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Background analyses for the 2020 stock assessments of bigeye and yellowfin tuna

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Contents

Executive Summary

This paper describes the data used and background analyses conducted for the 2020 stock assessments of bigeye tuna *Thunnus obesus* and yellowfin tuna *Thunnus albacares* in the western and central Pacific Ocean. This report contains all analyses of data where stand-alone papers were not considered warranted. Descriptions of the following model components and data inputs are contained within this report:

- Summaries of the catch, effort, and size composition data by fishery used within the stock assessment.
- Estimation of length-weight relationships used within the stock assessment models to transform numbers at age to biomass.
- Growth models used within the assessment.
- Estimation of natural mortality at age from the proportion female at length data from longline observers.
- A meta-analysis of natural mortality estimates using the growth curves and other biological information.
- Spawning potential ogive calculations.
- Preparation of tagging data used within the assessments.

The extraction fisheries structures used in the current assessment were consistent with the diagnostic case models used in the most recent assessments of these species. These assessments have moved toward using an index fishery for each region, which receives the standardized CPUE (Ducharme-Barth et al., 2020b), a nominal catch of one individual, and size composition reweighted by the index (Peatman et al., 2020). In this modeling technique, the effort for all other fisheries is removed so the standardized CPUE index in each region is the sole driver of abundance trends.

The length-weight conversion estimates were updated using data available to SPC from port sampling. The length-weight conversion factor was estimated from a combination of fish measured in whole weight or in gilled-gutted, the latter being converted to whole weight using a different conversion factor.

Natural mortality at age estimates and proportion female at age in the maturity ogives were updated with the addition of more observations since the most recent assessments. A meta-analysis on natural mortality was also conducted to provide an alternative estimate, which was used as the mean estimate for a number of models.

The continuous collection and analysis of basic biological data such as proportion mature at length, spawning fraction at length, fecundity at length, proportion female at length, length and weight measurements, whole weight to gilled gutted weight, etc. for these tuna is required to provide

reliable information to the assessments. Due to the Covid-19 pandemic, an increased emphasis on port sampling and acquisition of biological information is necessary in the (hopefully) short term, to fill the data gap that is created due to the lack of observers onboard vessels. Additionally, sampling of various biological information and catch estimation at canneries is encouraged.

1 Introduction

The most recent assessments for bigeye and yellowfin tuna in the western and central Pacific Ocean (WCPO) were conducted in 2018 and 2017, respectively. The data inputs used for the 2020 stock assessments of these species are generally similar to those assessments, although some additional information has become available. Additionally, some biological assumptions were reviewed and updated with additional information. This paper outlines the major changes and preparation of the data that were used in the 2020 assessments of these two species. These analyses should be considered in conjunction with several other analyses providing inputs to the stock assessments that were substantial bodies of work themselves, and which warranted their own stand-alone paper. These include: analyses of growth models (Eveson et al., 2020; Farley et al., 2020); analyses of tag seeding trials (Peatman, 2020) and tagging quality (Scutt Phillips et al., 2020); standardisation of CPUE indices (Ducharme-Barth et al., 2020b; Vidal and Hamer, 2020); and analyses of purse seine and longline size data (Peatman et al., 2020). Herein, we report on all remaining analyses of data where stand-alone papers were not considered warranted.

2 Fisheries Definitions

The fisheries structures used within the bigeye and yellowfin assessments were the same as those used in the most recent diagnostic case models, where the equatorial regions were bounded by 10°N and 10°S (Figure 1). There are summary plots of the data available for each fishery and these are presented in the appendix (Figures 20 to 101). There were 32 extraction fisheries modeled in the assessment within the nine regions consisting of 14 longline, 4 pole-and-line, 10 purse seine, 1 handline and 3 miscellaneous gear fisheries (Figures 20 to 51 and Figures 61 to 92). In addition to these extraction fisheries, an index fishery was created for each region (Figures 52 to 60 and Figures 93 to 101).

Each index fishery received the appropriate regional estimated CPUE index from the spatial-temporal (geostats) models (Ducharme-Barth et al., 2020b), a nominal catch of a single individual, and a size composition that was reweighted by the CPUE index (Peatman et al., 2020). The data inputs for the extraction were generally the same as those available for the most recent assessments of these species with an additional three years of data. However, the effort data provided to the extraction fisheries was removed to ensure that the index fishery was the primary driver of biomass trends. Additional size composition data for the Indonesia and Vietnamese domestic fisheries became available since the last assessments. This addition allowed these fisheries to be given a separate selectivity to the Philippines fishery, which caught slightly smaller fish. Weight composition for the handline fishery was also included in this assessment because there was close agreement between these two data-sources. An additional change to this assessment was that the small amount of purse seine catch that was taken outside of 10°N and 10°S was added into the corresponding purse seine fisheries in the equatorial region based on the longitude of recapture.

Previous yellowfin stock assessments have included a standardized CPUE index for the Indonesia and Philippines handline and purse seine fisheries and the associated purse seine in region 8 (Bigelow et al., 2020). This assessment used only the index from the spatial-temporal CPUE model for the diagnostic case model but one-off sensitivities were run including these indices. In addition, a spatial-temporal model for the associated purse seine fisheries in regions 3, 4, and 8 were included in an additional one-off sensitivity (Vidal and Hamer, 2020).

3 Growth

3.1 General

Stock assessments conducted using MFCL assume that growth is spatially and temporally constant, and historically the growth curve has been estimated internal to the assessment model (i.e., based on the modal progression of size composition data). The previous reliance on internally estimated growth was based on difficulties in estimating the age of individual tuna from hard parts (Schaefer and Fuller, 2006); therefore, there were no external estimates of growth for these species. The availability of strong modes in the size frequency data of some fisheries allows estimation of growth parameters for these species. However, the estimation of these parameters is inherently linked with the estimated selectivity of the fisheries within the stock assessment. Subsequent additional analyses of the bigeye and yellowfin models indicate that the starting values of the growth parameters can heavily influence the likelihood of the model. This indicates that these parameters may be poorly estimated within the model, potentially due to confounding with the selectivity parameters.

In the most recent assessment of bigeye an external estimate was used as the basis for the growth curve (Farley et al., 2017; Vincent et al., 2018). This assessment fixed the size of the oldest age in the model (L2) and the growth rate (k) at values estimated outside the assessment, and estimated the size of the smallest age within the assessment model (L1) to fit to the very small fish captured by the Philippines domestic fishery. In the most recent yellowfin stock assessment, growth was estimated within the stock assessment using only the modal progression information due to a lack of external growth estimates. The growth of yellowfin was modeled as a von Bertalanffy curve with additional parameters for the deviation away from the growth curve for the 2nd to 8th age classes. Subsequent to the most recent assessments of bigeye and yellowfin tuna, external estimates of growth from otoliths using annual rings and daily ring counts for small fish have become available (Eveson et al., 2020; Farley et al., 2020). The otolith data now available for yellowfin and bigeye are presented by Farley et al. (2020).

The otolith data can also be incorporated into assessment models by utilising the conditional age-at-length feature in MFCL (Davies et al., 2015). Conditional age-at-length input files were created using the otolith age-length data for the two species (Farley et al., 2020). The input files were created by assigning each otolith sample to a length and age class (quarter) and a fishing incident based on the collection date of the sample and the gear by which it was captured or the gear within the same region that caught the most similar sizes. Otolith samples that were collected after the end of the model period, i.e., 2019-2020, were assigned to a fishing incident in 2018. Models were developed that incorporated the growth information in the otolith data as well as the modal progression information available in the size composition data.

3.2 Bigeye growth

The data used to estimate the growth curve for bigeye tuna are consistent with those used in the previous assessment, but include additional daily counts of small fish following the recommendation from the 2018 assessment (Vincent et al., 2018). Two approaches for estimating these external growth curves were conducted - otolith only (Farley et al., 2020), and otolith and tag-integrated (Eveson et al., 2020), and for both approaches the von Bertalanffy and Richards growth curves were investigated. The Richards growth curve is very similar to the von Bertalanffy but includes an additional parameter which can allow for a more flexible 'S'-shaped curve. Following those external analyses, the bigeye assessment investigated the two Richards growth curves estimated from the high quality otolith only data and high quality otolith-tag integrated model. The length of the first age class in the assessment was calculated from these growth curve as the length at one-eighth of a year to allow the model to fit the very small fish observed in the Philippines size composition data (Figure 2). The length at the largest age was thus calculated as the length for 9.875 years old and the k parameter was converted to a quarterly (seasonal) rate by dividing by 4. The options considered in the development of the bigeye model were:

1. A fixed Richards growth curve from the external age-at-length estimate using the high readability otoliths,
2. A fixed Richards growth curve from the external age-at-length estimate for the model integrating the high readability otoliths and the tag increment dataset, and,
3. Estimation of a von Bertalanffy growth curve (no deviates) using the otoliths in a conditional age-at-length.

3.3 Yellowfin growth

Previous assessments of yellowfin tuna assumed that the oldest age in the model was 28 quarters (7 years) old due to few observed tag recaptures longer than this time at liberty and the fast growth rate estimates from the size composition data. However, the recent analysis of yellowfin otoliths and the estimated growth curves suggests that the oldest age may be more similar to that of bigeye

(Farley et al., 2020). Therefore, the diagnostic case for the yellowfin assessment was expanded to 40 quarters (10 years old). A Richards growth curve from the high quality otolith only data estimated similar L1 and L2 parameters to those from the previous assessment, but estimated k to be much lower (Figure 3). The tag and otolith integrated Richards model was not able to estimate a growth curve due to a conflict between these data sources (Eveson et al., 2020). A von Bertalanffy growth curve was successfully fitted to the otolith and tag increment data and was used in a one-off sensitivity model in the assessment. The options considered in the development of the yellowfin model followed a similar logic to the 2017 bigeye report, and were:

1. A fixed growth curve that was estimated by a model that did not down-weight the size composition data and estimated deviates for age classes 2-8 (similar to the previous assessment Tremblay-Boyer et al., 2017),
2. A fixed Richards growth curve from the external age-at-length estimate using the high readability otoliths, and,
3. Estimation of a von Bertalanffy growth curve (no deviates) using the otoliths in a conditional age-at-length.

4 Natural Mortality and Proportion Female

4.1 Background and methods

Natural mortality (M) is an important parameter within age-structured stock assessments. This parameter is the rate at which fish die due to natural causes, e.g. starvation, predation, disease or senescence. Natural mortality scales the size of the population relative to the catch within the stock assessment and can be closely correlated with the estimated fishing mortality. Natural mortality was assumed to be age specific as in previous stock assessments of bigeye and yellowfin (Davies et al., 2014; Harley et al., 2014; Tremblay-Boyer et al., 2017; McKechnie et al., 2017a). The previous stock assessments of both species estimated natural mortality at age external to the assessment model and used these as fixed values within the assessment. The fixed values used in the assessment models were derived from the methods presented by Hoyle (2008) and Hoyle and Nicol (2008). The analysis relies on the assumption that the decrease in the proportion of females at larger size, as seen in the fisheries data, is caused by their higher mortality relative to males. It has been hypothesized that this higher natural mortality-at-age may be related to reproduction being more physically demanding for females.

In summary, this analysis uses the observed proportion of males at length from observers on-board longline vessels to estimate the additive mortality that females must experience in order to produce this change in the sex-proportion at length (Figure 4). We restricted the analysis of proportion males at length for the analysis to the range of 110 cm to 170 cm, because outside this range there were either too few samples to accurately predict proportions or there was indication that immature females were being misclassified as males. Comparing the two species, there generally seems to be more of an increase in the proportion male with increasing length for yellowfin than for bigeye. Additionally, the proportion male is above 50% at 110 cm for yellowfin (Figure 4). The fitted models generally follow the methods first presented by Harley and Maunder (2003) that were used in previous assessments (McKechnie et al., 2017a; Tremblay-Boyer et al., 2017). The analysis differs from previous years in that the growth curve equations used to transform lengths to age were Richards curves for all of the bigeye growth curves, and the high confidence otolith only growth curve for yellowfin. Natural mortality at age was estimated for each of the growth curves used in the assessment.

The analysis uses a base natural mortality rate that is then adjusted by the estimated sex specific natural mortality and the proportion of each sex in that age class (derived from the growth curve). Natural mortality is also assumed to be highest ($M0$) in the first age-class and then declines linearly to a common mortality rate for both males and females at the so-called breakpoint age-class (a_{brk}). The breakpoint age-class is three quarters of age for bigeye and five quarters of age for yellowfin, consistent with previous assessments in the WCPO. The male mortality rate then remains constant over all subsequent age-classes at the assumed level. However, after the breakpoint age-class, the mortality rate of females is determined by the proportion of females that are mature (ψ) in that age-class, with immature and mature individuals having mortality rates of $M1$ and $M2$, respectively. Note that a lag can be imposed that delays the increase in mortality by l quarters after maturity. The model for natural mortality can therefore be defined for males as:

$$M_a^m = \begin{cases} M0 & \text{for} \quad a = 1 \\ M_{a-1}^m - (M1 - M0)/(a_{brk} - 1) & \text{for} \quad a = 1, 2, ..., a_{brk} \\ M1 & \text{for} \quad a = a_{brk} + 1, a_{brk} + 2, ..., a_N \end{cases}$$

and for females as:

$$M_a^f = \begin{cases} M0 & \text{for} \quad a = 1 \\ M_{a-1}^f - (M1 - M0)/(a_{brk} - 1) & \text{for} \quad a = 1, 2, ..., a_{brk} \\ M1(1 - \psi_{a-l}) + M2(\psi_{a-l}) & \text{for} \quad a = a_{brk} + 1, a_{brk} + 2, ..., a_N \end{cases}$$

where $M0$ is fixed at $2 \times M1$, and quarterly age-classes are notated a, and range from 1 to 40 (a_N). The parameters in the mortality model were estimated by optimising an objective function using the χ^2 distribution and the observed and model-predicted sex-ratios-at-length. This fit then gives a proportion of females at age, which was previously used in the assessments, and the joint natural mortality at age. Enhancements made to MFCL since the last stock assessment allow the input of maturity at length to be converted to maturity at age within the assessment based on the growth curve. Therefore, the predicted proportion at length from this analysis was used as a component of the maturity ogive.

This entire analysis is predicated on the assumption that the decrease in the proportion female at length is due to an increase in the natural mortality experienced by females. However, a decrease in the proportion at large sizes could also be due to a differential growth between the species. An alternative explanation of this observed phenomenon could be because females do not continue to grow after reaching maturity due to their higher energy expenditure while spawning, but males continue to slowly grow. Within the tissue bank database there are many fish whose maturity status is classified as indeterminate due to the gonads being removed by fishermen before being seen by the observer. Therefore, there is the possibility that the larger ovaries are easier to remove than the small testes in the males and could explain the decrease in the proportion female at larger lengths as their ovaries get larger. A thorough investigation of the hypothesis that the decrease in the observed proportion at length in females is due to natural mortality is required.

4.2 Natural Mortality (M) Meta-analysis

Natural mortality (M) is assumed to be fixed in WCPO stock assessments for bigeye tuna and yellowfin tuna as it is generally believed to be poorly estimated for these species due to a lack of catch-at-age data and size composition modal progression information. Given the recent developments in both bigeye tuna and yellowfin tuna growth (Eveson et al., 2020; Farley et al., 2020), the existing assumptions around the mean level of M were revisited for both species. Both life-history theory (Hoenig, 1983; Jensen, 1996; Roff, 1984) and empirical relationships (Pauly, 1980; Then et al., 2015) derived from fitted regressions of M against explanatory covariates can inform plausible estimates of M. In this analysis, we used the meta-analytic framework applied by Piner and Lee (2011) in order to generate an envelope of plausible M values from 14 different M estimators (Table 1). For each M estimator, uncertainty was generated by considering a range of reasonable biological and environmental assumptions (Table 2). Estimates of M from each estimator were combined as a random effects inverse variance weighted mean according to the methods described in Borenstein et al. (2009).

For bigeye tuna, this analysis yielded an estimated quarterly M of 0.1275 (0.1090 – 0.1459; 95% confidence interval). For yellowfin tuna, this analysis yielded an estimated quarterly M of 0.1298 (0.1100 – 0.1495 ; 95% confidence interval). These values of natural mortality were used to define the mean values used for one of the axes in the structural uncertainty grid in the bigeye assessment, but there was no natural mortality axes in the yellowfin assessment.

5 Maturity and Spawning Potential

The maturity ogive used to define whether fish were juveniles or adults was reviewed and modified. The ogive used in the most recent assessment of these species used maturity at age. Subsequent developments in MFCL allow the specification of a maturity at length ogive, internally converted to age within MFCL based on the estimated growth curve. The maturity at age used in the previous assessment consisted of the product of fecundity at age, proportion mature at age, proportion female at age, and spawning fraction at age (Figures 7 to 10). The difference between the three growth curves in the yellowfin tuna assessment resulted in slightly different fits to the proportion male at length data from the natural mortality function described above, and thus there were three slightly different maturity at length ogives used in the yellowfin assessment. The two ogives used in the bigeye assessment were nearly identical. We investigated whether there were additional data available since the analyses performed in 2008 (Hoyle, 2008) for yellowfin and the assessment in 2017/2018 for bigeye (McKechnie et al., 2017a). However, there were no new biological samples for either of these species to update previous analyses of each of these components.

Given the new feature in MFCL and the updated growth curve for these species, we decided to use maturity at length for these assessments. The proportion female at length came from the fit to the data in the natural mortality analysis (Section 4). We noticed that the spawning fraction for both species came from an analysis of EPO yellowfin tuna. Since this was a different species (for the bigeye assessment) and outside the assessment region we decided that this component of the maturity ogive was inappropriate to include. Analysis of the currently available bigeye data for spawning fraction was conducted. However, the samples size was insufficient to adequately fit a curve. Therefore, the maturity ogives used in the current bigeye and yellowfin assessments were the product of the fecundity at length, proportion female at length, and proportion mature at length. Fecundity at length was divided by mean weight at length so that the fecundity measure was expressed on a 'per kg' basis. This was necessary because the computation of spawning potential within MFCL multiplies maturity-at-age by mean weight-at-age by population number-at-age. Expressing fecundity as a 'per kg' measure therefore avoided double counting the increase in fecundity due to increase in body weight alone.

In most stock assessments, important biological parameters such as the maturity ogive are updated in each assessment. However, the maturity ogive for yellowfin tuna has not been updated since 2008 due to a lack of new analyzed samples. Similarly, most components of the maturity ogive are from a single study with relatively few samples. Analysis of available gonad samples in the tissue bank database is needed to update the fecundity at length and proportion mature, and to validate the proportion female. A temporally continuous collection of biological samples for all of the main fish species across the entire WCPO is needed to provide valuable information to all the assessments. Additionally, these samples need to be analyzed by trained scientists and funding to conduct such analyses on a continuous basis is required. Specifically, studies of the spawning fraction of the four main tunas within the WCPO are required. However, these studies should not be seen as one-off projects, but should be incorporated into long-term collection of all forms of biological data, including length, weight, maturity, otoliths, fecundity, and conversion factors.

6 Construction of Tagging data files

Mark-recapture data can provide valuable information to an assessment if it is representative of the entire population. Tagging data can influence the estimation of fishing mortality, natural mortality and movement among regions within an integrated assessment model. The creation of the tagging files used in MFCL for the 2020 assessments of bigeye and yellowfin (hereafter referred to as .tag files) follow the general methods previously outlined in Berger et al. (2014); McKechnie et al. (2016, 2017b). The raw .tag files, which are produced based on the number of tags released and usable recaptures, underestimate the recapture rate of tagged fish. Many returned tags are unusable because they do not have a recapture date, location, gear, or cannot be attributed to a fishery because they are captured by a gear that is not included in the assessment. Additionally, the number of releases will generally be larger than the number of surviving tagged fish, either because of tagging induced mortality or tag shedding. If these factors are not accounted for, then the estimated fishing mortality in MFCL, based on this tag information, will be lower than the true population rate. Corrections to make the observed proportion of tag returns in the .tag file consistent with the actual recapture rate were conducted using the same methods as the previous assessment (McKechnie et al., 2017a; Tremblay-Boyer et al., 2017). The formulae and methods used are presented in detail in McKechnie et al. (2016) and we refer the readers to that report. The modifications to that approach are outlined in Section 6.2.

6.1 Tagging programs with data available

Mark-recapture information from four tagging programs were included in these assessments: the Regional Tuna Tagging Programme (RTTP; 1989-1992), Coral Sea Tagging Program (CSTP, sporadically over 1991-2001), Pacific Tuna Tagging Program (PTTP; 2006-present) and the Japanese Tagging Program (JPTP 2000-present). For model simplicity we modeled the CSTP tag events assuming the same reporting rates as the RTTP because some of the tagging events that were assigned as CSTP in the previous assessments were actually part of the RTTP. This also reduced the number of reporting rate parameters that needed to be estimated within MFCL.

Tag reporting rate penalties were calculated using the methods outlined in Peatman et al. (2020). The datasets were updated to include tag seeding data that have become available since the 2017 assessments. The assumption that the Japanese purse seine fishery have the same reporting rate as Chinese Taipei purse seine vessels was removed and empirical estimates from tag seeding were used in the reporting rate penalties.

6.2 Extraction of data and the correction of ‘unusable’ tags

To create the .tag file we conducted the following general procedure:

- A ‘raw’ .tag file from MFCL was produced using a software programme (MUFDAGER) written in FoxPro (Long, 1994) which only includes usable tag recaptures (those assignable to a fishery and recapture quarter).
- A program was created in the R statistical language (R Core Team, 2019) to replicate the ‘raw’ .tag file but also simultaneously extracts all recaptures (usable and unusable).
- Tags with a time at liberty less than one quarter or two quarters are assigned to the appropriate

recapture quarter.

- Tags that are recaptured within the release period but do not have a recapture location are assigned to the PS fishery in the release region.
- The usability ratio is calculated as the ratio of usable to total recaptures at the scale of the length bin within a tagging release event.
- The number of releases is then scaled down by the usability correction ratio and then further scaled by tag shedding rate (6.97%, Vincent et al., 2019b), base-tag-induced mortality (7%, assumed) and additional mortality from fish condition and tagger experience (Scutt Phillips et al., 2020) resulting in a set of 'effective tag releases'.
- All release events with less than 10 effective tag releases were excluded.
- All release events that occurred after the end of 2017 were excluded from the assessment to prevent biases from not including re-caught fish that were not reported or entered into the database at the time of the assessment (there is often a substantial lag between recapture and reporting, in one case 5 years).

6.3 Modifying mixing period

Tags can be very informative in stock assessments if they are representative of the overall population or region. However, due to the schooling behavior of tuna, fish that are tagged within the same school may not evenly distribute throughout the population quickly. Therefore, the tags that are captured shortly after release may not be representative of the population as a whole, but instead an indicator of whether that school happened to be found and caught. To account for this in an attempt to make the tag returns representative of the population, a mixing period is implemented within MFCL where the tag release groups are modeled by a separate fishing mortality that does not influence the overall population. This allows the model to accurately account for the number of tags that are removed from the release group in this time period but does not influence the fishing mortality estimate of the population. The diagnostic case models for bigeye and yellowfin assume two quarters of mixing period, wherein tags captured before the second quarter after release do not influence the population mortality rate.

Previous assessments created the .tag file based on the best estimate of release and recapture dates to assign the release and recapture period (quarter) within the model. However, this could result in tags that are released the day before the end of a quarter and recaptured a few days later in the next quarter being assigned to have a mixing period of 1. To ensure that an equal mixing period was applied to every tag released, tag recapture periods in the .tag file were adjusted. Individual tag returns were classified to a recapture quarter based on the time at liberty. For the tag file where the mixing period was assumed to be 1 quarter, if the time at liberty was less than 92 days (one quarter) the tag return was assigned to be recaptured in the quarter that the tag was released. For the .tag file where the mixing period was assumed to be 2 quarters, an additional adjustment was made for tags that had a time at liberty between 92 and 182 days to assign them to the quarter after release. Tags that were recaptured after the mixing period (either 91 days or 182 days) were not adjusted and were assigned to a quarter of recapture based on the recapture date. The need to ensure a uniform mixing period across all tag releases was noted in Vincent et al. (2019a) and at the pre-assessment workshop (Hamer and Pilling, 2020).

6.4 Reduction of usability correction and additional changes

Another change in the creation of the .tag file conducted for these assessments was to include any tag recaptures that occurred within the mixing period. The motivation behind this change in methodology was to reduce the amount of tags that were classified as 'unusable'. An implicit assumption in the usability correction is that the lack of useful information randomly occurs and is not due to a specific fleet or fishery. If tags reported by specific fisheries are generally lacking the information to be a usable tag, then estimates of fishing mortality can be biased by the usability correction. Generally, tags that can not be assigned to a recapture fishery (with missing recapture gear or recapture location) are excluded from the .tag file and used in the correction factor to calculate the effective releases. However, for the .tag files created for this assessment these tags that were not missing a recapture location in the database and had a time at liberty less than 183 days for a mixing period of 2 (less than 92 days for a mixing period of 1 quarter) were assigned to the purse seine in the release region. Since these tags do not influence the fishing mortality experienced by the total population before the mixing period, but are corrected for by the reporting rate, it was believed that that this change in methodology would be a more accurate modeling of the data.

