3. Contributions to the objective function in the MPD model run.

Objective function components	Values
Observations	
CPUE $_{LLH}$	-16.6
CPUE $_{LLU}$	-37.5
Catch-at-age $_{FIN}$	161.6
Catch-at-age $_{LLH}$	428.7
Catch-at-age $_{LLU}$	537.1
Catch-at-age $_{LOL}$	54.1
Catch-at-age $_{RFIN}$	65.1
Catch-at-age $_{RLOL}$	59.8
Tags 2016	16.5
Tags 2017	19.6
Tags 2018	43.4
Tags 2019	8.9
Tags 2020	5.7
Tags 2021	13.0
Tags 2022	11.3
Tags 2023	13.4
Tags 2024	5.6
Priors	
SSB_0	10.1
YCS	-27.1
q $_{LLH}$	-12.0
q $_{LLU}$	-8.7
All selectivity priors	0.0
Penalties	
YCS $_{MEAN\_1}$	7.5
All catch limit penalties	0.0
Total objective function	1359.2

LLH – Spanish-system longline, LLU – umbrella-system longline, FIN – finfish trawl, LOL – calamari trawl, RFIN – groundfish survey, RLOL – calamari pre-season survey.

Appendix 4. Harvest control rules

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Based on the CASAL model output, the following decision matrix of harvest control rules has been established to manage the Falkland Islands toothfish longline fishery (Farrugia and Winter 2018):

1. *Expansion range:* If the ratio of $SSB_{current}/SSB_0$ has remained above the upper target reference point (45%) for 3 consecutive years and the SSB projection with the current TAC shows no decrease below 45% for at least 10 years (one generation) under precautionary assumptions, the Director may authorise an increase in longline TAC to a level that continues to show no projected $SSB_{current}/SSB_0$ decrease to below 40% (trigger point) for at least 10 years under precautionary assumptions.

2. *Target range:* If the ratio of $SSB_{current}/SSB_0$ is between 40% and 45% (within the target range), current longline TAC is reviewed in relation to stock trends. Current TAC may be maintained if $SSB_{current}/SSB_0$ has increased from the previous assessment, or if the SSB ratio projection shows a level status under precautionary assumptions. TAC may not be increased, but it may be decreased in response to substantial indications of unfavourable conditions for the stock.

3. *Trigger point and range:* If the ratio of $SSB_{current}/SSB_0$ falls to ≤ 40% (trigger point), longline TAC will be decreased to a level that projects an increasing SSB trend under precautionary assumptions. The magnitude of the proposed TAC reduction will be examined using three methods (adapted from ICES, 2017):

    a. Indexed to the reduction of the MSY estimates:
    $$TAC_{year} = TAC_{year-1} * \left(MSY_{year}/MSY_{year-1}\right)$$
    b. Indexed to the reduction of the SSB estimates:
    $$TAC_{year} = TAC_{year-1} * \left(SSB_{year}/SSB_{year-1}\right)$$
    c. Indexed to the reduction in SSB ratios:
    $$TAC_{year} = TAC_{year-1} * \left(SSB\ ratio_{year}/SSB\ ratio_{year-1}\right)$$

    TACs obtained from all three methods will be projected forward in the stock assessment model and the trends in SSB will be compared. The final method will be chosen based on it returning the SSB ratio to above 40% within 10 years (one generation) of the SSB ratio falling below 40%. If more than one method meets this requirement, the chosen method will also depend on discussions between the Fisheries Department and the industry.

4. *Limit reference point:* If the ratio of $SSB_{current}/SSB_0$ is ≤ 20%, the longline fishery will be closed pending a comprehensive evaluation of conditions required to rebuild the stock. The Director may authorise test fishing to measure the biological parameters of the stock, subject to close monitoring by the Fisheries Department.