Some minor changes have been implemented to the creation of the .tag files since the previous assessments. Firstly, tags from fish that were double tagged were excluded from the assessment because these fish could have a higher probability of return than the other tags. For the yellowfin .tag file, tags that had an unknown release condition were not included in the file. However, for bigeye there were a large number of tags from several release events in the CSTP that did not record the release condition of the fish and thus were retained in data file (this was not relevant for yellowfin as very few were tagged in these release events). Secondly, the correction factor for the 'tagger effect' model was changed to remove some of the high correlation between tagger and release school (Scutt Phillips et al., 2020). This new correction factor did not make much difference for the yellowfin .tag file but made more of an impact for bigeye. The tagger effect model used in the 2017 assessments had high co-variability between numerous levels such as tagger, tagging cradle, and tag school. This correction thus artificially reduced the number of releases in the bigeye model due to overestimating the impact of these levels due to a sparsity of data. The new methodology is more statistically defensible than previous models due to its parsimony and removal of highly correlated covariates. Finally, the new correction methodology combines the RTTP and PTTP database, whereas previously they were analyzed separately and no corrections were applied for bigeye in the RTTP due to a lack of data. To show the effect of the change caused by the new tagger effects correction model for bigeye, we created .tag files that updated the data and attempted to replicate the previous correction factor models conducted in 2016 (Figure 11, Berger et al., 2014)

While creating the R script to replicate the FoxPro software for the 'raw' tag returns we discovered some interesting issues in the SPC databases. For example, in the RTTP database there were numerous tags that were captured by longline that were given a flag of 'CH' (Switzerland). We decided that this was likely a data entry error and assumed that the intended country code was 'CN'(China) and assigned these tags to the appropriate fishery. Additionally, we found a tagging cruise that had been not previously been included in the bigeye assessment that had released tags that were captured on longline. These data could potentially provide information on movement of these large fish and it was therefore incorporated into the assessment as part of the RTTP. We attempted to get the most information possible from the tag databases by including as many tag recaptures as possible within the .tag file by looking at the comments for individual tag recoveries that were not assigned to a fishery. However, there were still many tags that did not have sufficient recapture information to assign to a fishery within the assessment model, and thus were included in the usability correction factor. Additional investigation of these tagging databases and the impact of including tags that are recaptured by gears not included within the assessment model is recommended.

6.5 Japanese Tag database

The same procedures for preparing the .tag file as outlined above were conducted for preparation of the Japanese tag data. The tag shedding and base tagging mortality rate were assumed to be the same as those estimated from the SPC tagging studies. For the purposes of correction for tagger effects, the median correction factor for all release groups was assumed. It should be noted that there are a moderate number of recaptures from this tagging program by small-scale fisheries that are not included in the assessment model. However, these were accounted for by the usability correction factor that was applied in the same manner as tags from the SPC databases.

6.6 Summary and comparison to 2017 tag files

The inclusion of the JPTP within the .tag file provided release and recapture information for region 1 which was only included in sensitivity models for the previous stock assessments. This amounted to an additional 3,938 and 10,551 effective releases for bigeye and yellowfin, respectively (Table 3). For the other programmes there were a number of differences in the construction of the tagging files that have led to different numbers of releases and recaptures when compared to the 2017 .tag files. Some changes such as inclusion of subsequent tagging cruise data, addition of extra usable tags where possible, and a reduction in the tagger effects correction ratio all lead to increases in the effective number of releases in the 2020 files. This is most noticeable for the PTTP data for bigeye where the increase in effective number of releases from 11,377 to 25,841 fish can mainly be attributed to a reduction in the tagger effects correction for these release events. Other changes such as the removal of double-tagged fish reduce release and recapture numbers but their impact is generally more than offset by the changes in the opposite direction.

The effective recapture rates for both species were very similar between the 2017 and 2020 files for the RTTP and PTTP programmes, while the rates for the CSTP was significantly lower in 2020, particularly for bigeye (Table 3). This can be attributed to the increased effective number of releases utilised in 2020. The effective recapture rates were substantially lower for the CSTP and JPTP programmes in comparison to the RTTP and PTTP, presumably partly due to most fish in these programmes being tagged in the temperate regions where fishing mortality is lower.

7 Length-weight relationship

Length-weight relationships in stock assessments are important for converting the numbers at age to biomass. Similarly, these conversion factors are ultimately used to convert the weight composition data to distributions of age via the growth curve. The length-weight relationships used in the bigeye and yellowfin stock assessments were reviewed and updated. It was discovered that the length-weight relationships used in the previous assessment came from estimates by Morita (1973). Therefore, this relationship was updated with data available in the SPC databases. Length and weight measurements from SPC's port sampling database were extracted and filtered for fish with length measured as upper jaw to fork in the tail (UF). We used records where weight was measured in either whole weight or gilled and gutted weight. The gilled and gutted weights were converted to whole weights using the conversion factors from Langley et al. (2006). The conversion for bigeye was

$$WW = 1.3264 * (GG + R - 0.5)^{0.969} \tag{1}$$

and the conversion for yellowfin was

$$WW = 1.189346 * (GG + R - 0.5)^{0.972009} \tag{2}$$

where WW is whole weight, GG is gilled gutted weight, and R is a random number from a uniform distribution between 0 and 1 which is added to prevent vacant bins from invalidating the calculations. The yellowfin database contained length-weight observations that may have been from imperial measurements (potentially in pounds and inches) that were clear outliers from the observed length-weight curve. Since we could not verify the units of these measurements, we excluded any observations that were above the line $y = -55 + 1.25 * x$ in the yellowfin data. For both species, we fit a length weight relationship using the TMB package in R (R Core Team, 2019). The estimated length-weight relationship for bigeye was $WW = 6.48e - 5 * L^{2.781}$ and fit to both the whole weight and gilled gutted weight reasonably well (Figures 16 and 17). For yellowfin the estimated length weight relationship was $WW = 2.01e - 5 * L^{2.986}$. The model fit the data well for both weight measurement types, athough for the largest individuals there was a tendency to overestimate the weight, but many of these points are potential outliers (Figures 18 and 19).

Similar to the lack of information regarding maturity, the analysis of length and weight highlighted the need for continued collection of biological information and some deficiencies in our current knowledge of these species. The length-weight relationship previously used was primarily from fish collected in temperate waters, whereas the current relationship came from fish collected from across the range of the species but primarily within the tropics. The difference in environment between tropical fish and temperate fish could potentially explain the difference between the previously used growth curve and the one used in the current assessment. It is important that biological information used within the assessments be representative of the entire stock that is being modeled. This requires that biological samples are collected in a spatially stratified manner across the entire WCPO to allow accurate analyses of these data. Continued biological sampling expanded to incorporate the entire WCPO is needed to provide accurate representation of the biology in the assessments. Additionally, such information could inform whether there are regional differences in growth, and whether there may be different populations within the overall stock.

In this analysis, we also discovered that the conversion factor used to transform the gilled gutted weights into whole weights is based on less than 100 fish. This is a relatively small sample size given the thousands of weight samples that are used within the assessment that are converted based on this relationship. This reinforces the importance of Project 90 and the collection of biological information that comes from a fishery independent source, to allow measurement of fish in various states (whole weight, gilled gutted, gilled gutted and truncated) to be used in conversion factors within the assessment.

8 Size Composition Data

The size composition used in these assessments for the 'longline ALL' and purse seine fisheries were re-weighted based on the catch. The methodology used to conduct this re-weighting are detailed in Peatman et al. (2020). Similarly, the index fisheries were provided with a size composition that were re-weighted by the spatial CPUE as estimated from the spatial-temporal model (geostats, Ducharme-Barth et al., 2020b). The re-weighted size composition data used in the assessment are shown in the bottom panels of Figures 20 to 101.

9 General Discussion

Very few changes were made to the fundamental fisheries structures used in the 2020 bigeye and yellowfin stock assessments. However, the adoption of the index fisheries approach did change how the data were input to the model and improved how MFCL was able to model the changes in CPUE of the longline fisheries and the size distributions of the underlying stock and the fish taken by these fisheries, in particular. The consequential changes in data summaries are displayed in the appendix plots. Other minor changes were made to several other fisheries and the further addition of data, notably size compositions, continues to occur for some of the previously data-poor fisheries.

Considerable work was conducted on the biological inputs to the assessments this year and while some of these are reported herein, others are presented in more detail in ancillary papers (e.g. Eveson et al., 2020; Farley et al., 2020). The developments were particularly noticeable for yellowfin due to the provision of a new set of otolith ageing data. As a result, investigation of different growth curves forms an important facet of the 2020 yellowfin assessment. This information also has consequences for other biological parameters in the assessment model, such as maturity and natural mortality at age or length. Consequently, this provided an opportune time to examine the appropriateness of data used to construct these ogives that have been input to most yellowfin and bigeye assessments over the last decade. This exercise highlighted a paucity of data in some cases, for example the relationship between length and spawning fraction, fecundity at length, the length-weight relationships, and also uncertainty in the sex ratio of fish caught across the length range. This is important information that informs the assessment model on many aspects of population dynamics that are directly related to stock status.

These analyses highlight a clear need for further investigation of these biological features of the bigeye and yellowfin stocks in the WCPO. Currently, the biological assumptions made for many of the important relationships in the assessments are based on relatively small samples sizes (e.g., whole weight to gilled gutted weight conversion, and fecundity relationships). Overall, the biological data available for these assessments is sparse compared to stock assessments for many other commercially important species. Furthermore, the vast spatial extent of these stocks creates issues in formulating biological inputs that are representative of the stock across its entire range, especially given that biological studies are often very spatially restricted. We strongly recommend developing a research plan (potentially as part of a wider tuna research plan; SPC-OFP, 2020) with the aim of continuing to improve the crucial biological inputs to the stock assessments, and our understanding of the biological dynamics of the stocks in general. This is particularly important for those ogives presented in this report that we have identified as based on limited data. This will require a coordinated programme of biological sampling and analysis across the WCPO, building on, and expanding, existing processes with the aim of reducing these key uncertainties in the assessment, and hence management advice.

The final aspect of this report outlined the construction of the tagging files input to MFCL and the calculations and filtering necessary to provide reliable data. The processes undertaken were generally similar to the previous assessments of these species (Tremblay-Boyer et al., 2017; Vincent et al., 2018). There were however revisions made to the data available, some of the correction factors applied (such as the tagger effects addressed in Scutt Phillips et al., 2020) and technical details in the usability corrections. These generally had limited effects on the resulting .tag files and the consequences of the changes are closely investigated in the stepwise model development and sensitivity analyses of the bigeye (Ducharme-Barth et al., 2020a) and yellowfin assessments (Vincent et al., 2020). However, ongoing review of the processes for preparing input tag data is recommended.

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10 Tables

Table 1: M estimators considered in the meta-analysis

Name	Reference	Type	Equation
Maximum age sample size	Hoenig (1983)	Maximum age theory	$M = \frac{\log(2N_{otolith}+1)}{\mathrm{T}_{max}-\mathrm{T}_{min}} - F$
Jensen K	Jensen (1996)	Life history theory	$M = 1.5K$
Jensen T_{mat}	Jensen (1996)	Life history theory	$M = \frac{1.65}{\mathrm{T}_{mat}}$
Jensen empirical	Jensen (1996)	Empirical	$M = 1.6K$
Roff	Roff (1984)	Life history theory	$M = \frac{3K}{e^{(\mathrm{T}_{mat}K)}-1}$
Revised Alverson and Carney	Zhang and Megrey (2006)	Life history theory	$M = \frac{3.6165K}{e^{(K(0.302\mathrm{T}_{max}-t_0))}-1}$
Pauly empirical	Pauly (1980)	Empirical	$M = e^{(-0.0152-0.279\log(L_\infty)+0.6543\log(K)+0.4634\log(C))}$
Empirical t_{mat}	Charnov and Berrigan (1990)	Empirical	$M = \frac{2}{\mathrm{T}_{mat}}$
One parameter T_{max}	Then et al. (2015)	Empirical	$M = \frac{5.109}{\mathrm{T}_{max}}$
Hoenig lm	Then et al. (2015)	Empirical	$M = e^{(1.717-1.01\log(\mathrm{T}_{max}))}$
Hoenig nls	Then et al. (2015)	Empirical	$M = 4.8998\mathrm{T}_{max}^{-}0.916$
One parameter K	Then et al. (2015)	Empirical	$M = 1.692K$
Two parameter K	Then et al. (2015)	Empirical	$M = 1.55K + 0.098$
Pauly nls	Then et al. (2015)	Empirical	$M = 4.118K^{0.73}L_\infty^{-0.33}$

Table 2: Life history and environmental parameters considered in the M meta-analysis for WCPO bigeye tuna

Factor	Reference	Bigeye Range	Yellowfin Range
K	Farley et al. (2020); Tremblay-Boyer et al. (2017)	0.339 to 0.386	0.349 to 0.562
L_∞	Eveson et al. (2020); Farley et al. (2020); Tremblay-Boyer et al. (2017)	151.1 to 161.1 cm	
t_0	Farley et al. (2020)	-0.466 to -0.410	0.409 to -0.244
T_{max} [(1)]	Farley et al. (2020)	12 to 16 years	12 to 16 years
T_{min} [(2)]	McKechnie et al. (2017a); Vincent et al. (2018); Tremblay-Boyer et al. (2017)	1.25 to 7.75 years	1.25 to 7.75 years
T_{mat} [(3)]	Farley et al. (2017); Itano (2000)	2.2 to 3 years	2.2 to 3 years
F [(4)]	McKechnie et al. (2017a); Vincent et al. (2018); Tremblay-Boyer et al. (2017)	0.2 to 1	0.2 to 1
$N_{otolith}$ [(5)]	Farley et al. (2020)	1277	1471
C [(6)]	Brill (1994)	11 to 30° C	20 to 30° C [(7)]

[(1)] Age of oldest individual from Farley et al. (2020) was 14.38 for bigeye tuna and 15.23 for yellowfin tuna

[(2)] The minimum age of full exploitation

[(3)] Age at 50% maturity

[(4)] Average annual F experienced

[(5)] Number of otoliths aged in Farley et al. (2020)

[(6)] Temperature in ° C experienced in the WCPO

[(7)] Includes range of possible oceanographic conditions experienced in the WCPO

Table 3: Summary of the tagging file used in the 2017 and 2020 diagnostic case models, showing the raw number of usable releases (Raw), the corrected effective number of releases (Eff), and the raw and effective recapture rates by tagging program (Prog). The values for 2017 are denoted in the headings and the rest of the columns relate to the 2020 .tag file.

Species	Prog	2017 Eff	2017 Rec	2017 Rate	Raw	Eff	Rec	Raw Rate	Eff Rate
BET	RTTP	2,938	622	0.21	3,304	2,732	592	0.18	0.22
	CSTP	3,571	340	0.10	4,292	3,976	443	0.10	0.11
	PTTP	11,377	5,382	0.47	41,298	25,841	7,776	0.19	0.30
	JPTP				5,048	3,938	445	0.09	0.11
YFT	RTTP	20,574	4,151	0.20	35,225	24,014	4,303	0.12	0.18
	CSTP	2,343	70	0.03	2,999	2,221	77	0.03	0.03
	PTTP	55,888	14,883	0.27	108,453	79,339	17,002	0.16	0.21
	JPTP				15,437	10,551	1,024	0.07	0.10

11 Figures

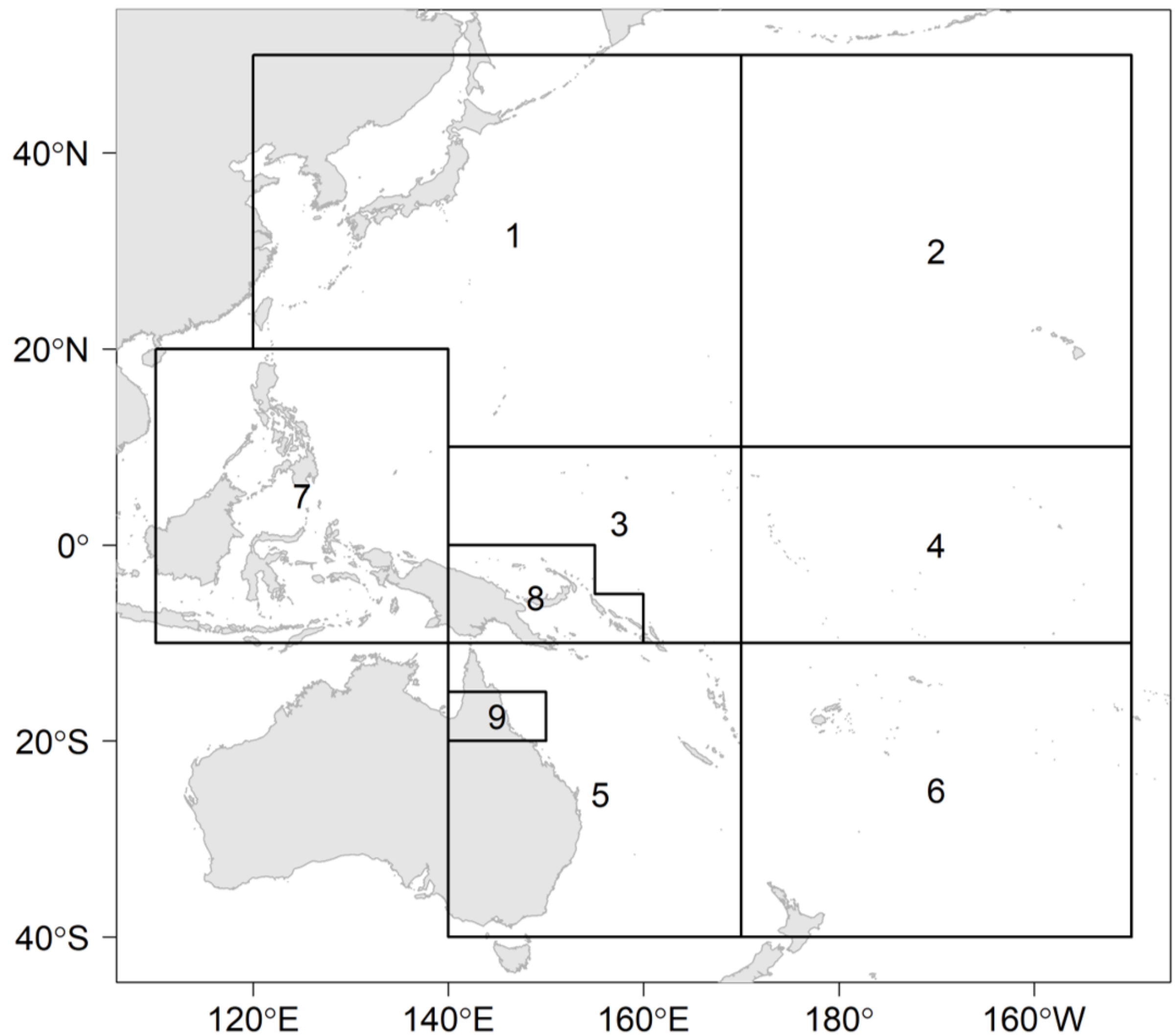

Figure 1: Regional boundaries used in the 2020 stock assessment of bigeye and yellowfin tuna.

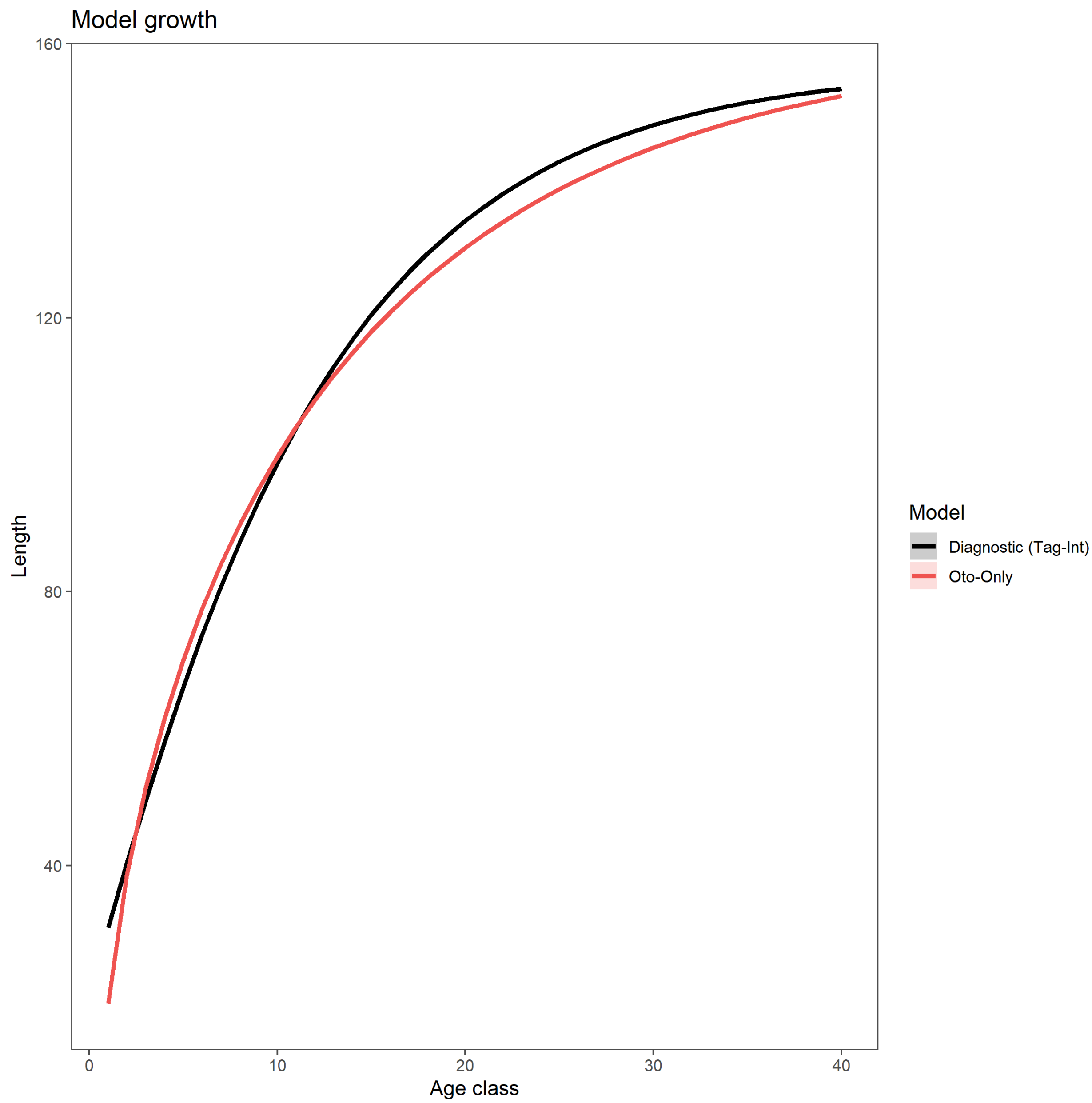

Figure 2: Richards growth curves used in the 2020 bigeye stock assessment estimated for otolith data only (Oto-Only) and from tag and otolith data (Tag-Int).

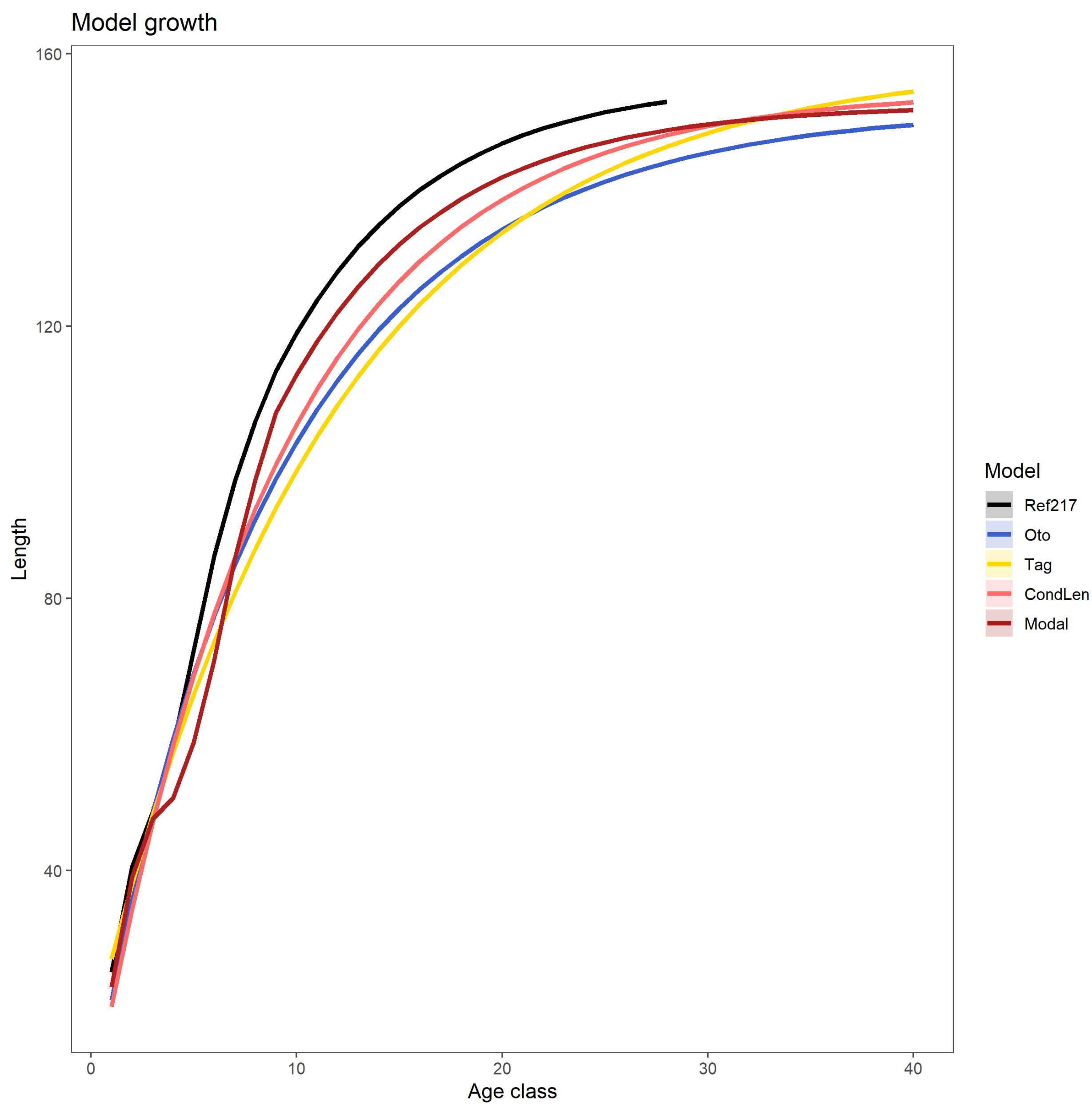

Figure 3: Five growth curves considered in the 2020 yellowfin stock assessment, where Oto is the Richards growth curve estimated from only otolith data, Tag is the von Bertalanffy growth curve from the otolith and tag data, CondLen is the conditional age at length withing MFCL, Modal is the growth estimate internal to MFCL without the inclusion of otolith data, and Ref2017 is the estimate from the 2017 diagnostic model.

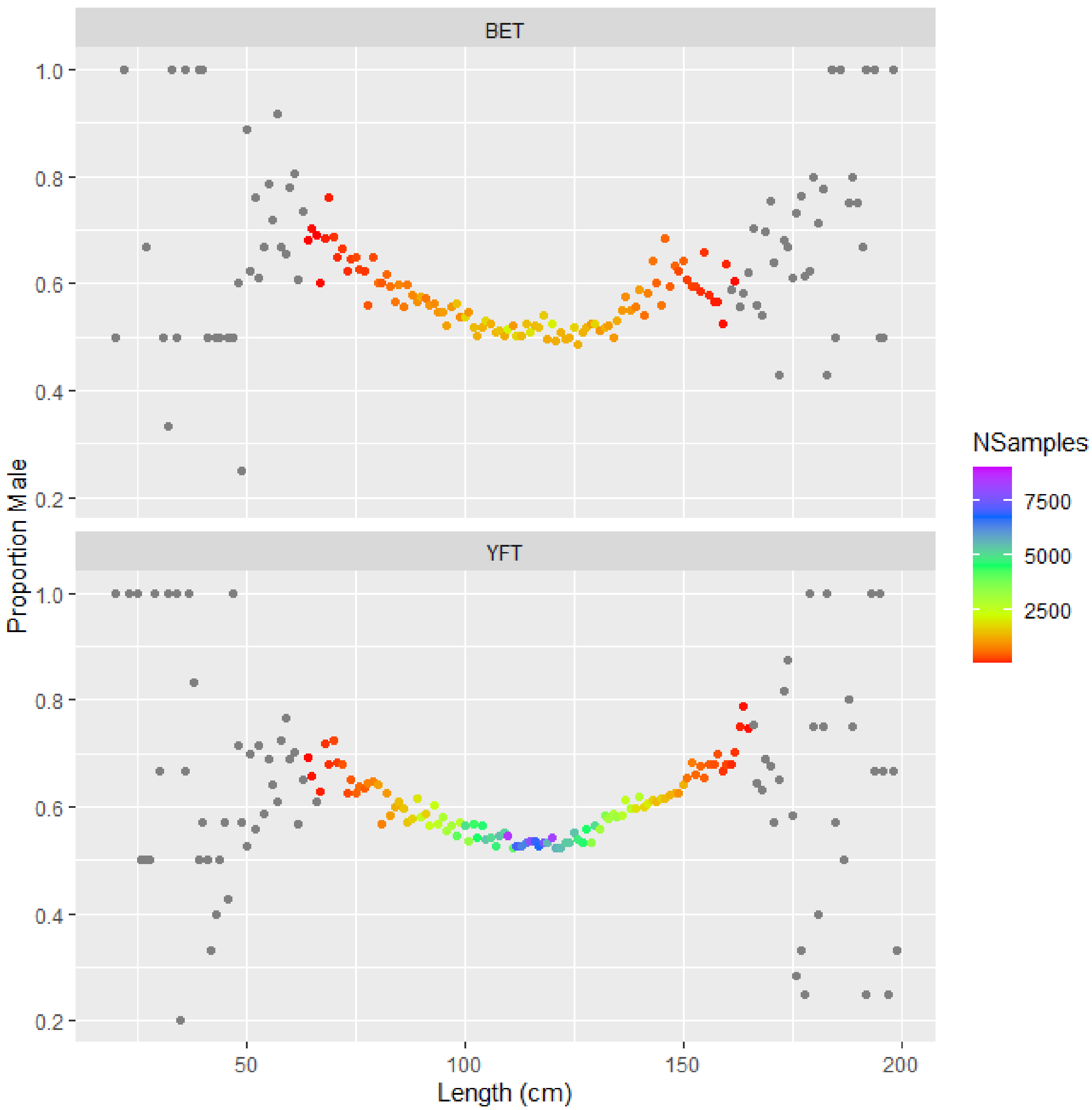

Figure 4: The proportion of fish that are male by length for bigeye (BET) and yellowfin (YFT) from longline observers in the WCPO, where the color of the point indicates the sample size and lengths with less than 100 samples are colored grey.

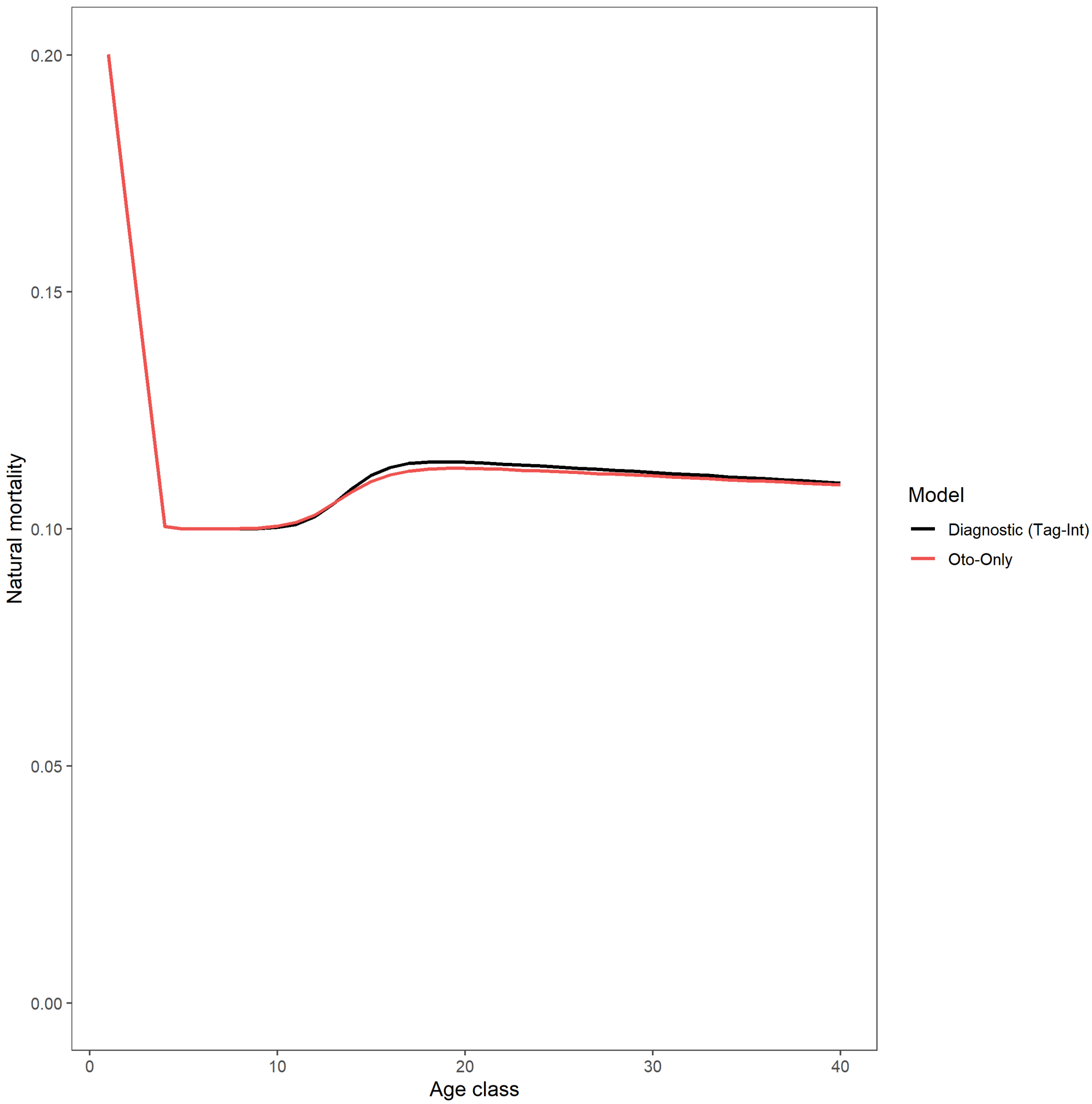

Figure 5: Natural mortality at age estimates used in the 2020 BET stock assessment based on models fitted to data on the proportion male at length using different growth curves. Oto-Only is M from the otolith only Richards growth curve, and Tag-Int is M from the integrated tag-otolith Richards growth curve.

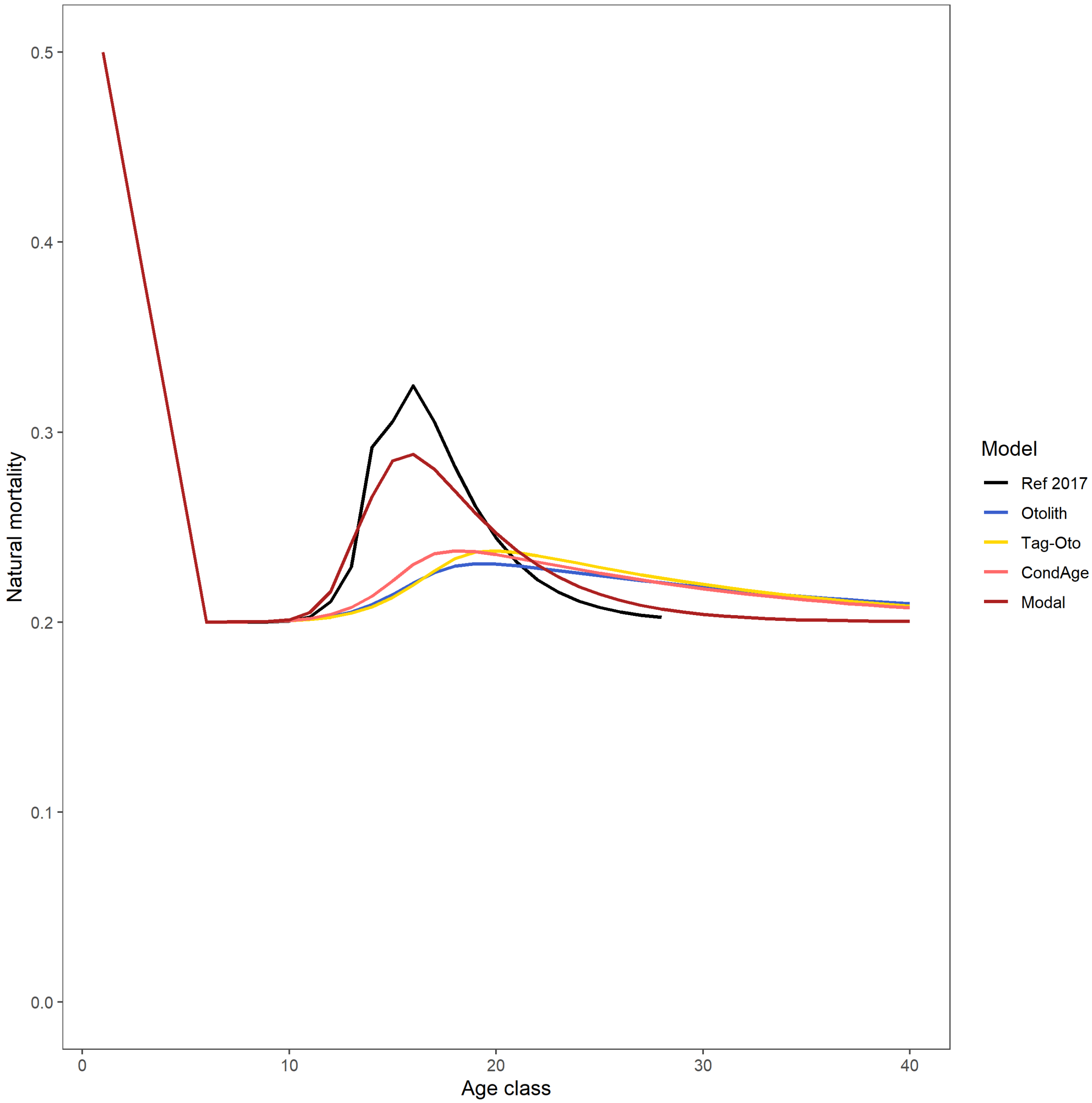

Figure 6: Natural mortality at age estimates used in the 2020 YFT stock assessment based on models fitted to data on the proportion male at length using different growth curves. Ref 2017 is M used in the 2017 assessment, Oto is M from the otolith only Richards growth curve, Tag-Oto is M from the integrated tag-otolith von Bertalanffy growth curve, CondAge is M from the conditional age at length diagnostic model, and Modal is the growth estimate from the modal progressions in the size composition.

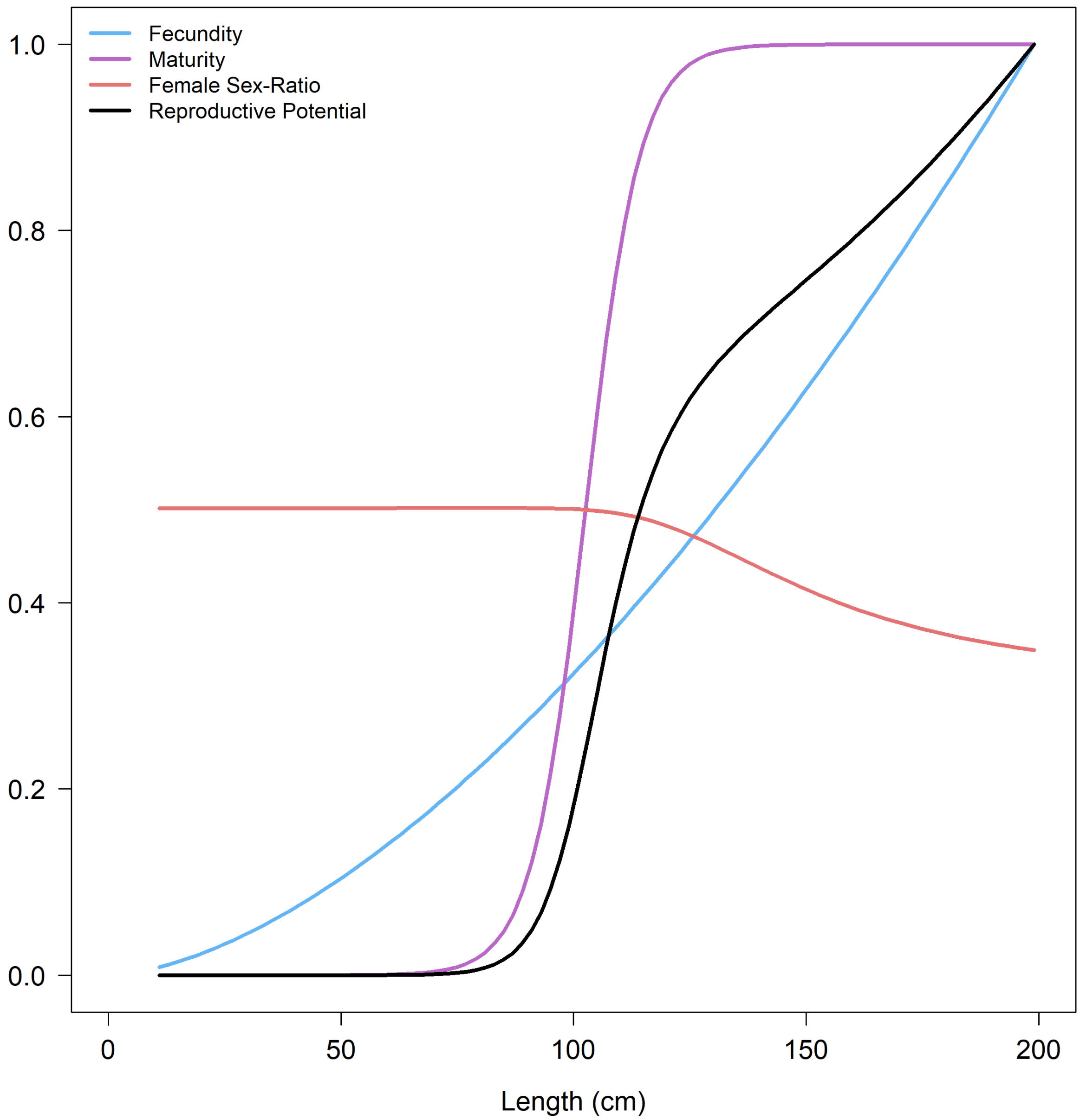

Figure 7: Reproductive potential and multiplicative components used in the 2020 assessment of BET for the tag integrated growth curve and the otolith only growth curve was nearly identical.

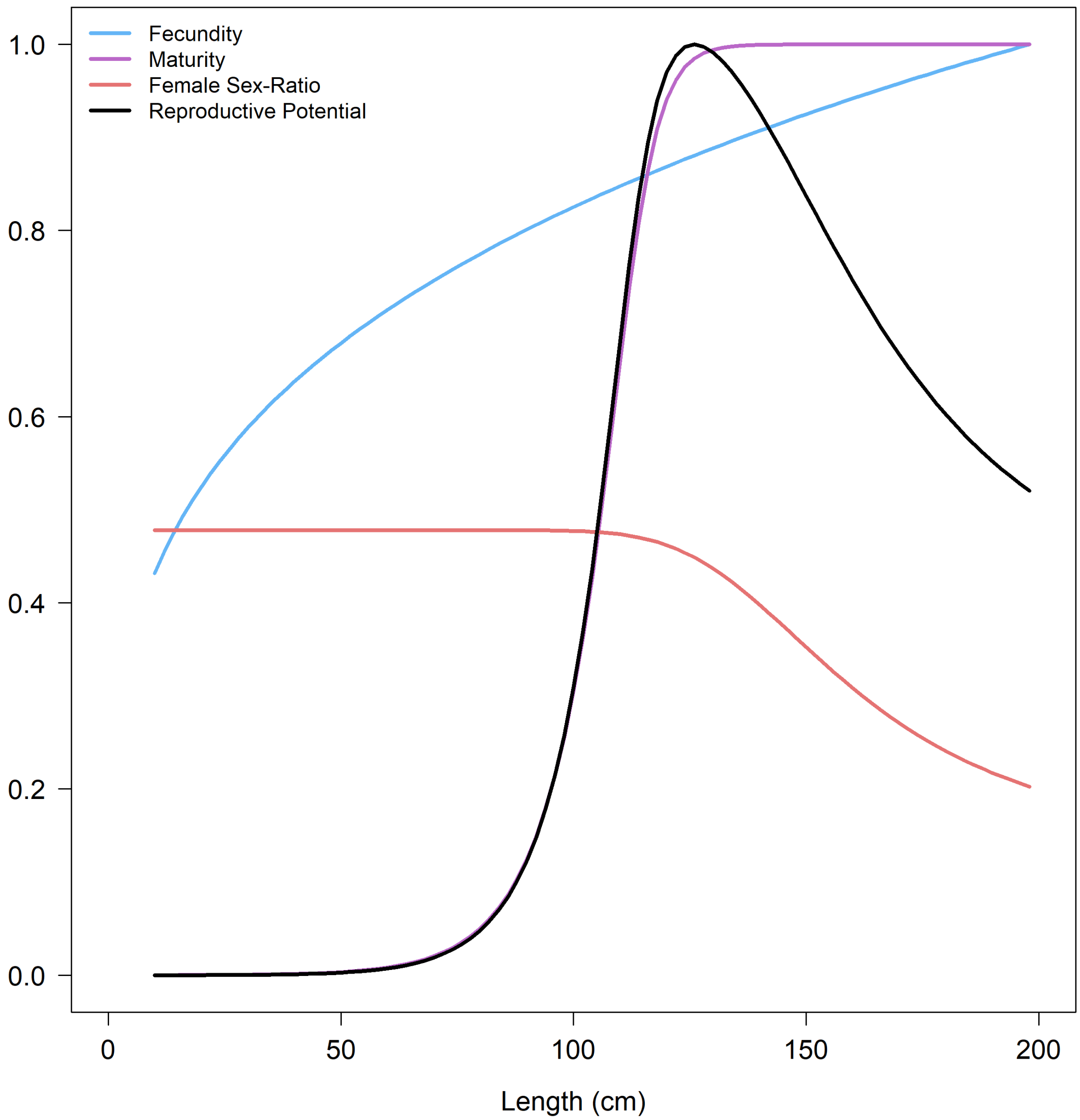

Figure 8: Reproductive potential and multiplicative components used in the 2020 assessment of YFT from the otolith only Richards growth curve.

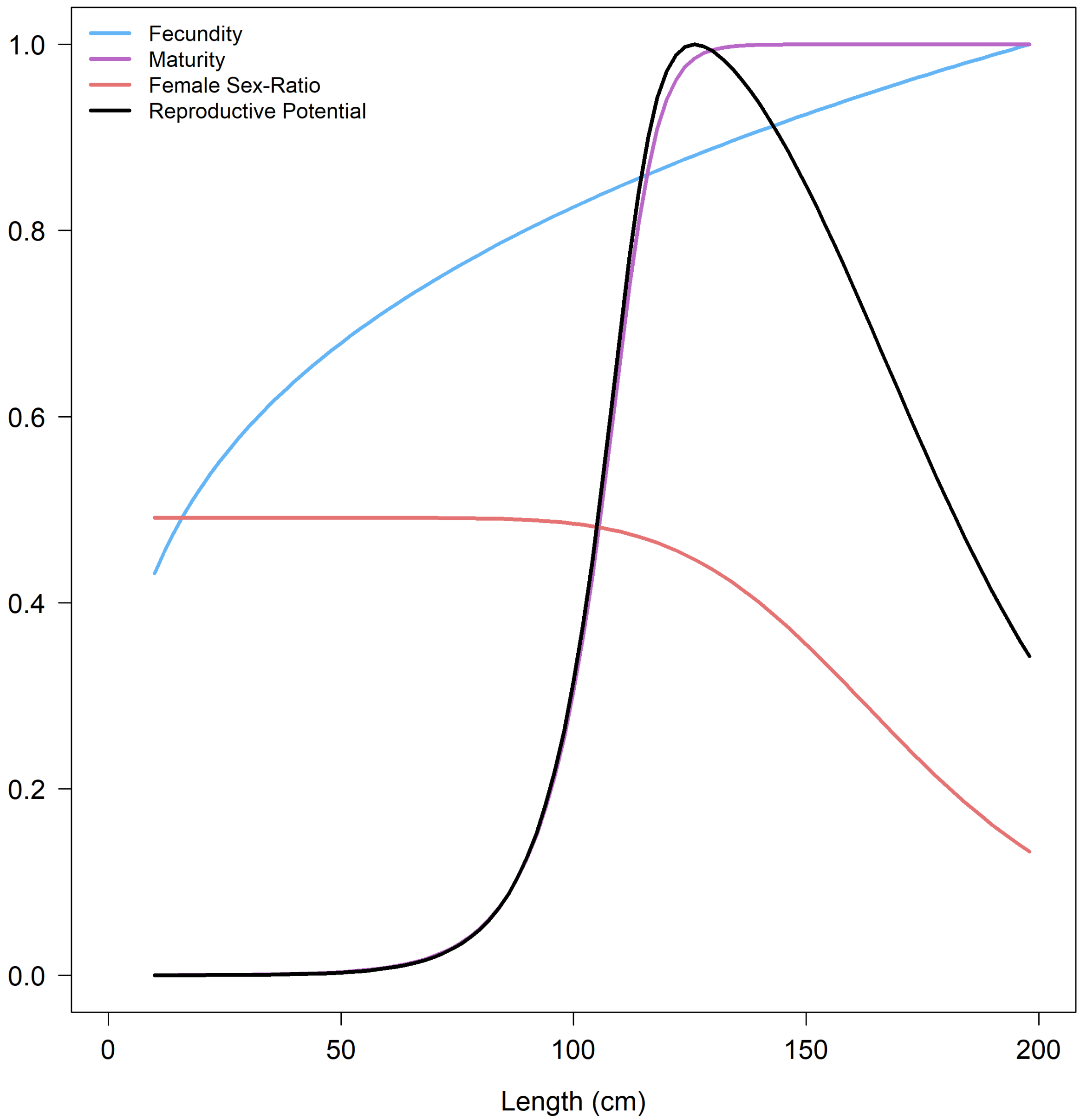

Figure 9: Reproductive potential and multiplicative components used in the 2020 assessment of YFT for the growth curve estimated from the modal progression in the size composition data.

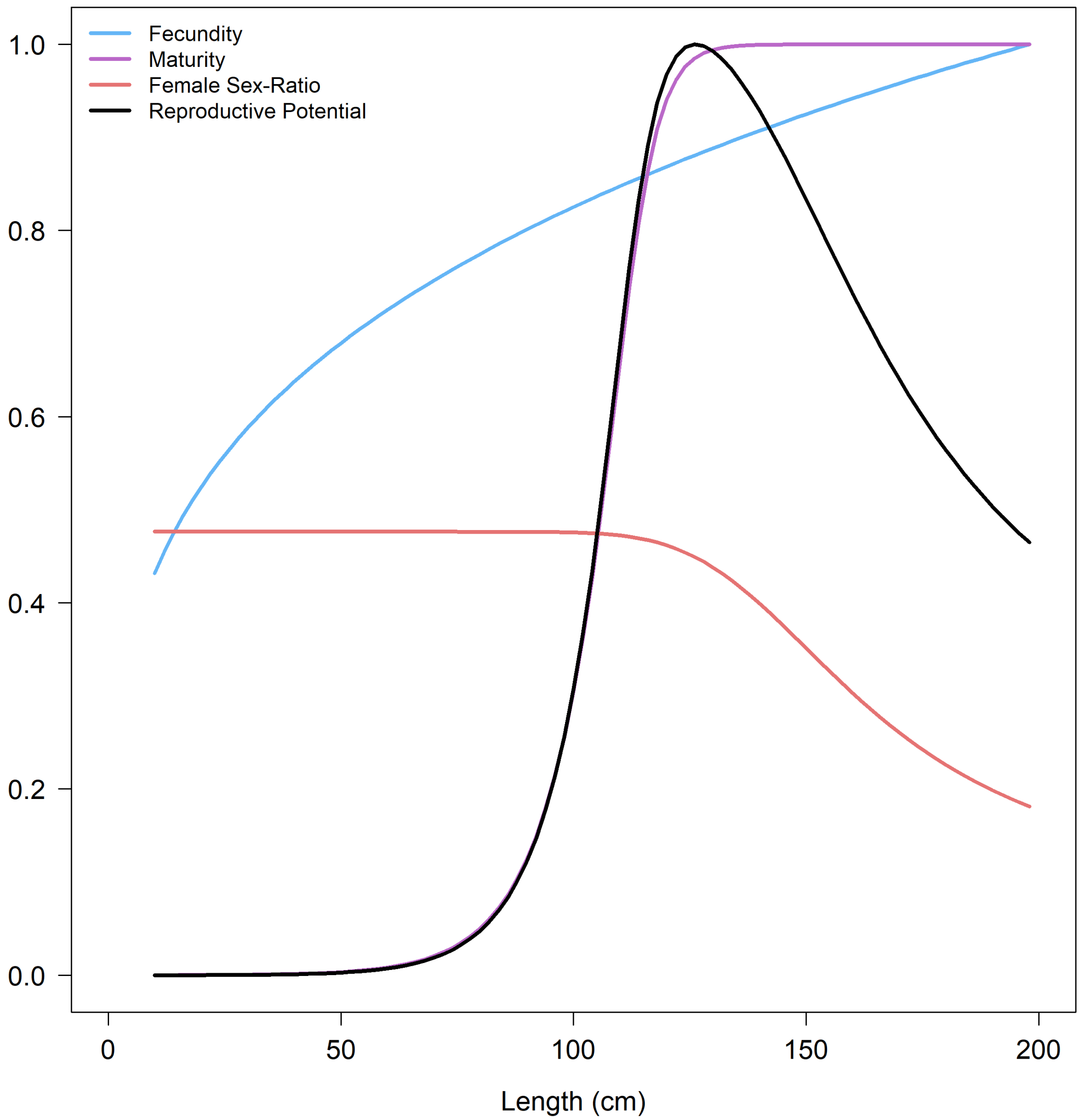

Figure 10: Reproductive potential and multiplicative components used in the 2020 assessment of YFT from the growth curve estimated by the conditional age-at-length diagnostic model.

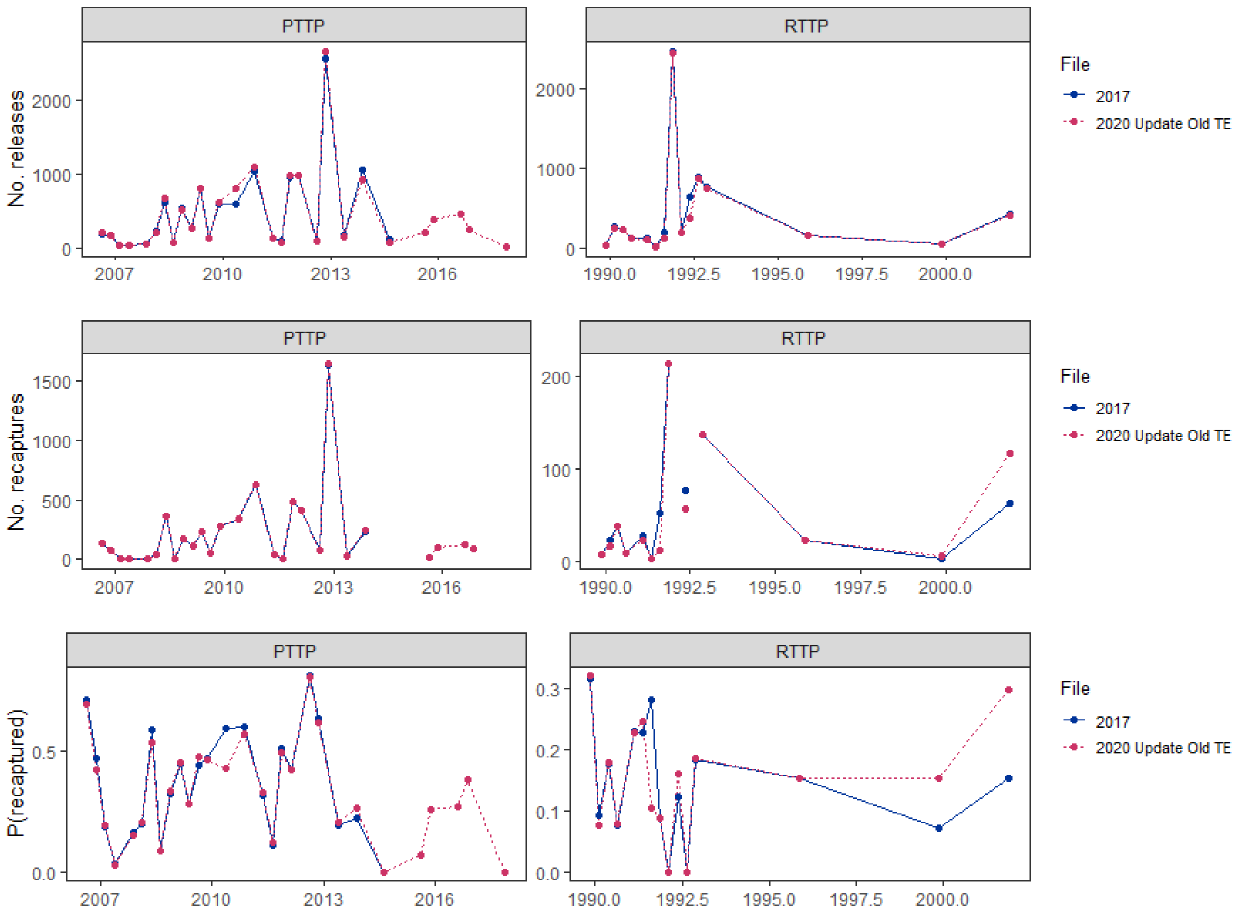

Figure 11: Comparison of the number of tag releases, recaptures and proportion recaptured for the RTTP and PTTP programmes between the 2017 and 2020 bigeye tag files. Note that 2017 tagger effects methods were used to allow a 'like for like' comparison of the files.

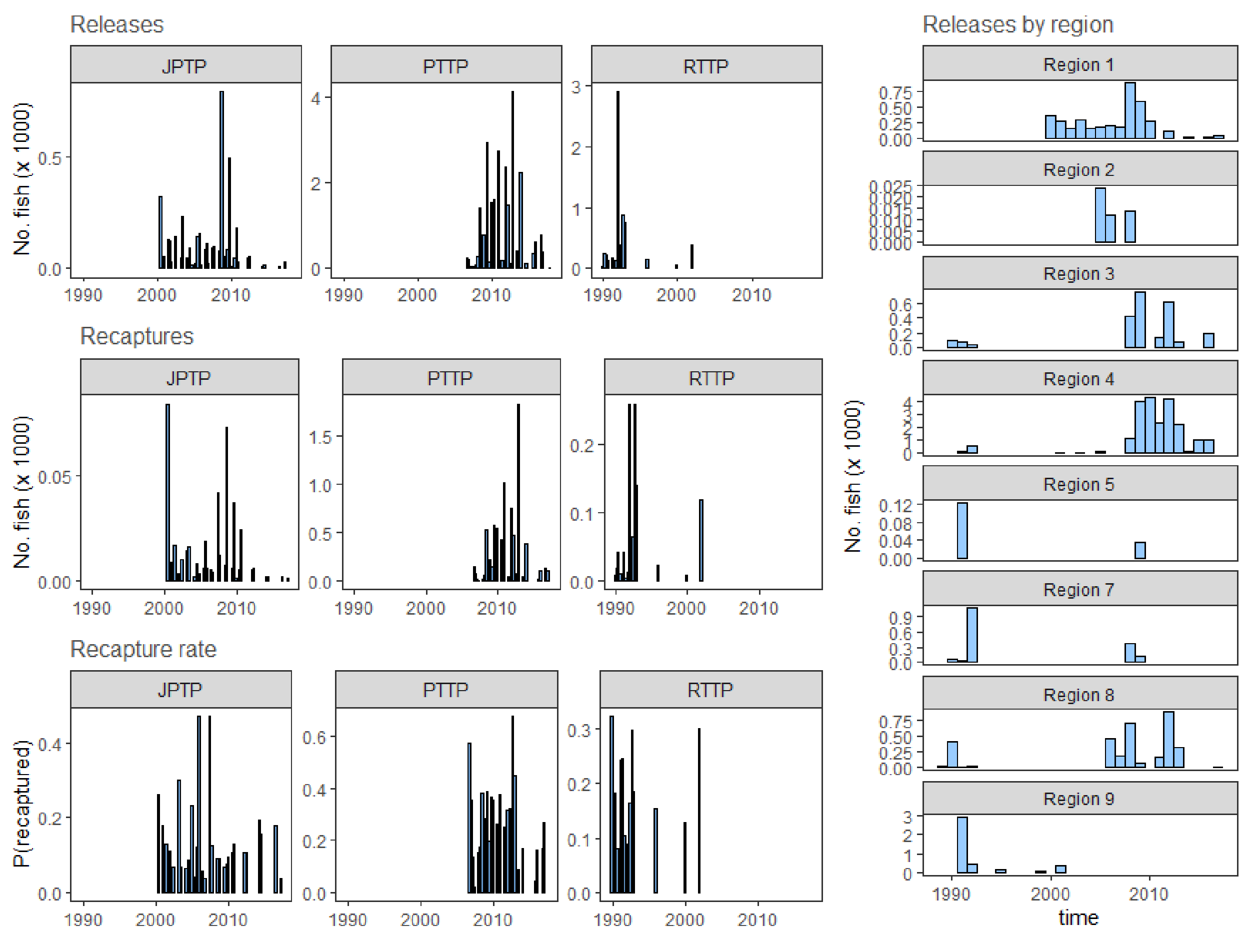

Figure 12: Comparison of the number of tag releases, recaptures and proportion recaptured for the JPTP, RTTP and PTTP programmes for the 2020 bigeye tag file, with the number of releases separated into regions in the right panel.

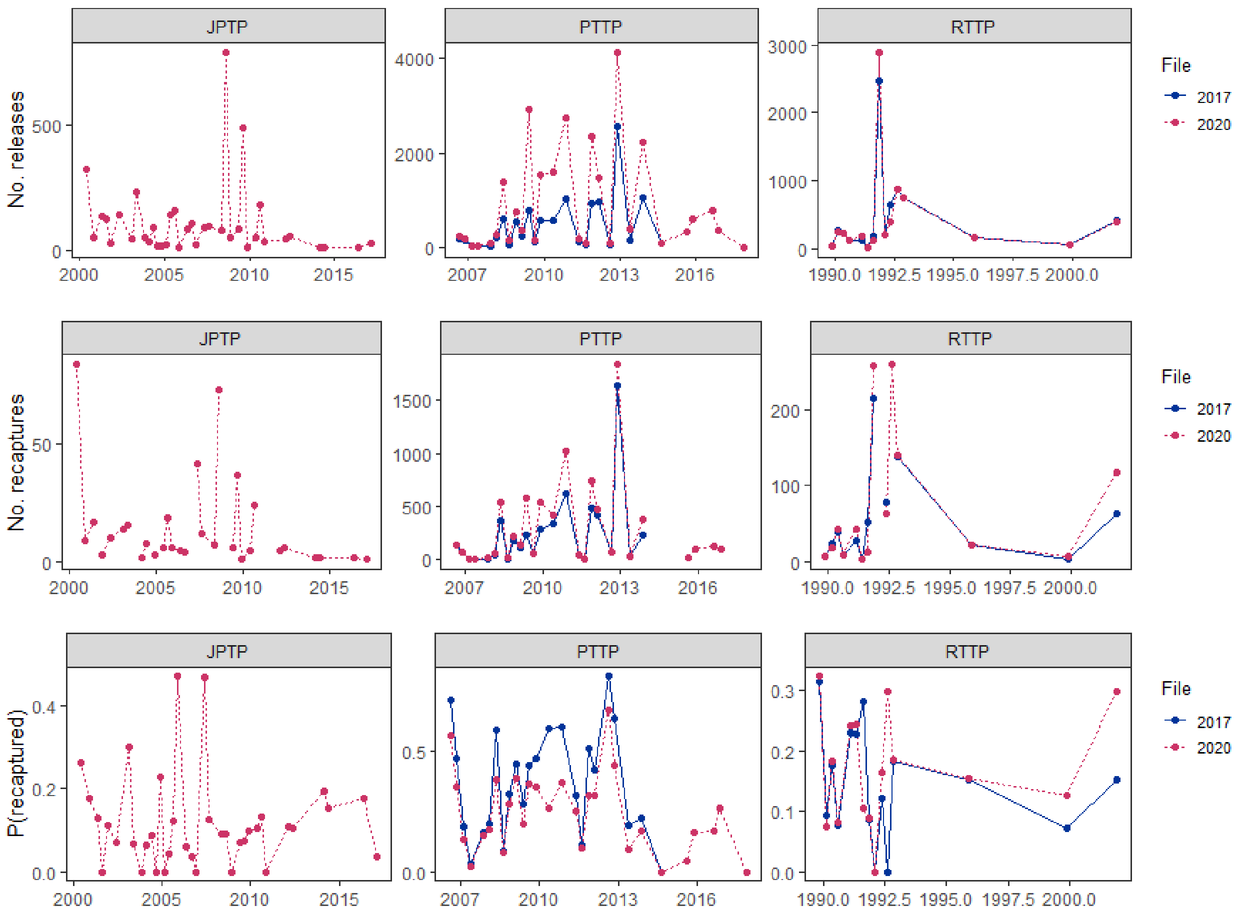

Figure 13: Comparison of the number of tag releases, recaptures and proportion recaptured for the RTTP and PTTP programmes between the 2017 and 2020 bigeye tag files. Note that this is the same as Figure 11 except that the 2020 tagger effects correction ratios were used for the 2020 file, so that the final differences between files are shown.

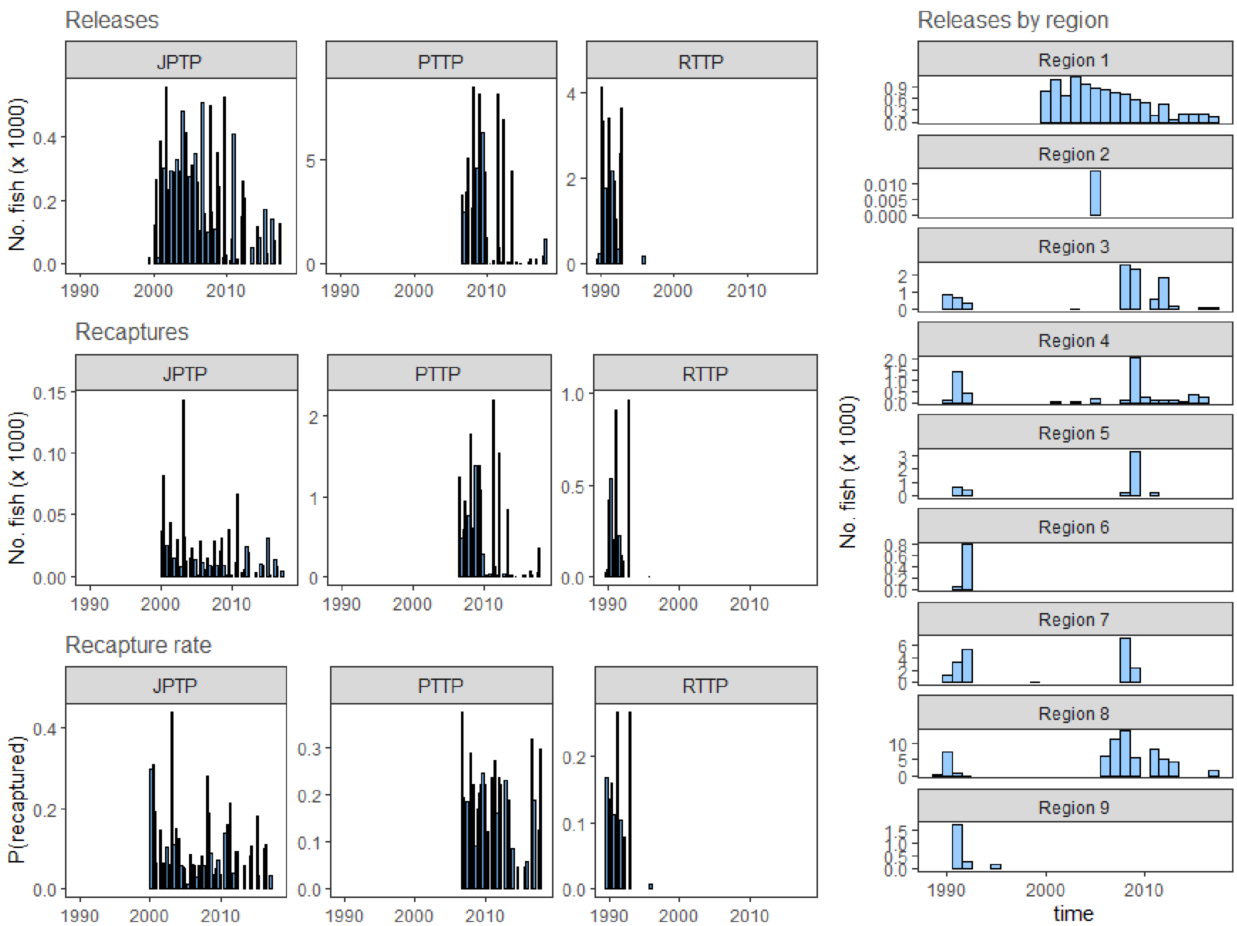

Figure 14: Comparison of the number of tag releases, recaptures and proportion recaptured for the JPTP, RTTP and PTTP programmes for the 2020 yellowfin tag file, with the number of releases separated into regions in the right panel.

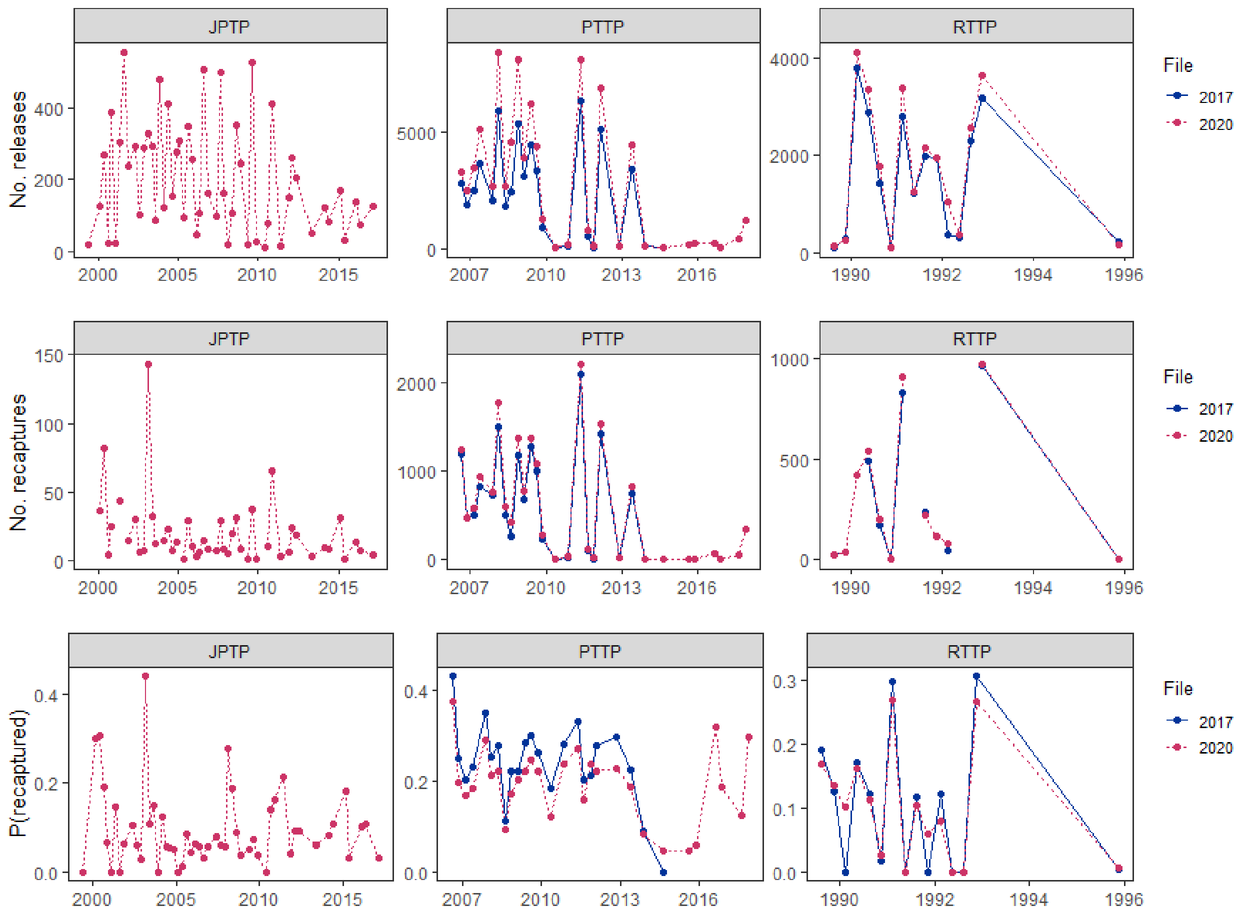

Figure 15: Comparison of the number of tag releases, recaptures and proportion recaptured for the RTTP and PTTP programmes between the 2017 and 2020 yellowfin tag files. Note that the 2020 tagger effects correction ratios were used on the 2020 file, so that the final differences between files are shown.

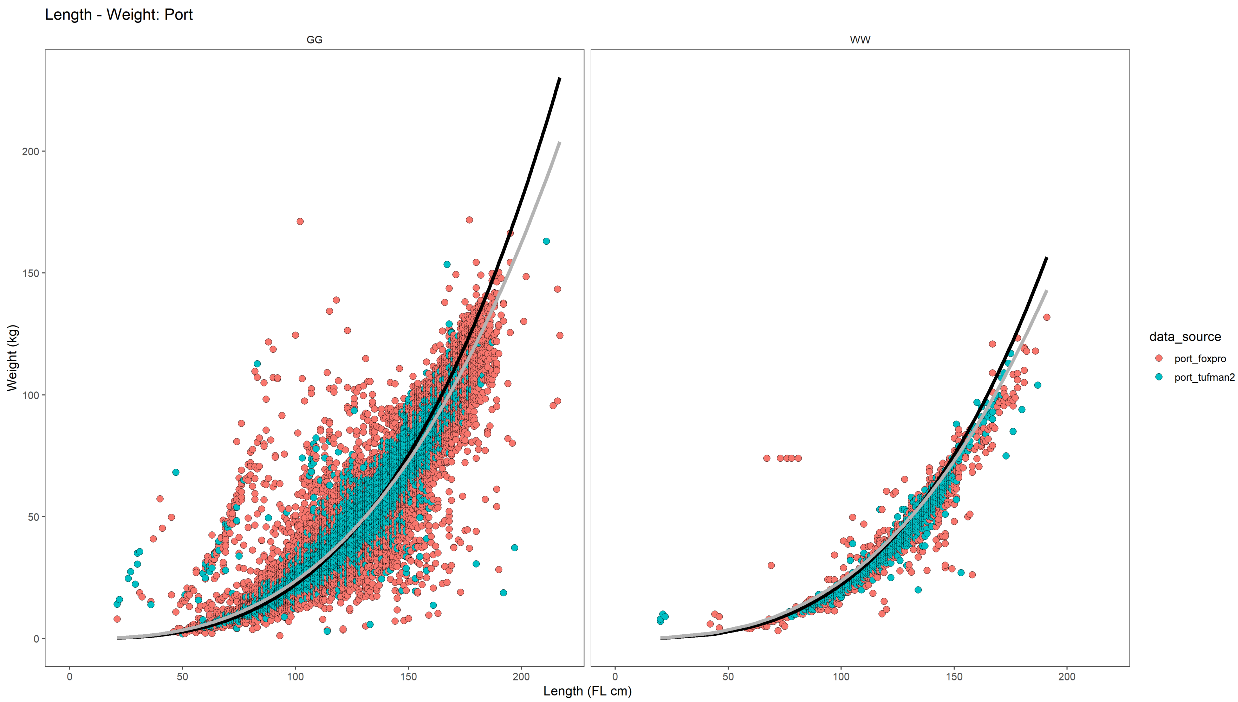

Figure 16: Length-weight relationships for bigeye used in the 2020 stock assessment. The red and green points represent samples of fish from two data bases (foxpro and tufman) representing years of sampling and the black line represents the model fit to all the data combined. The grey line represents the length-weight relationship used in the 2017 stock assessment. The two panels show the relationships for gilled and gutted (GG) and whole weight (WW) samples.

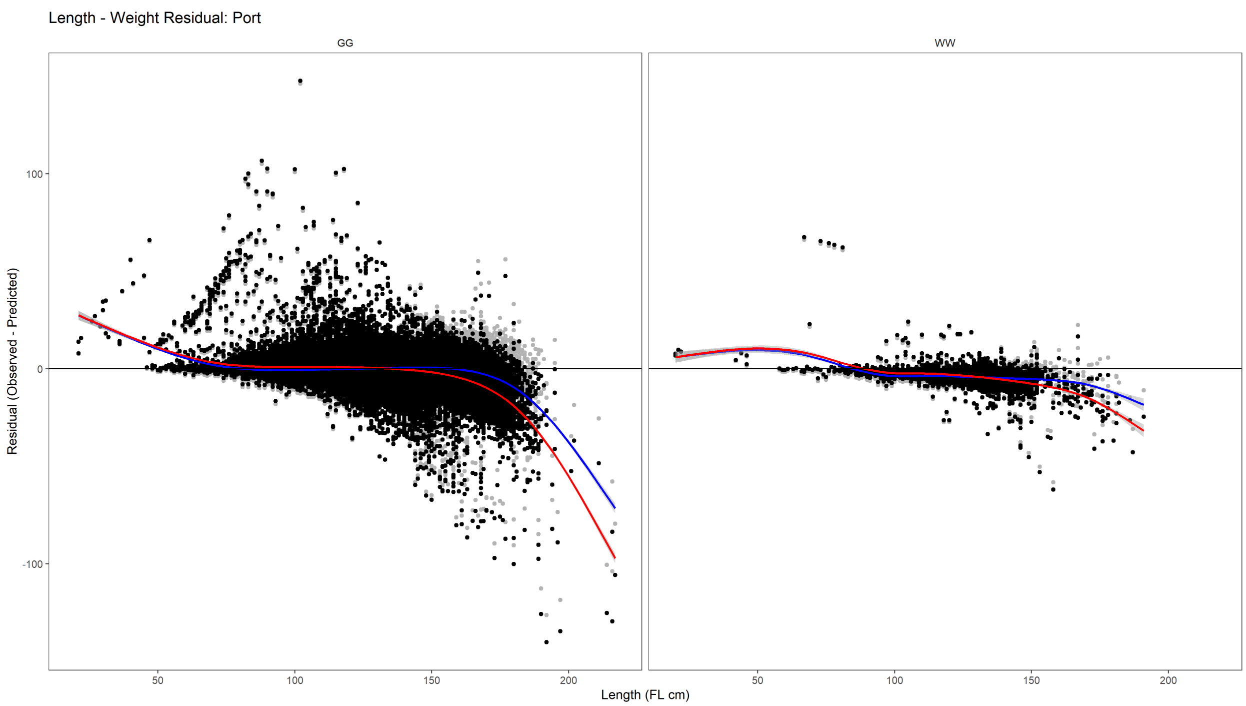

Figure 17: Residual plots for the data and models shown in Figure 16. The black and grey points represent the foxpro and tufman data respectively and the red and blue lines show the fit of a smoother through these two sets of residuals, respectively.

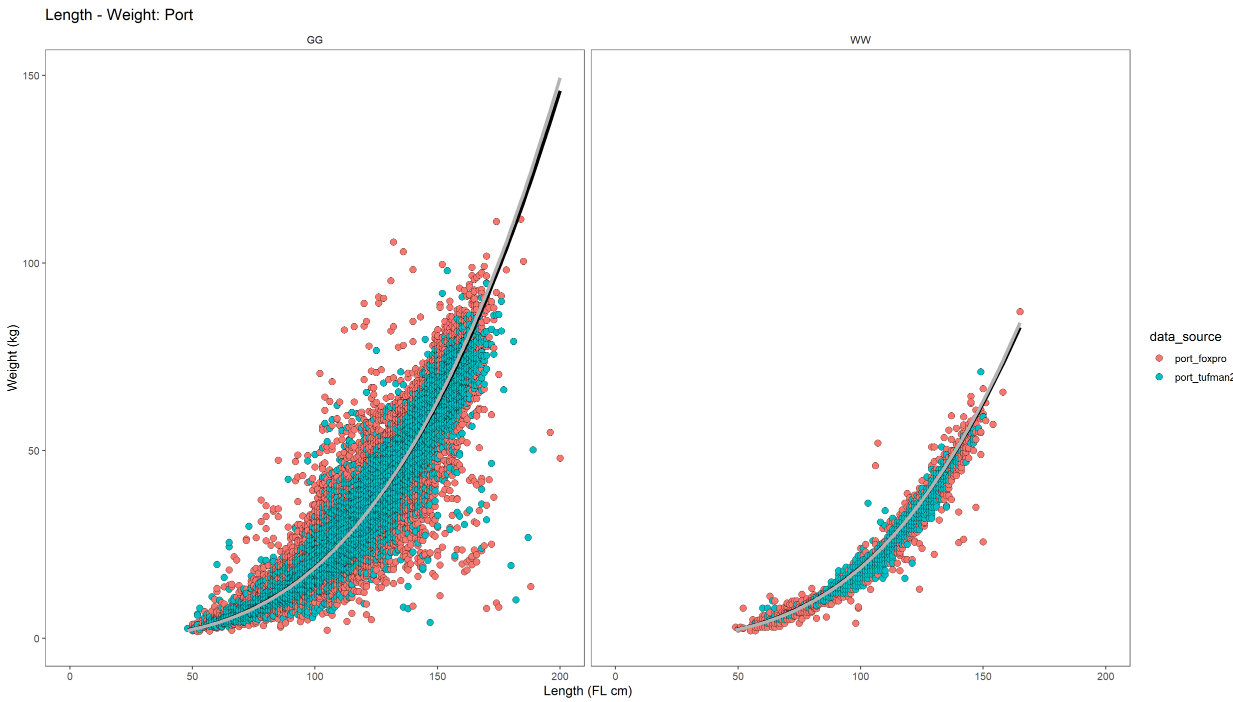

Figure 18: Length-weight relationships for yellowfin used in the 2020 stock assessment. The red and green points represent samples of fish from two data bases (foxpro and tufman) representing years of sampling and the black line represents the model fit to all the data combined. The grey line represents the length-weight relationship used in the 2017 stock assessment. The two panels show the relationships for gilled and gutted (GG) and whole weight (WW) samples.

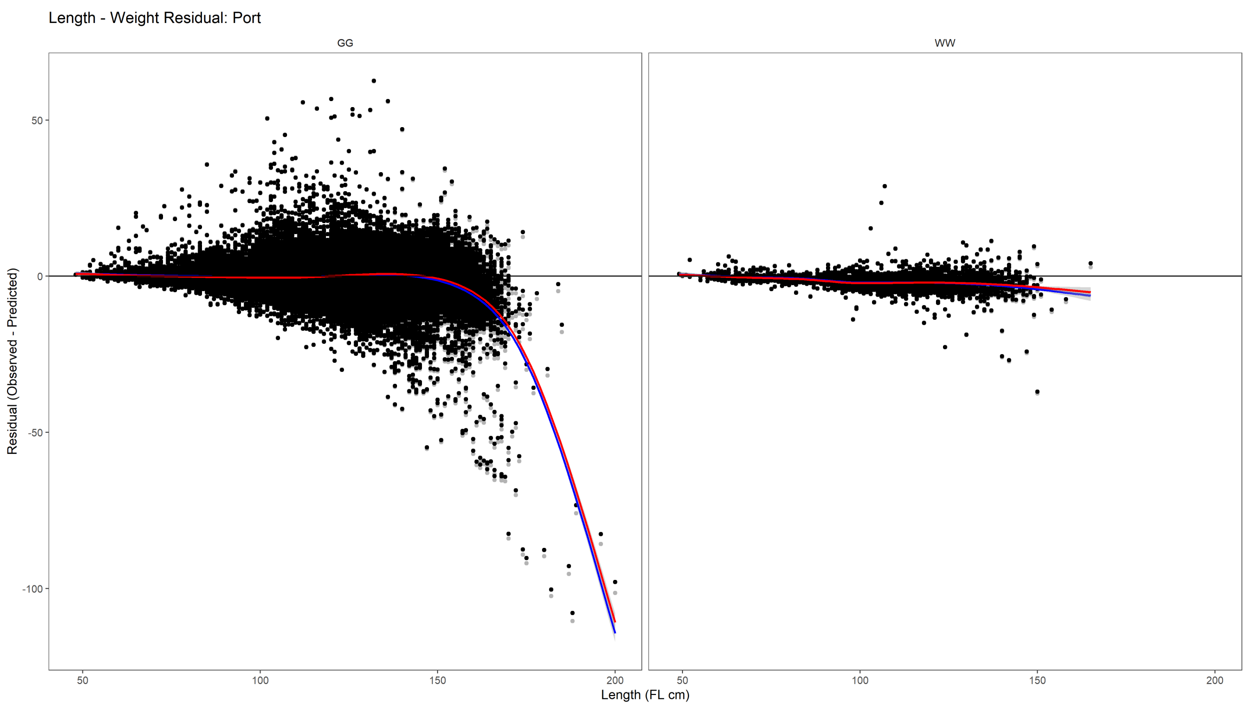

Figure 19: Residual plots for the data and models shown in Figure 18. The black and grey points represent the foxpro and tufman data respectively and the red and blue lines show the fit of a smoother through these two sets of residuals, respectively.

12 Appendix

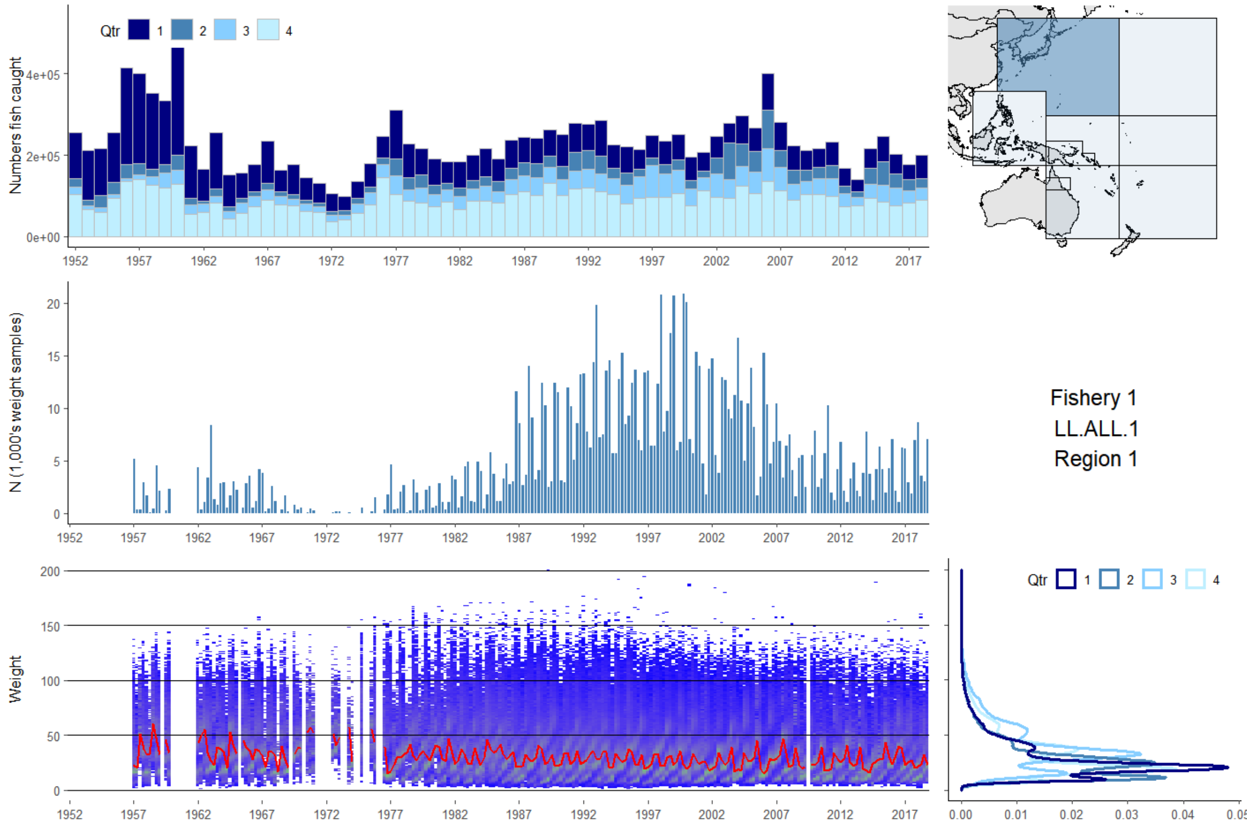

Figure 20: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 1.

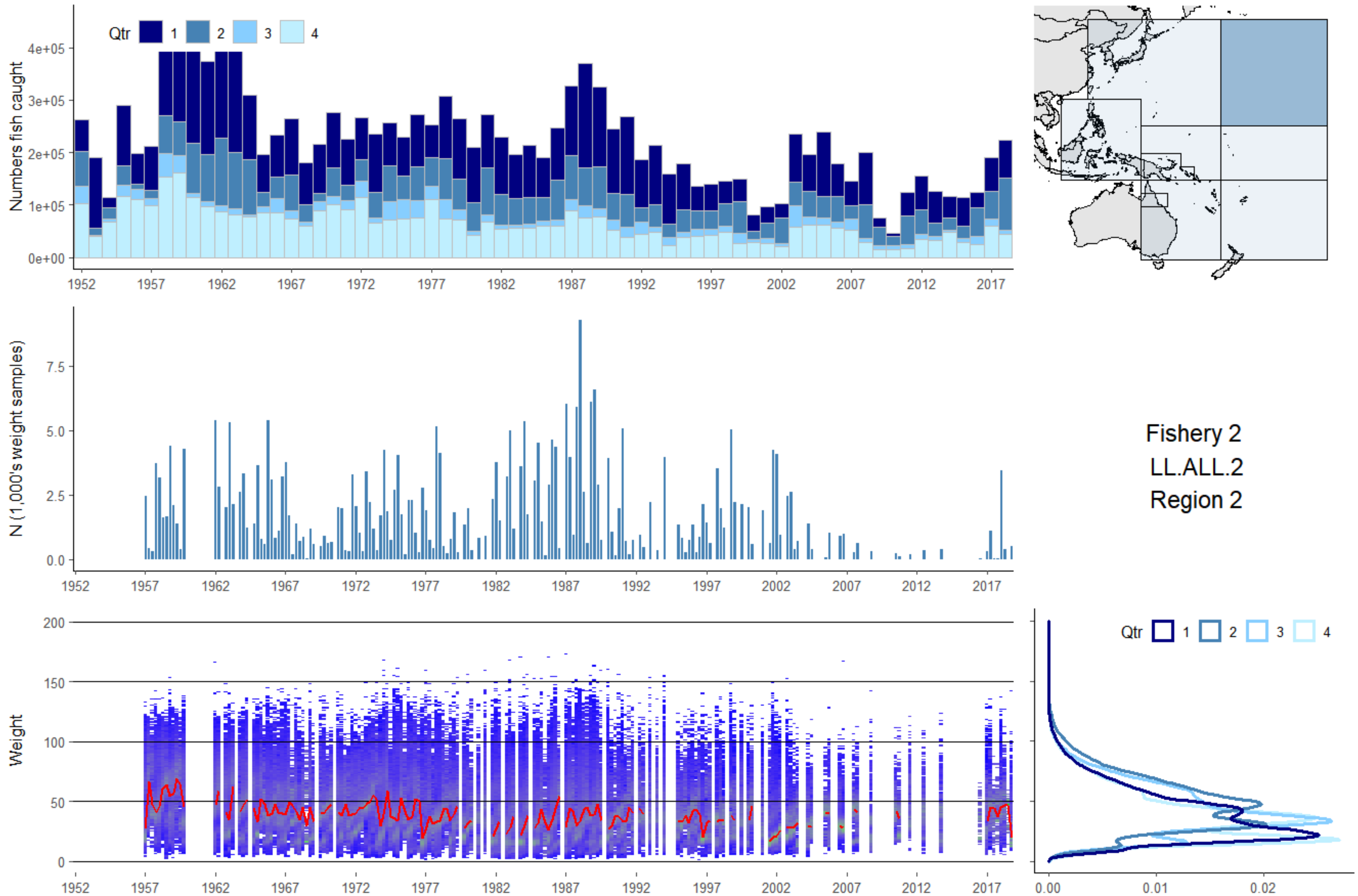

Figure 21: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 2.

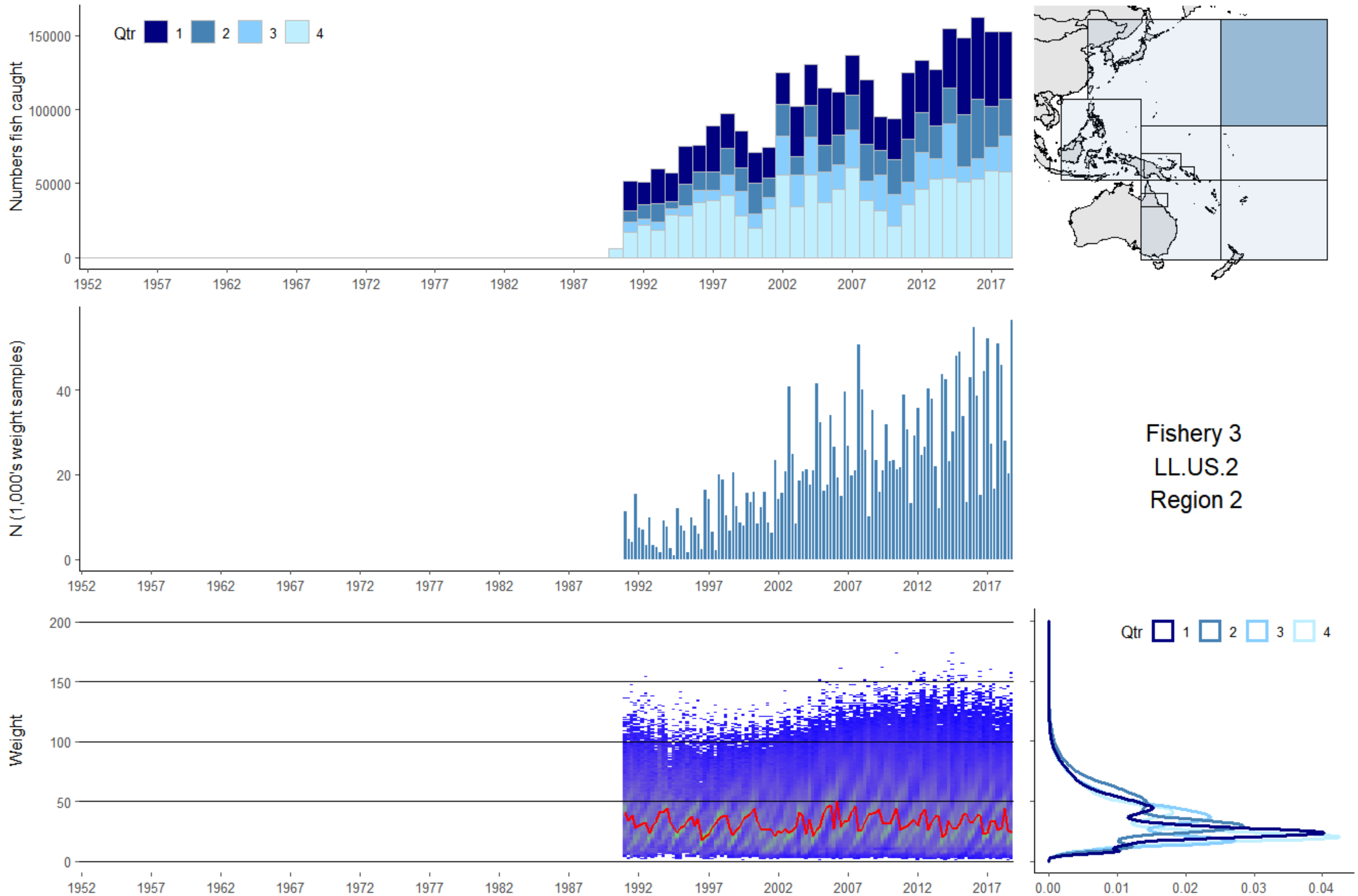

Figure 22: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 3.

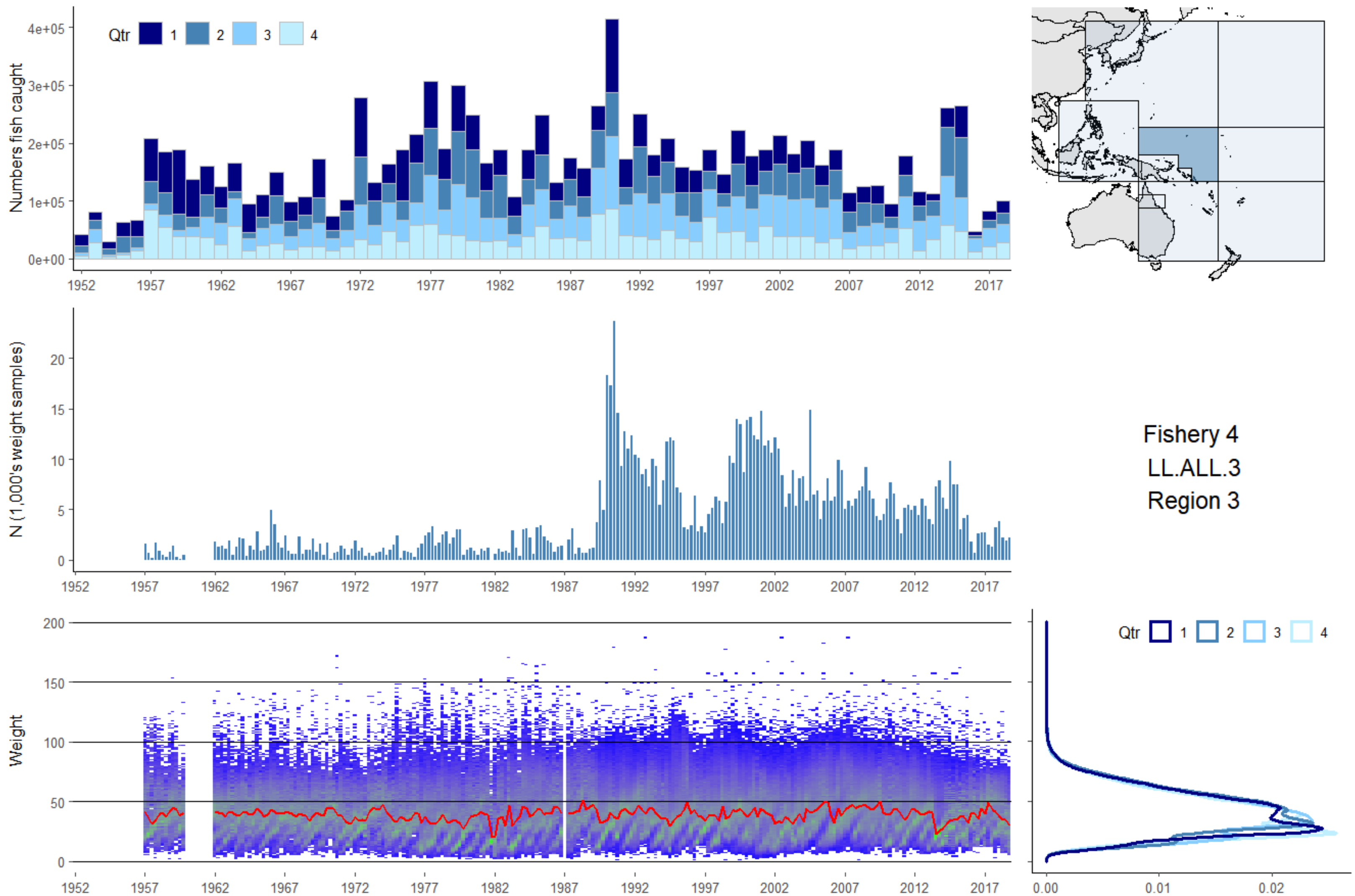

Figure 23: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 4.

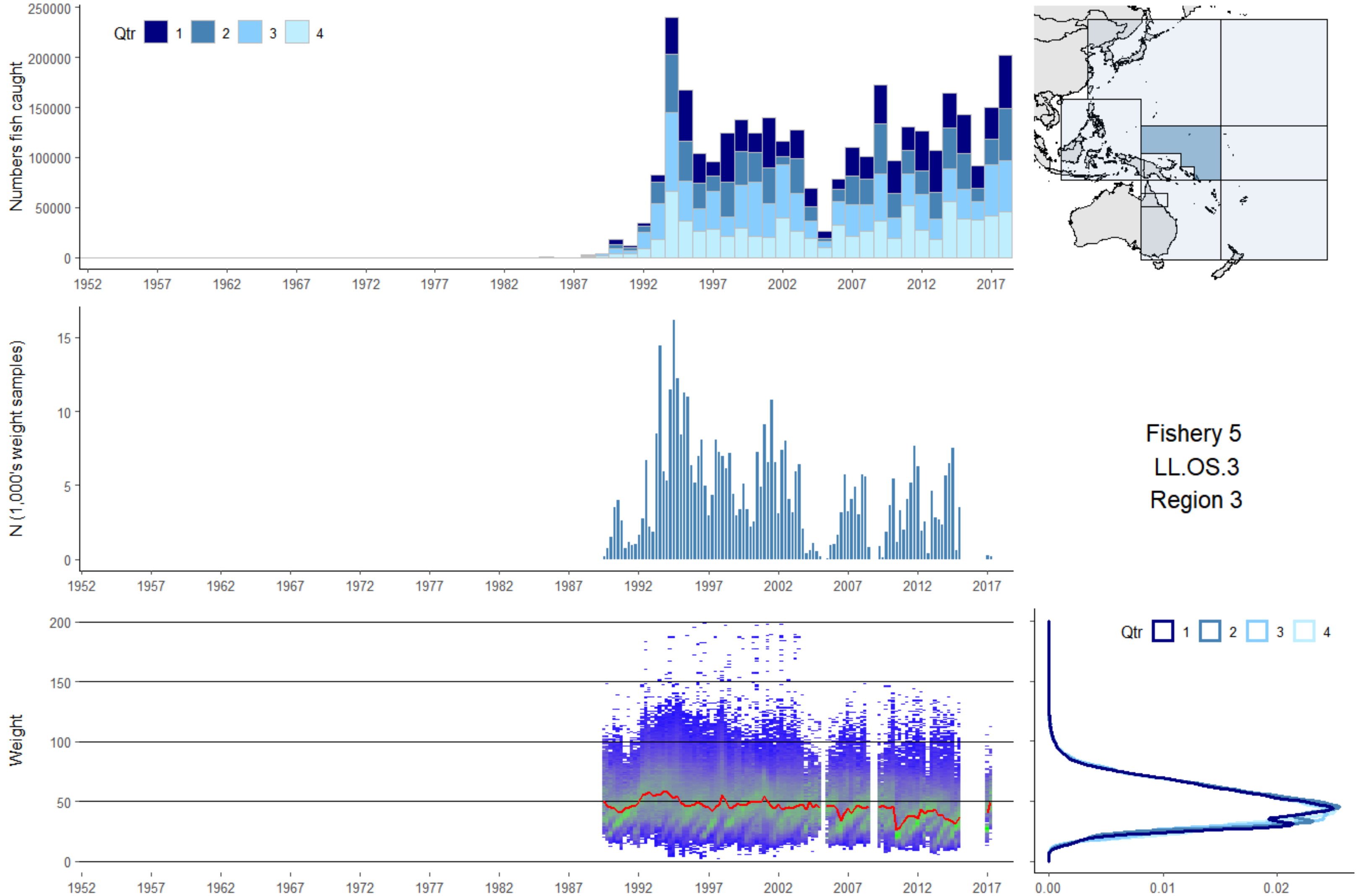

Figure 24: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 5.

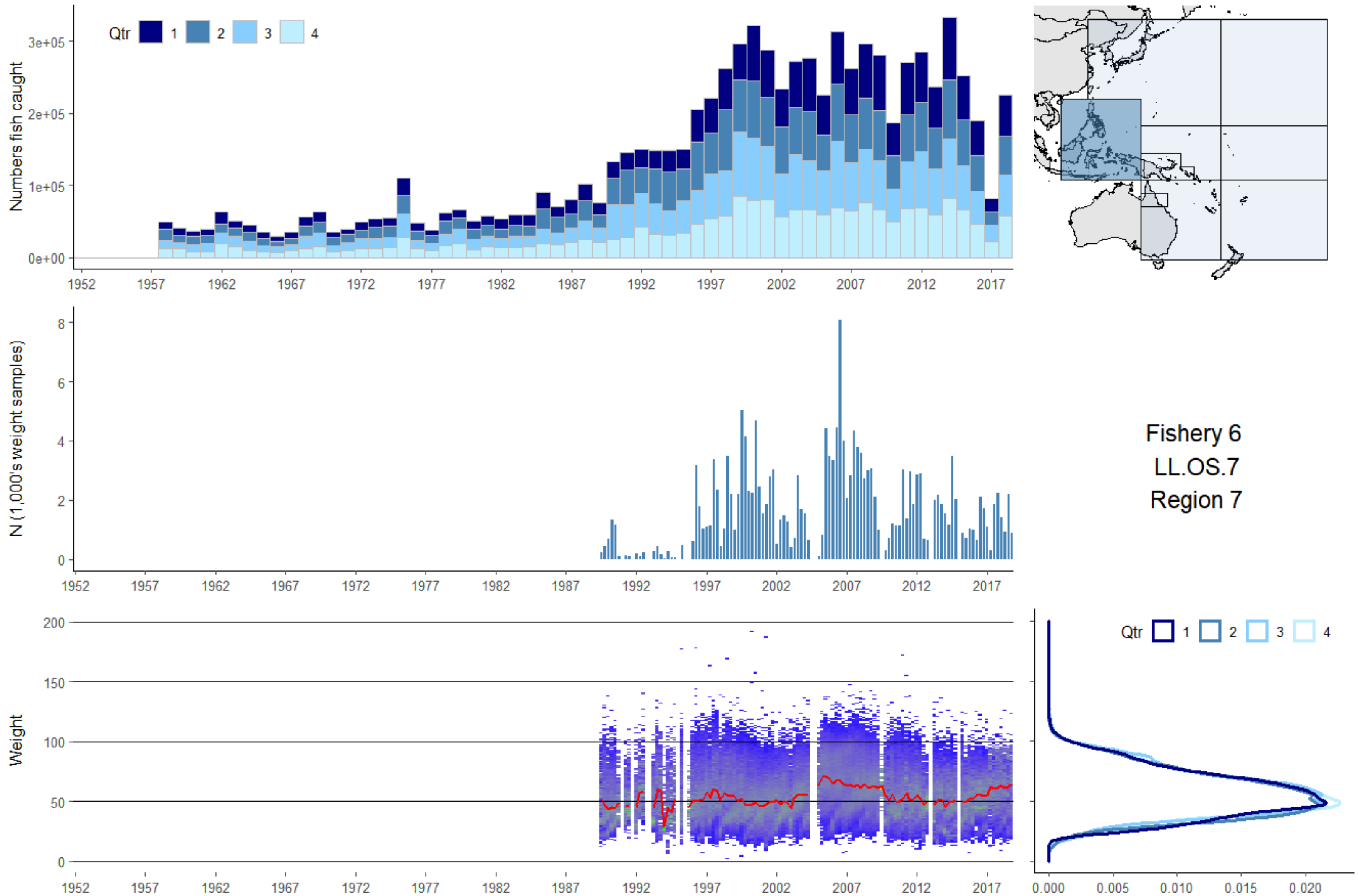

Figure 25: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 6.

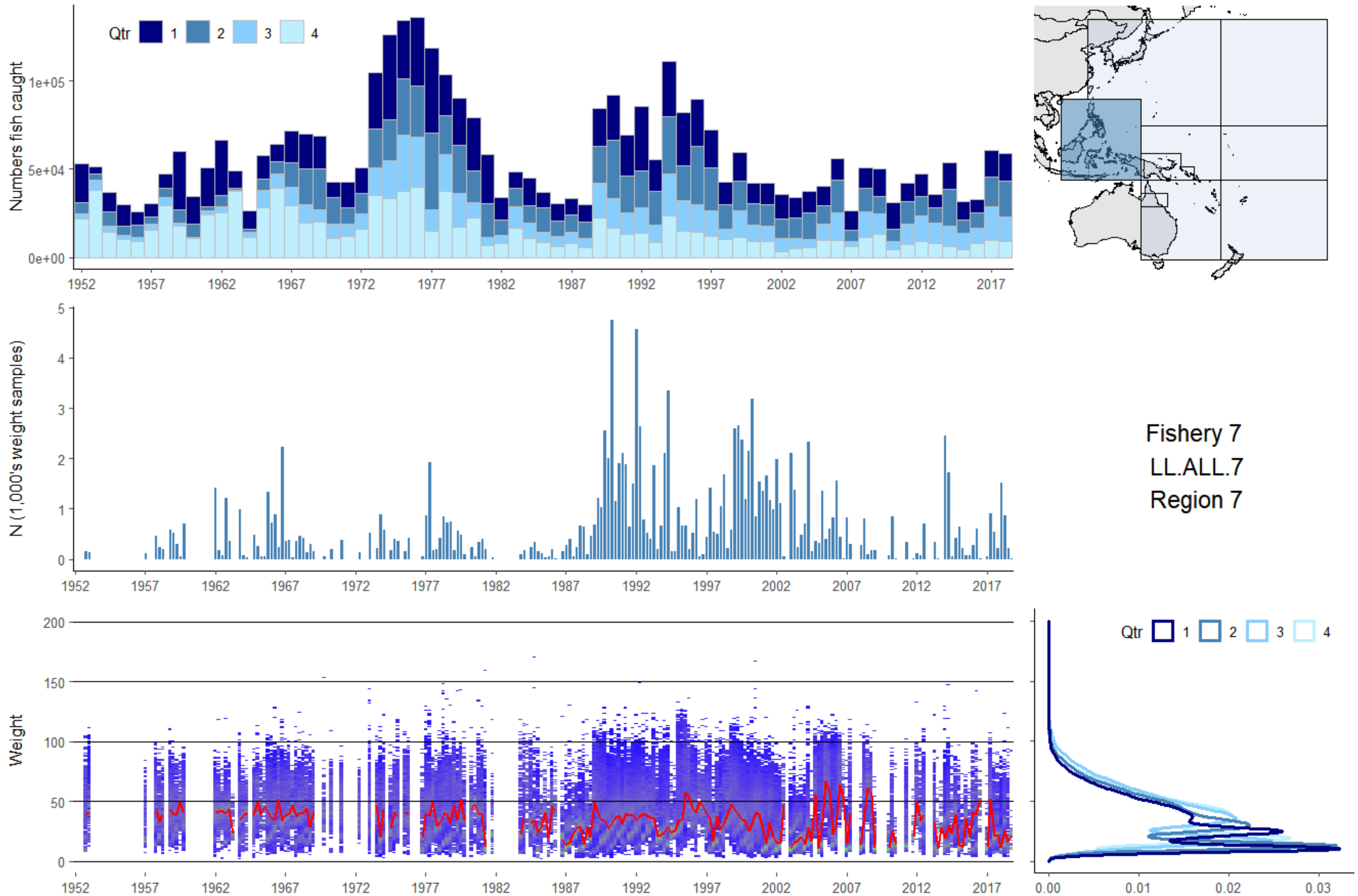

Figure 26: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 7.

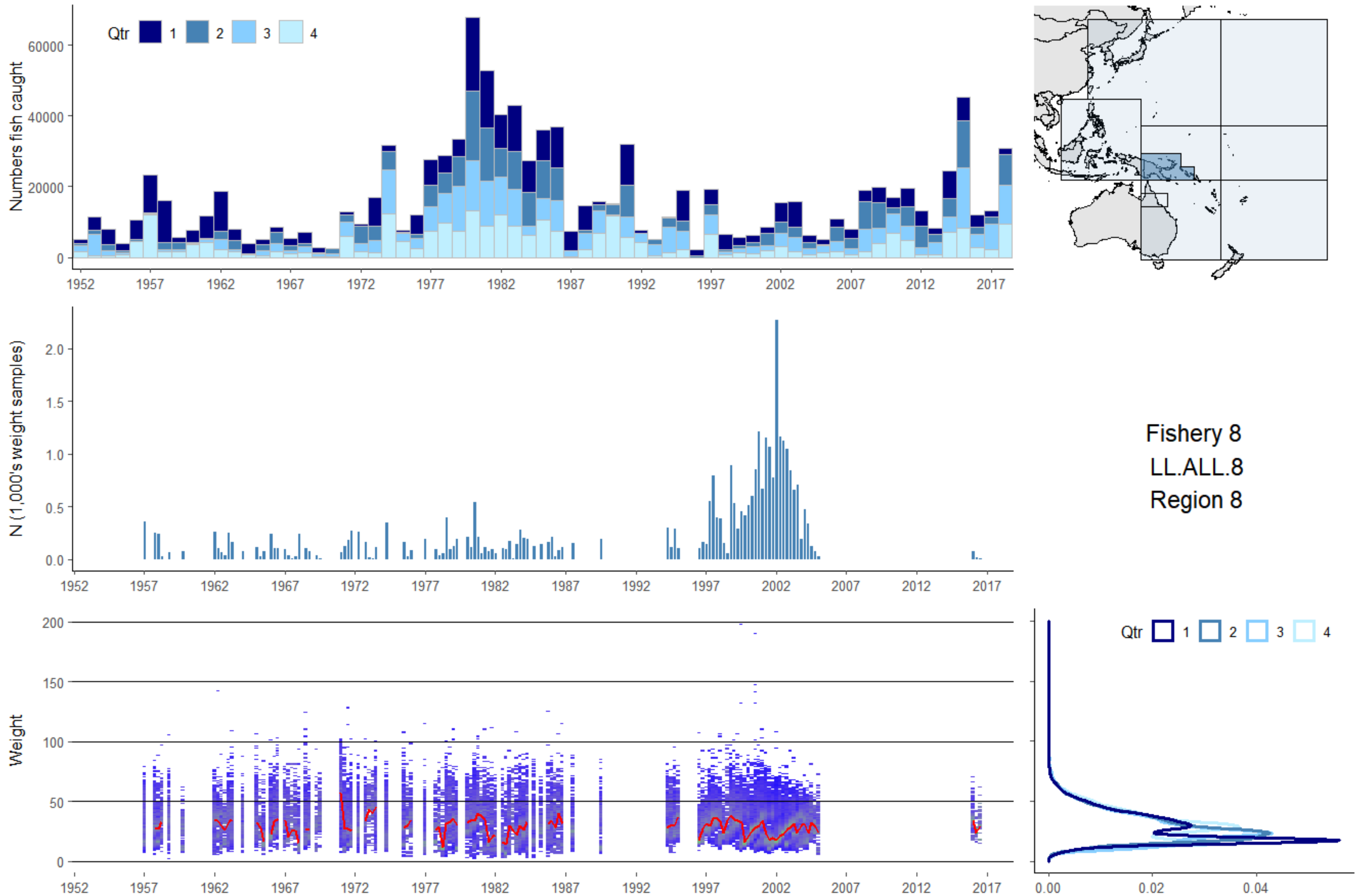

Figure 27: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 8.

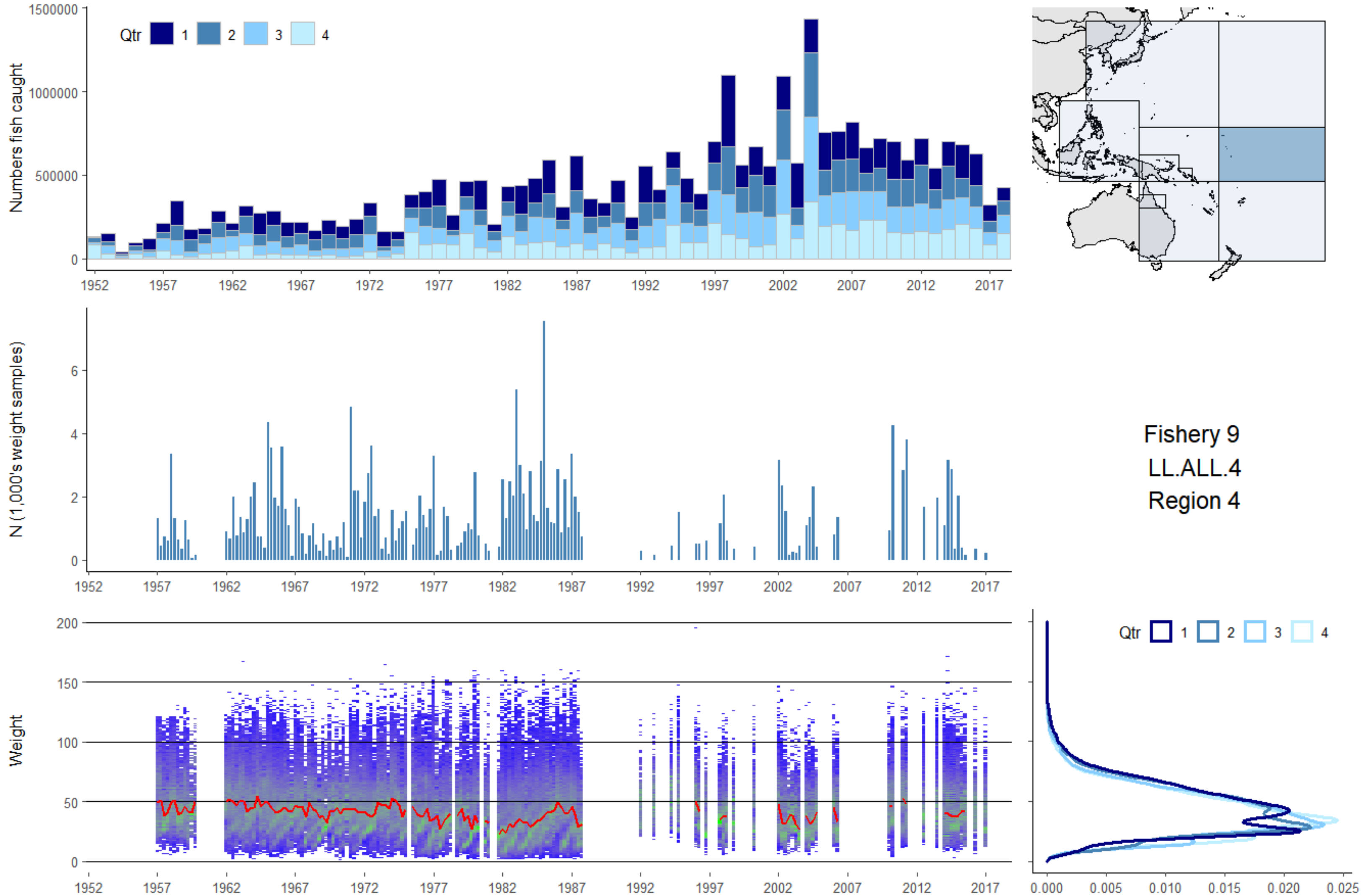

Figure 28: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 9.

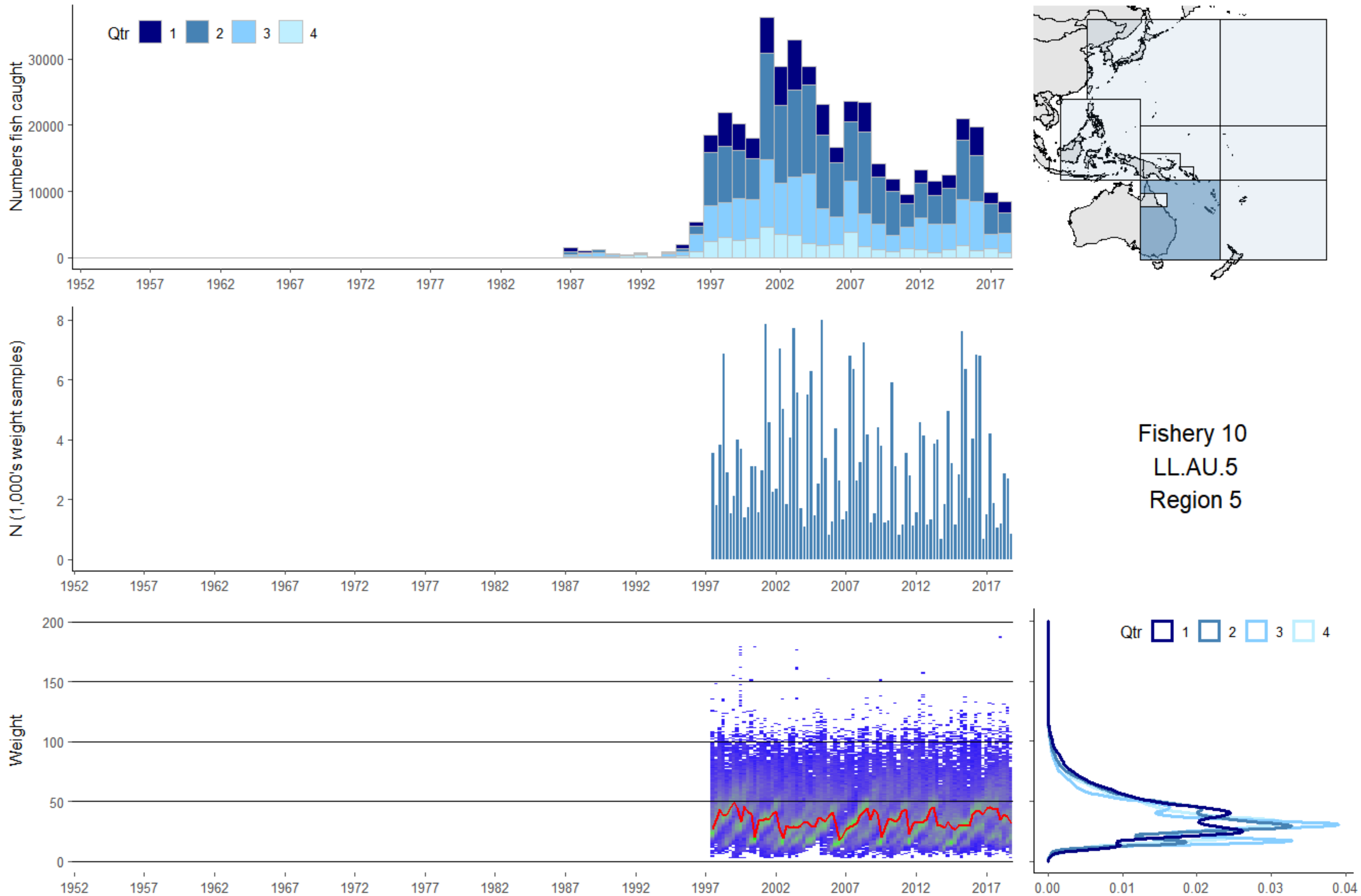

Figure 29: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 10.

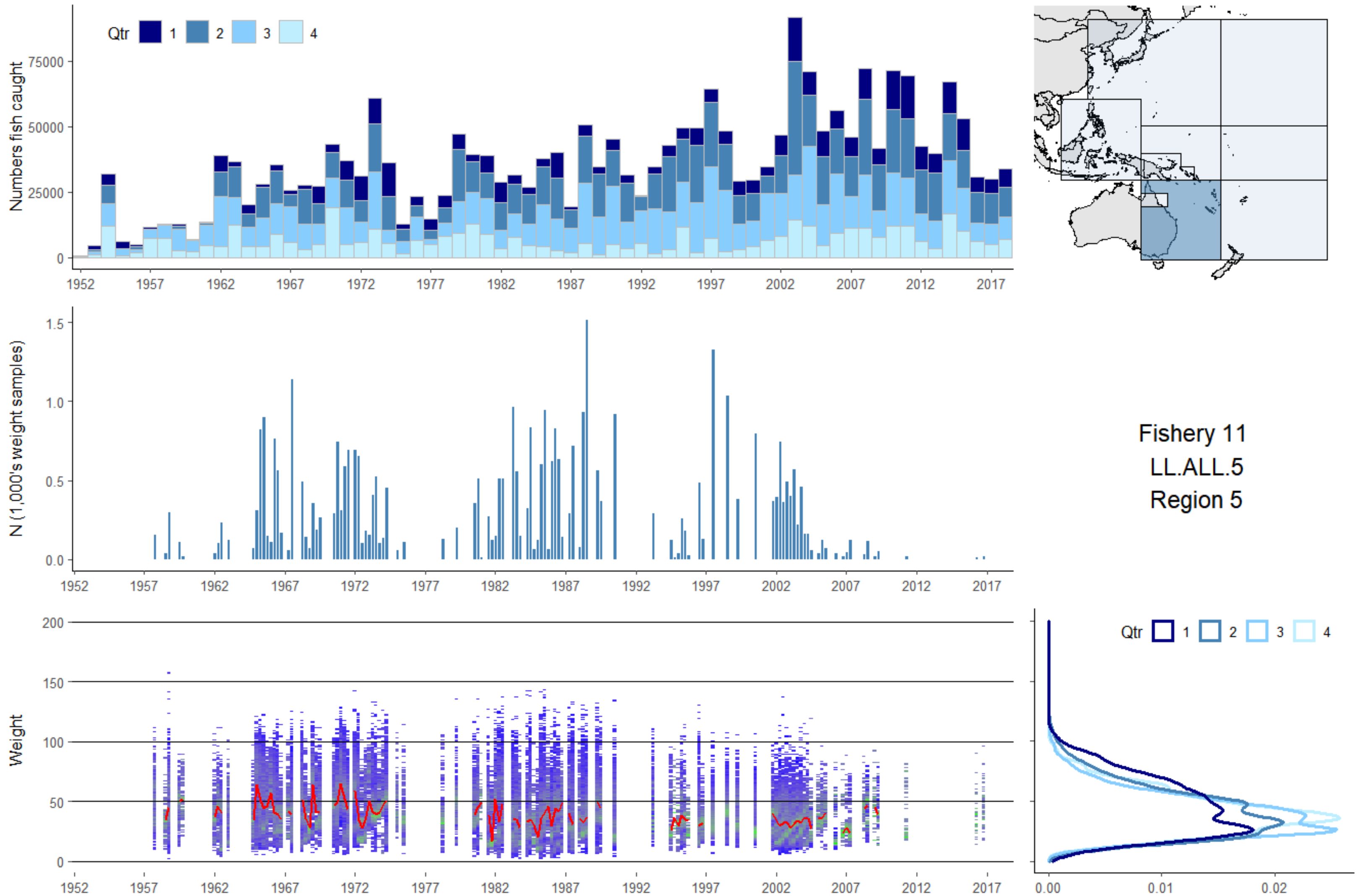

Figure 30: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 11.

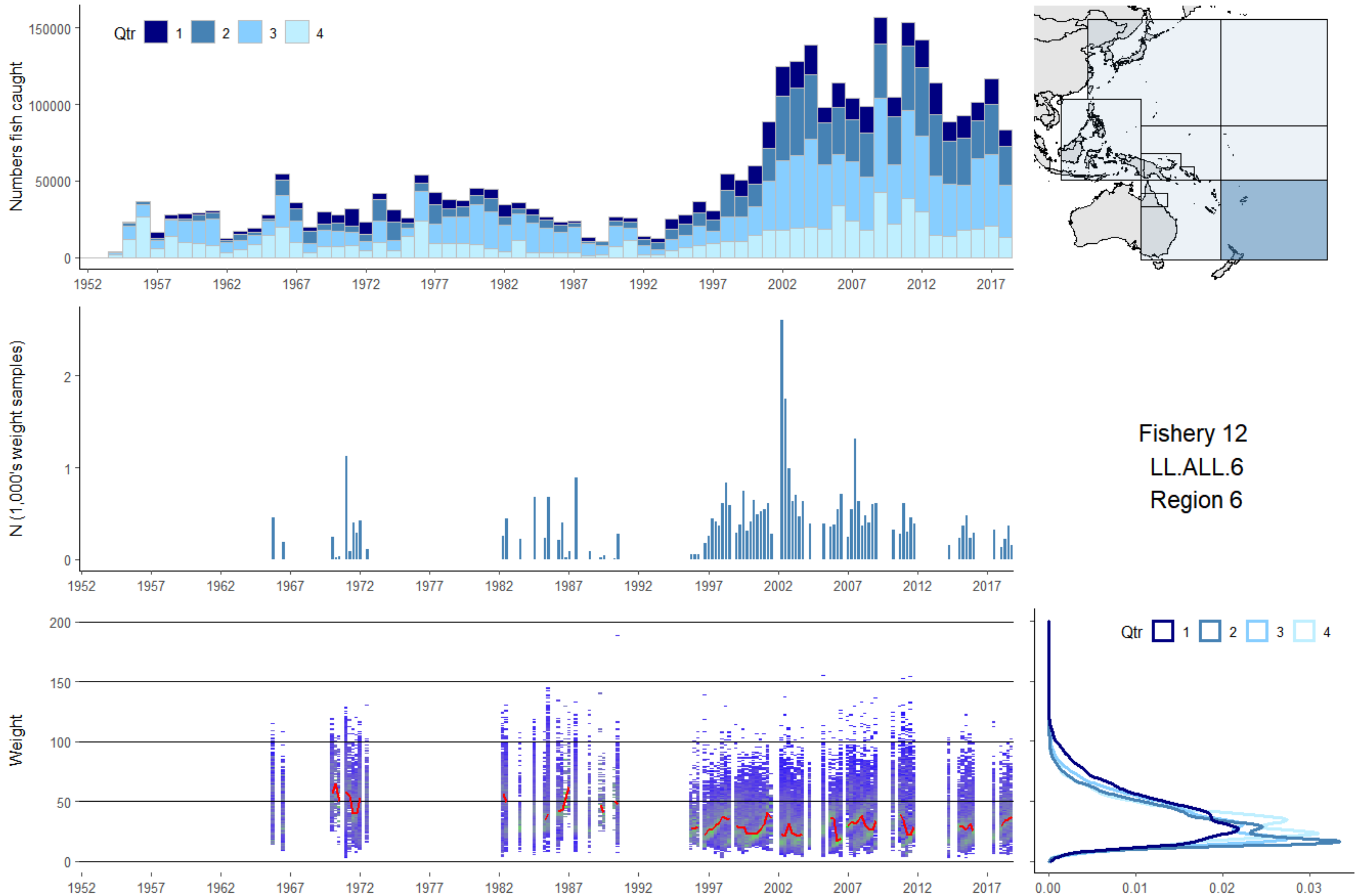

Figure 31: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 12.

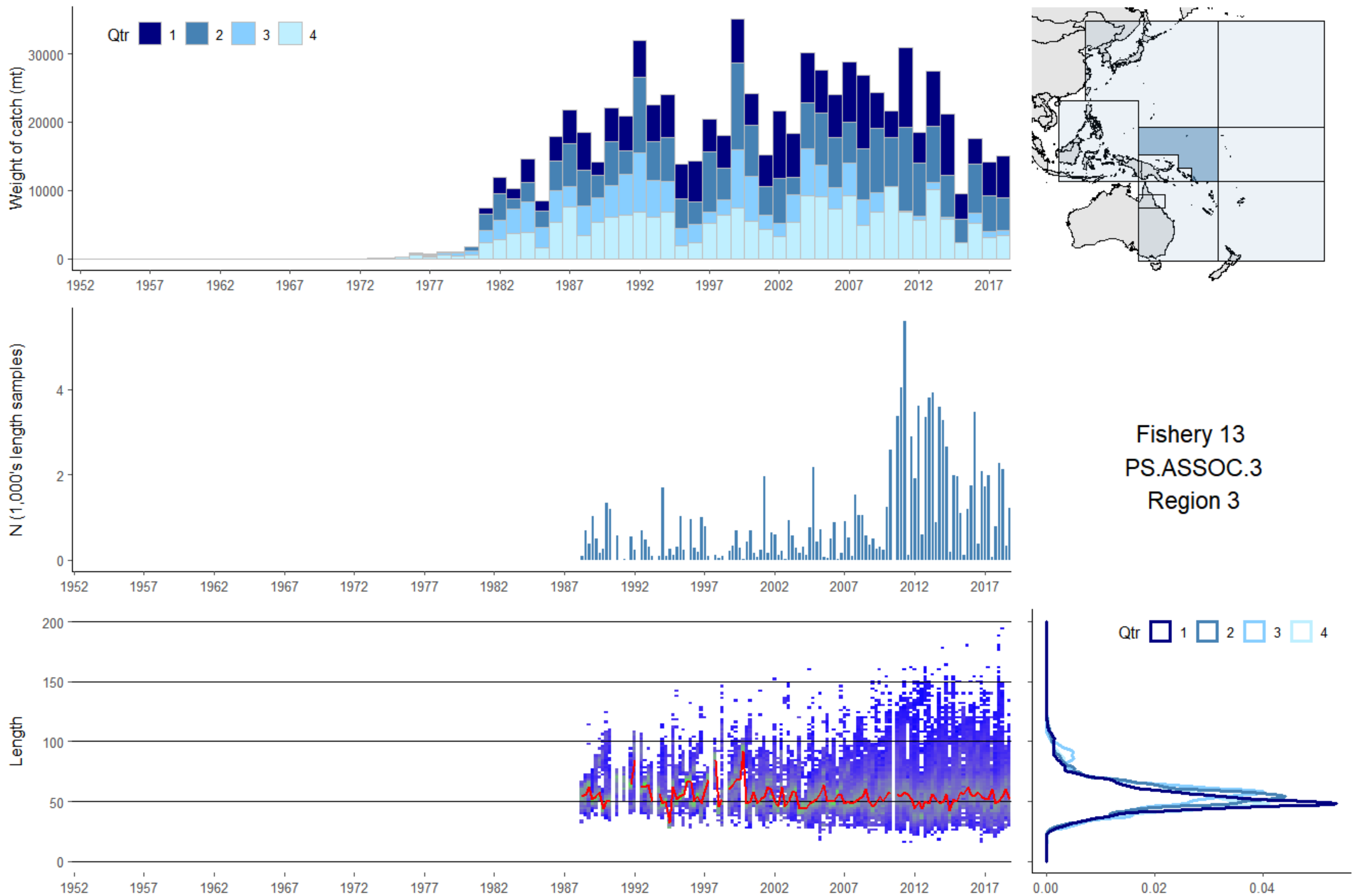

Figure 32: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 13.

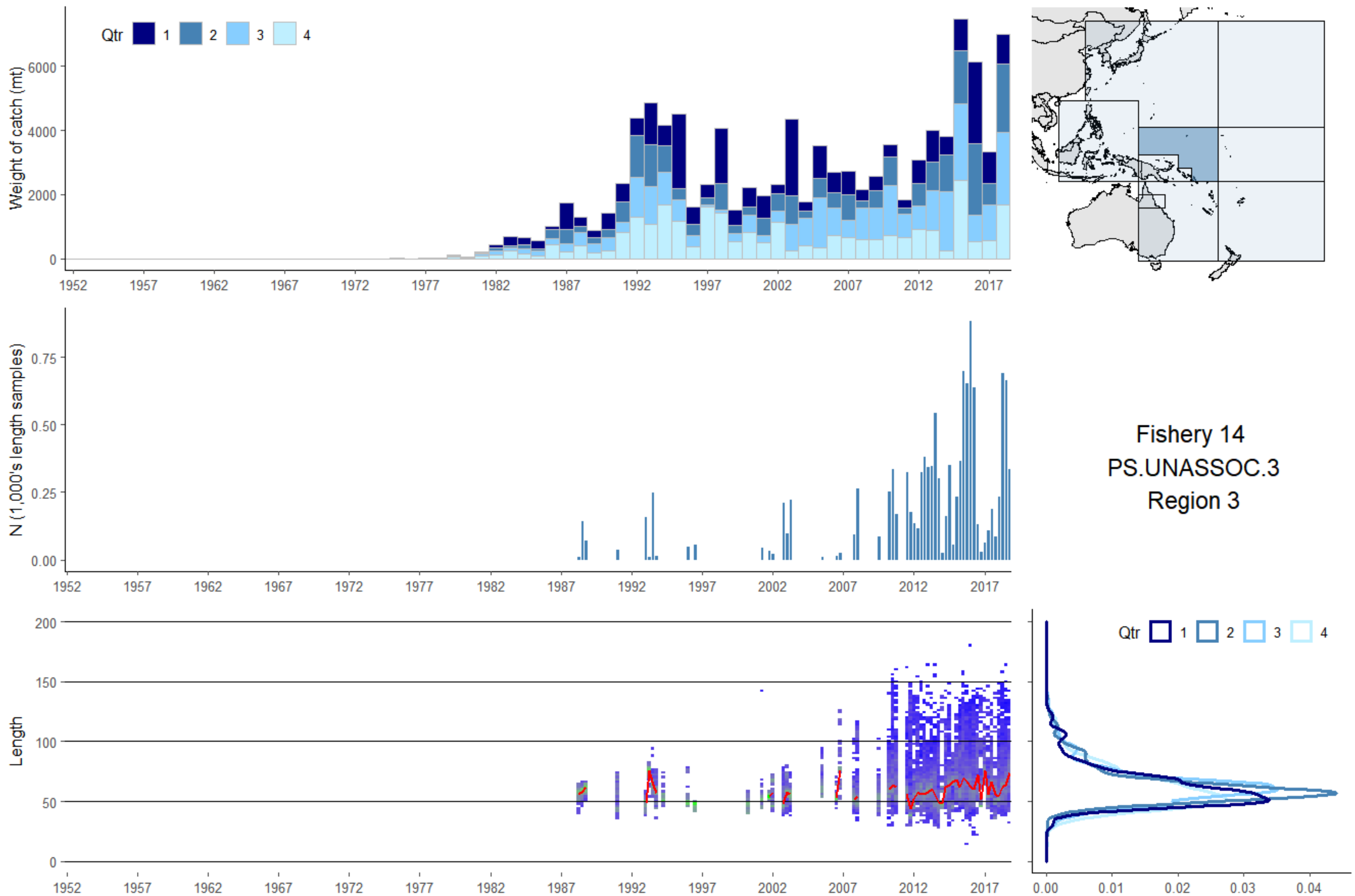

Figure 33: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 14.

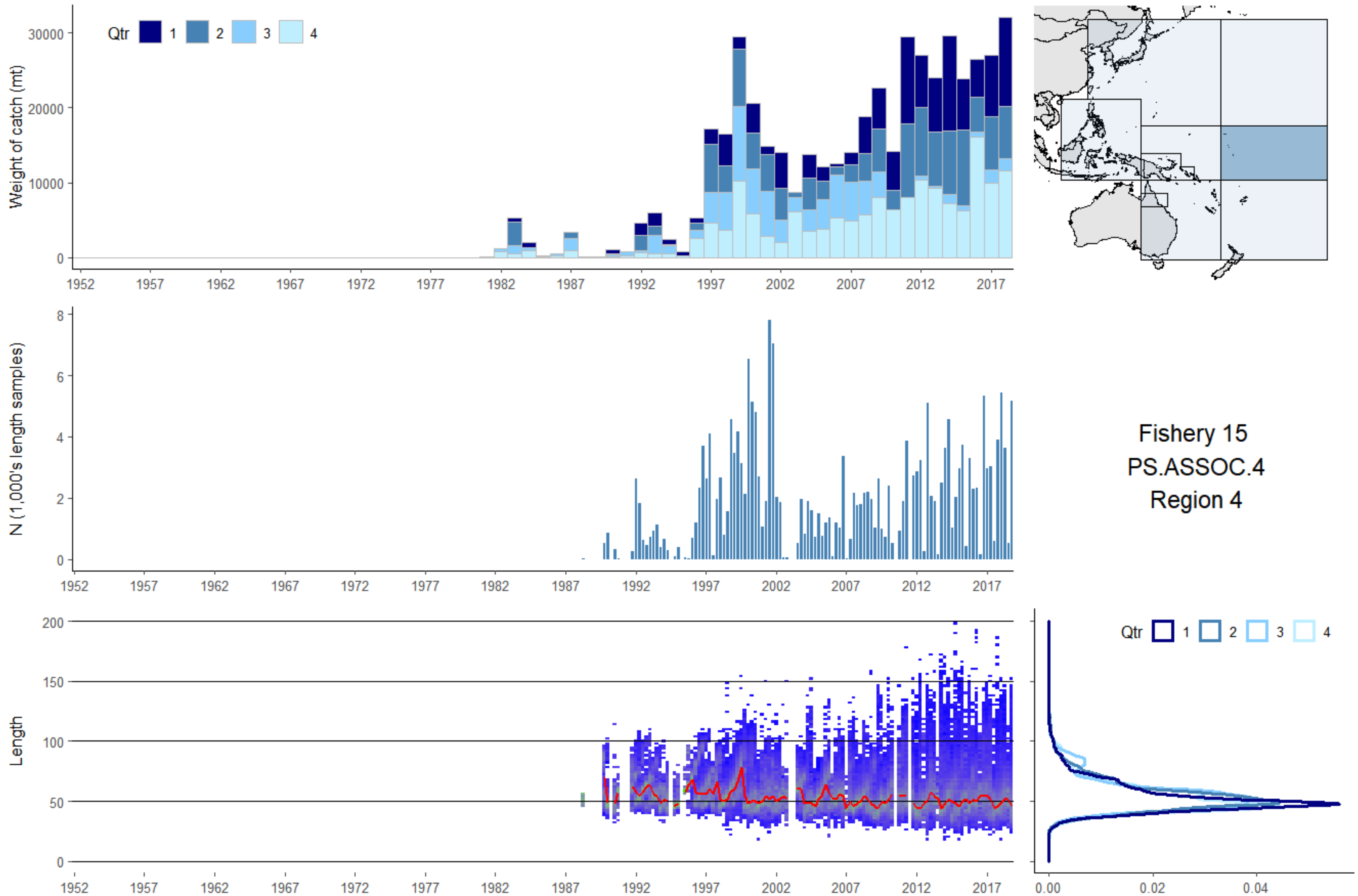

Figure 34: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 15.

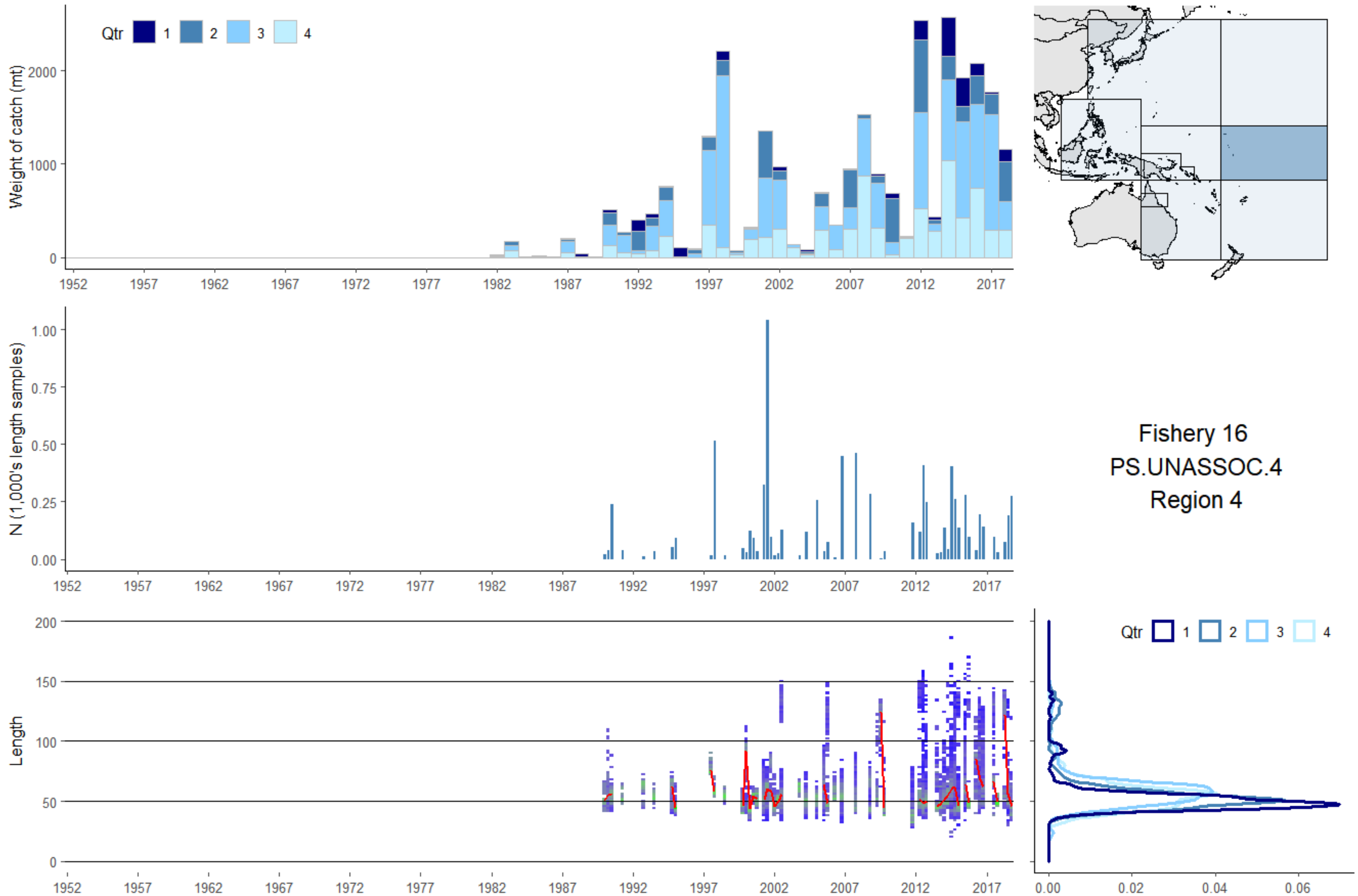

Figure 35: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 16.

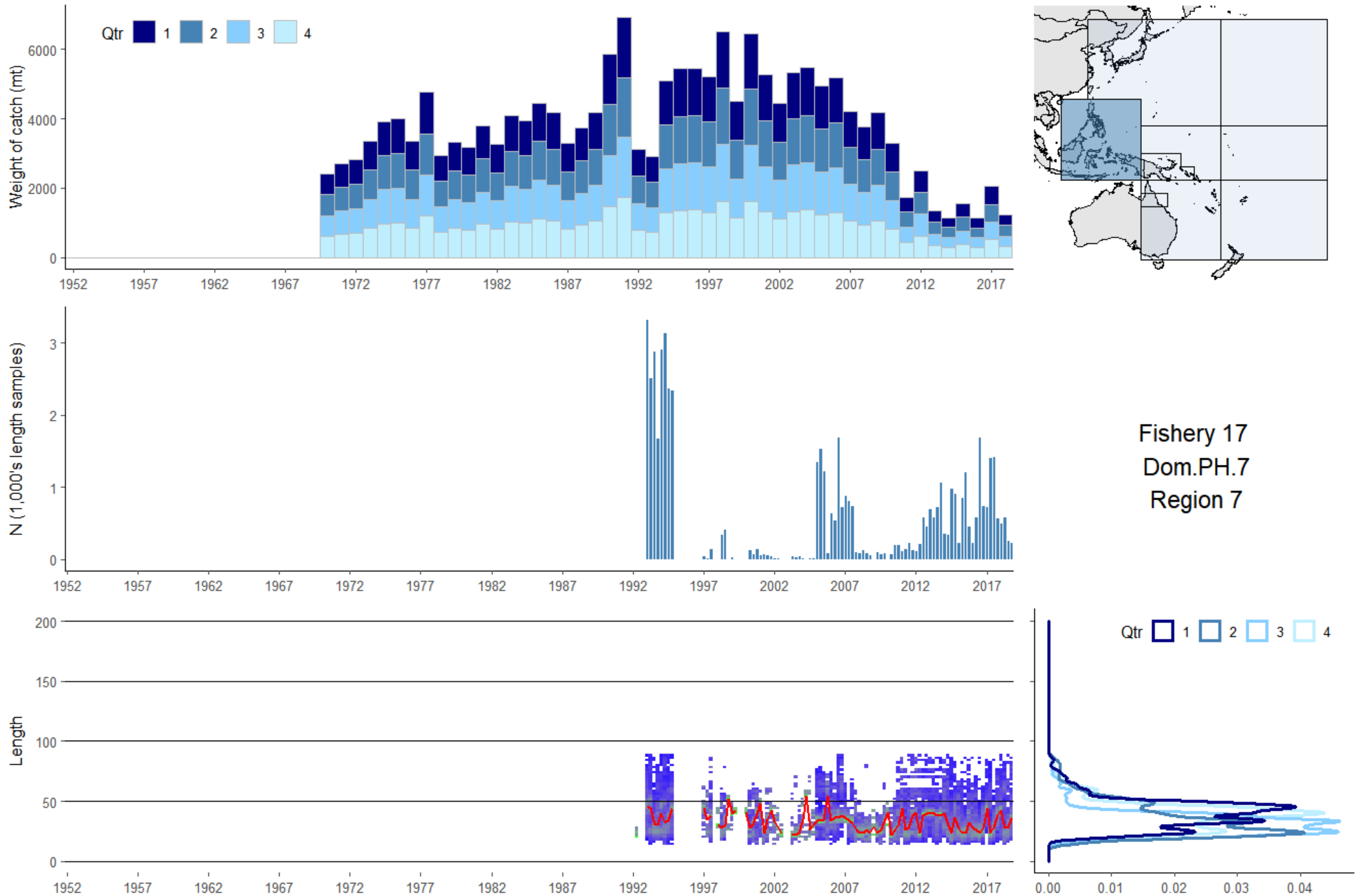

Figure 36: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 17.

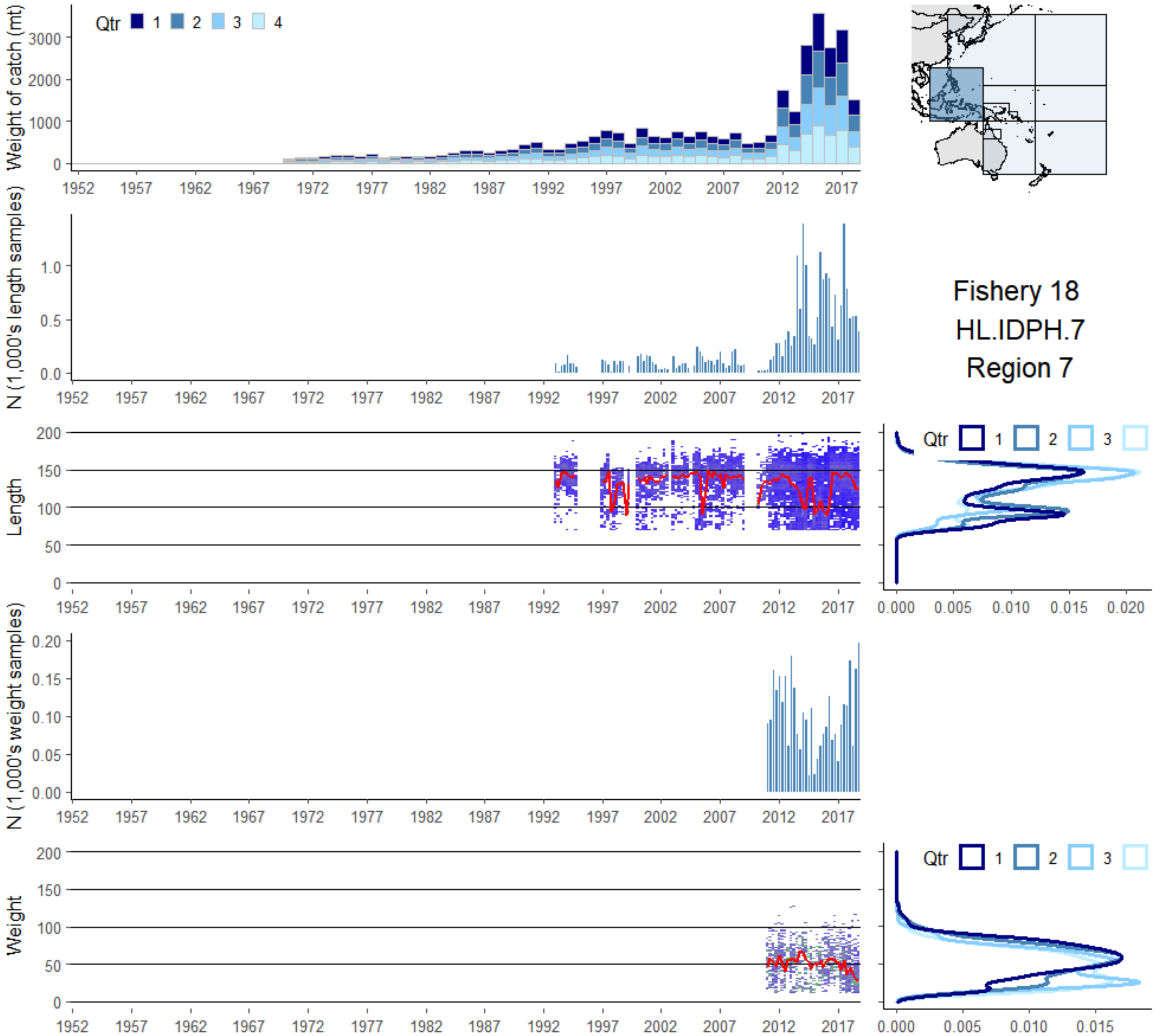

Figure 37: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 18.

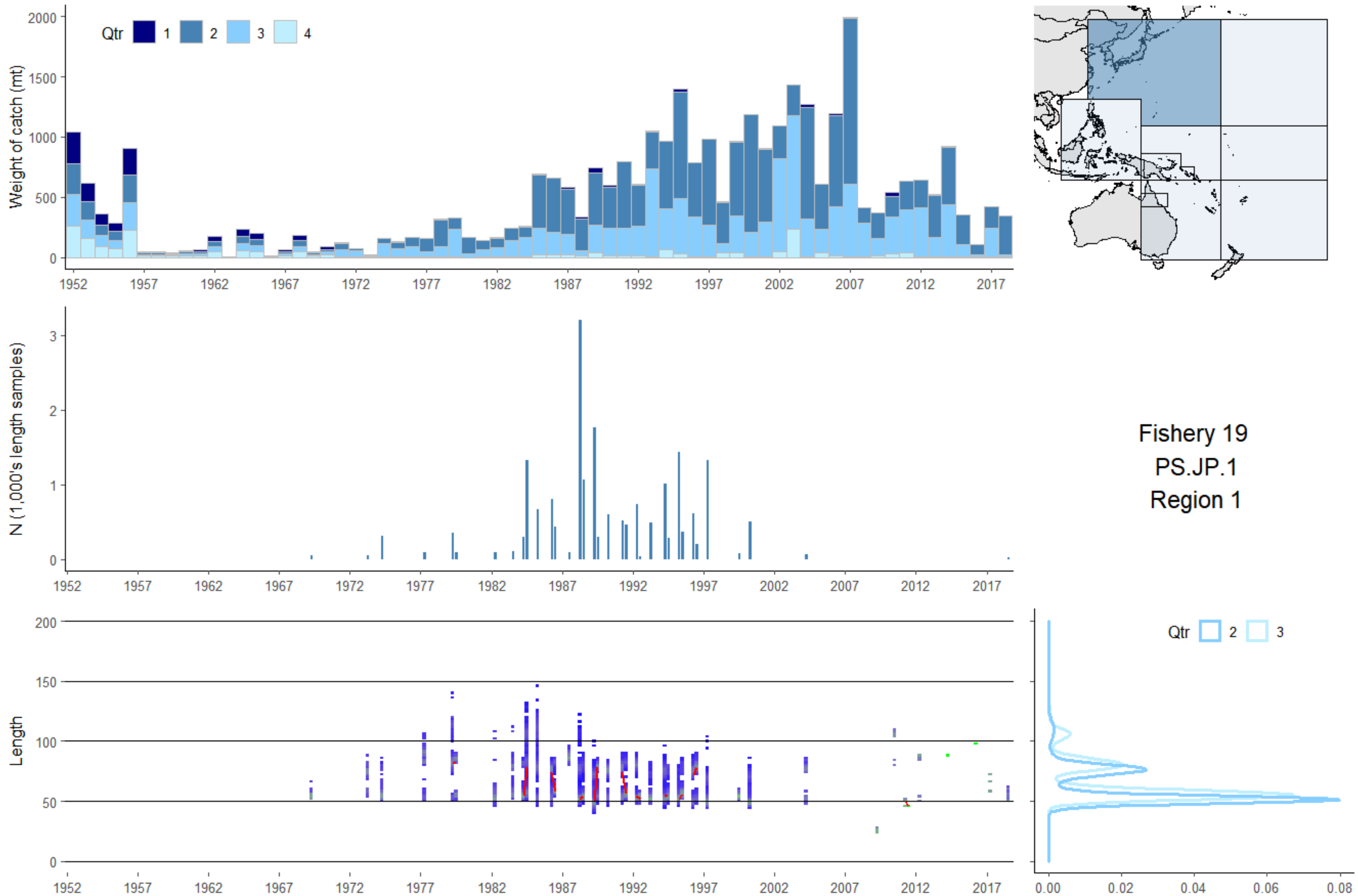

Figure 38: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 19.

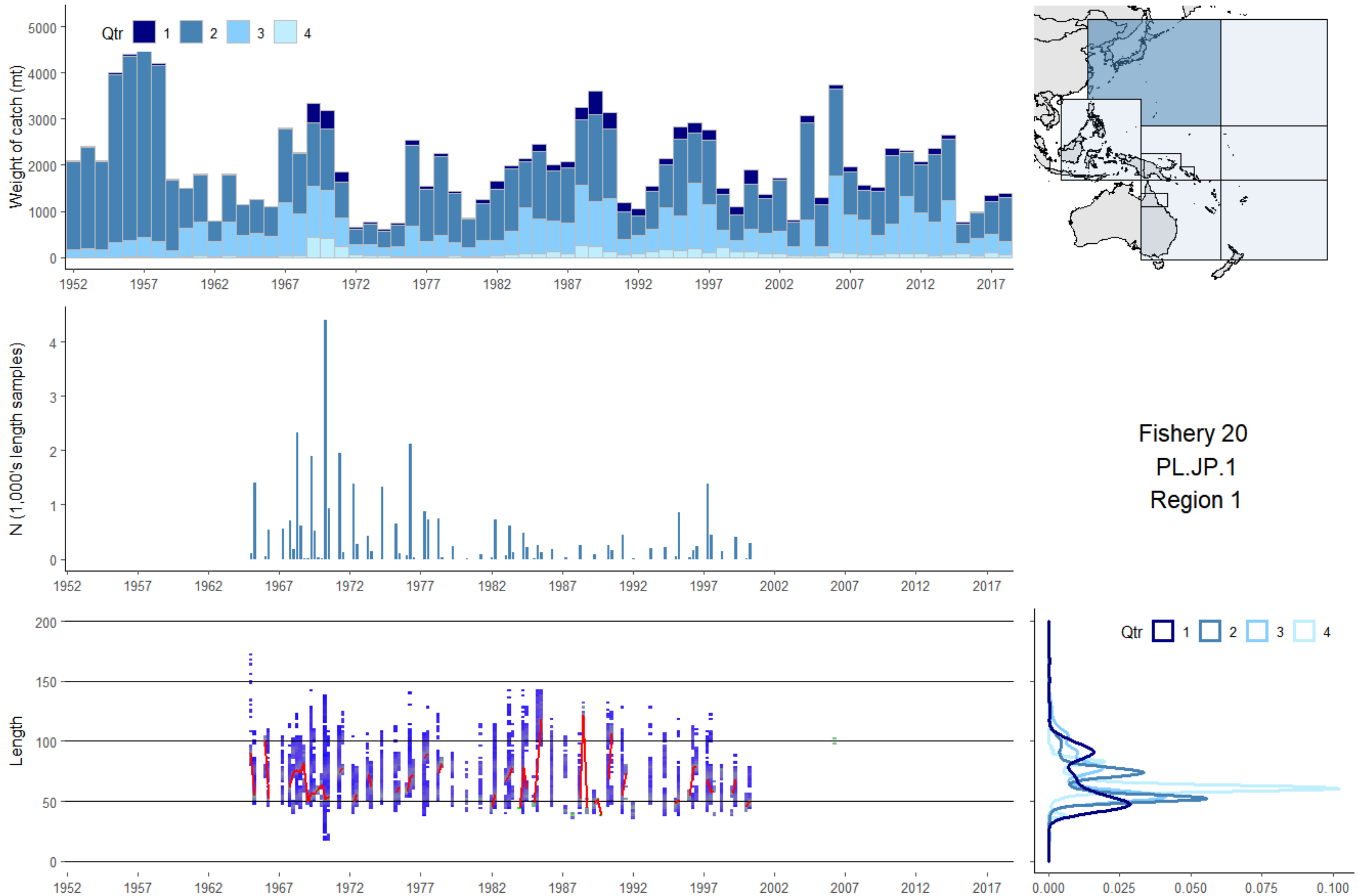

Figure 39: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 20.

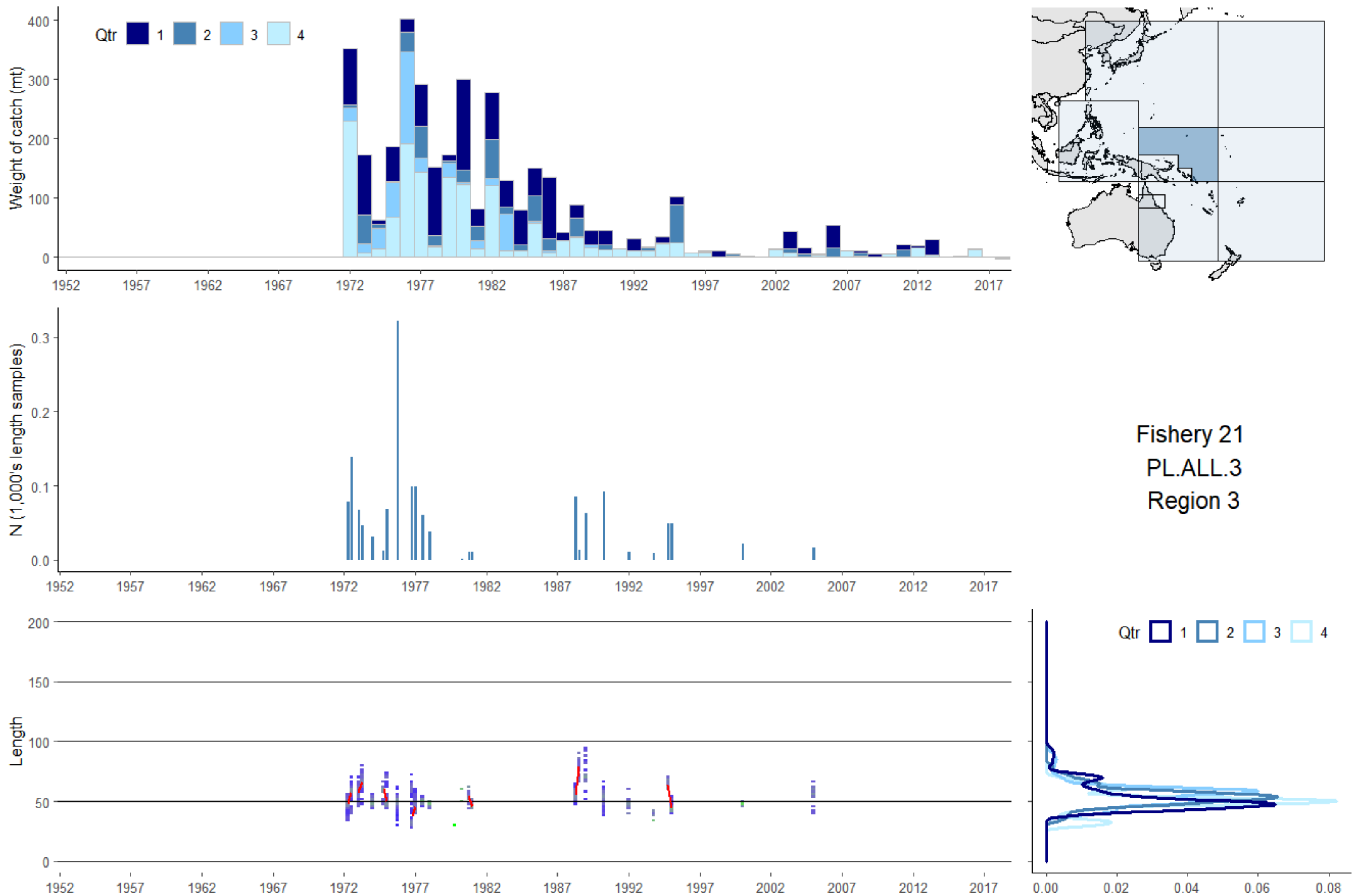

Figure 40: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 21.

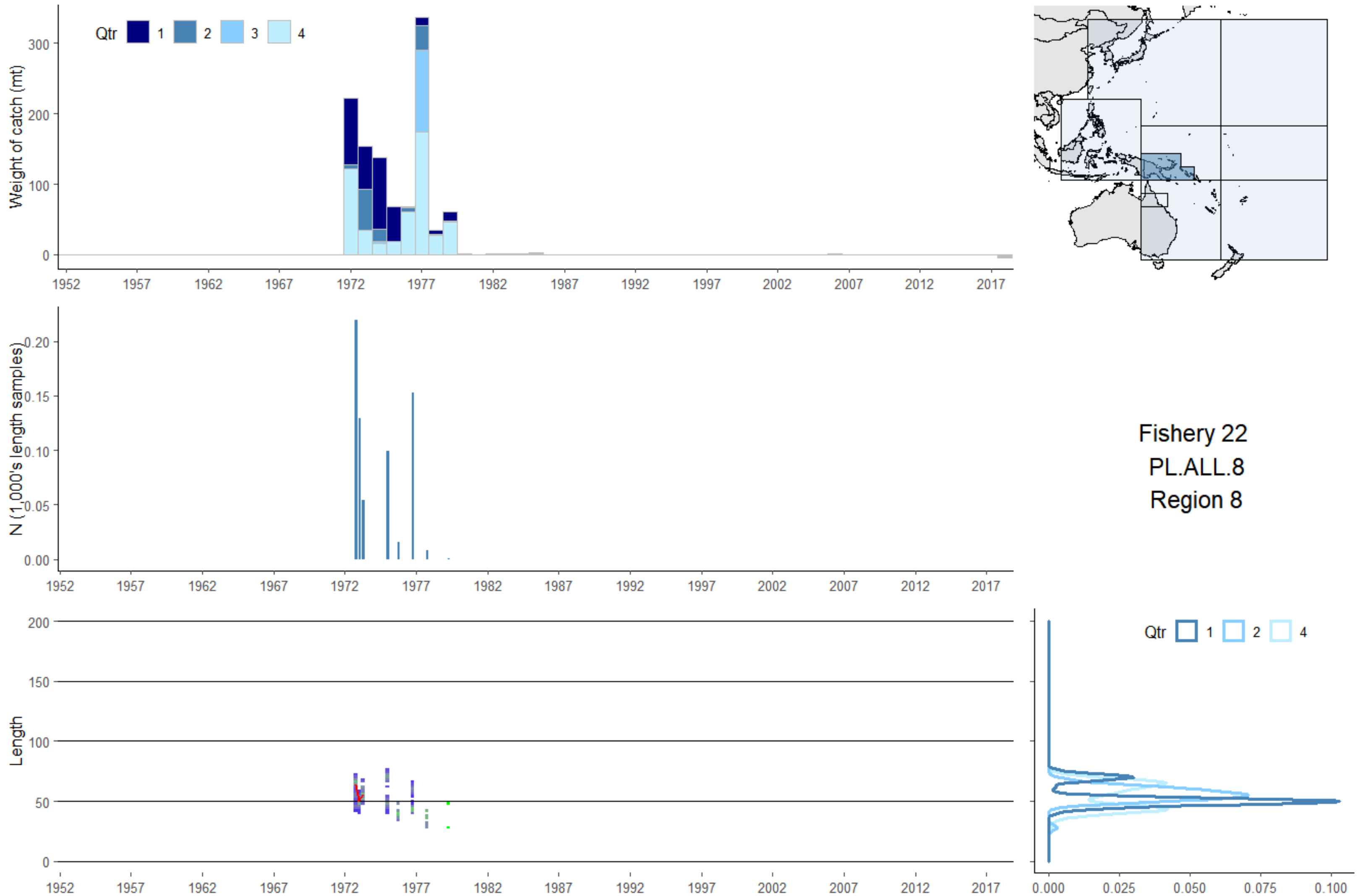

Figure 41: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 22.

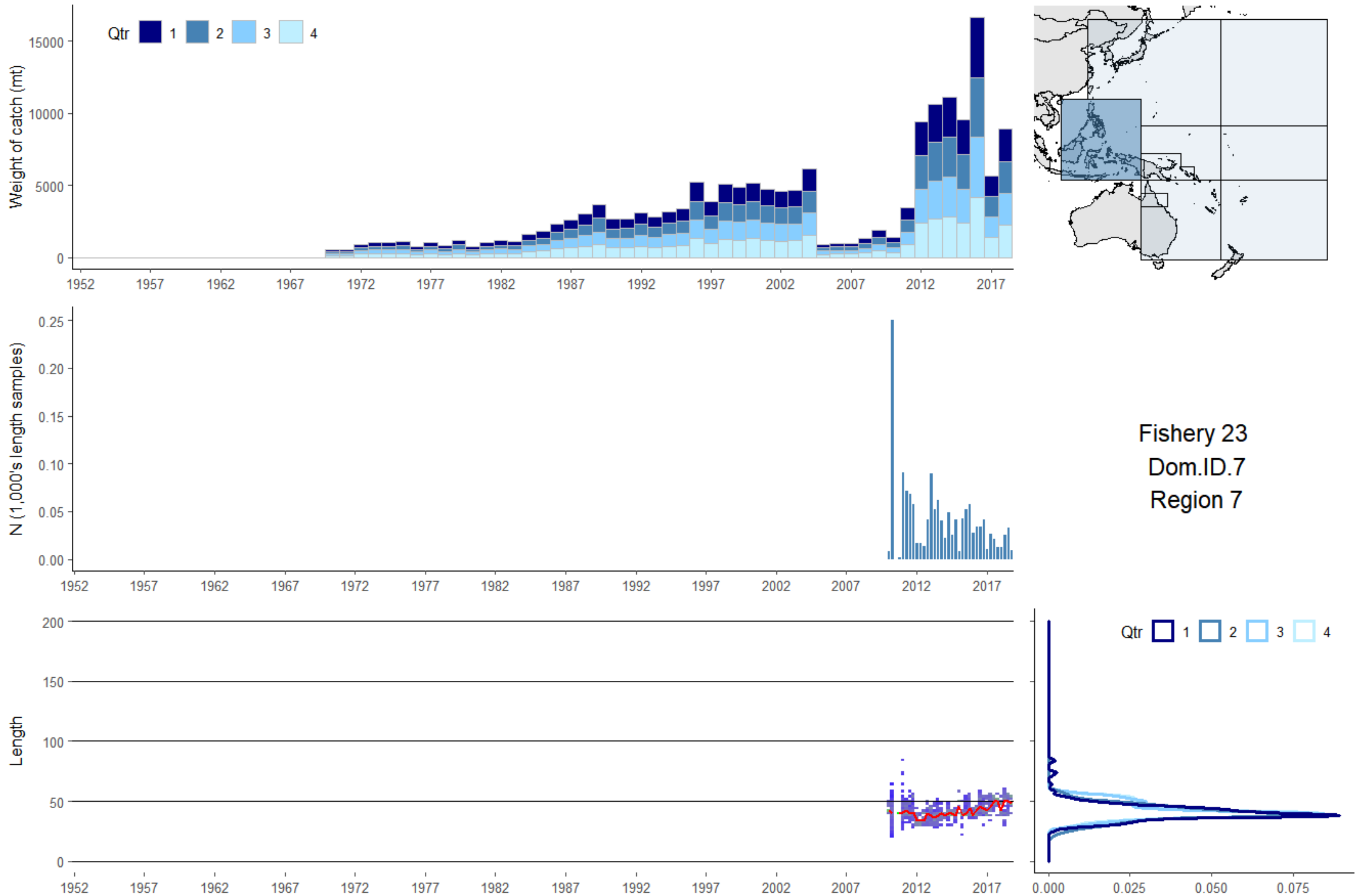

Figure 42: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 23.

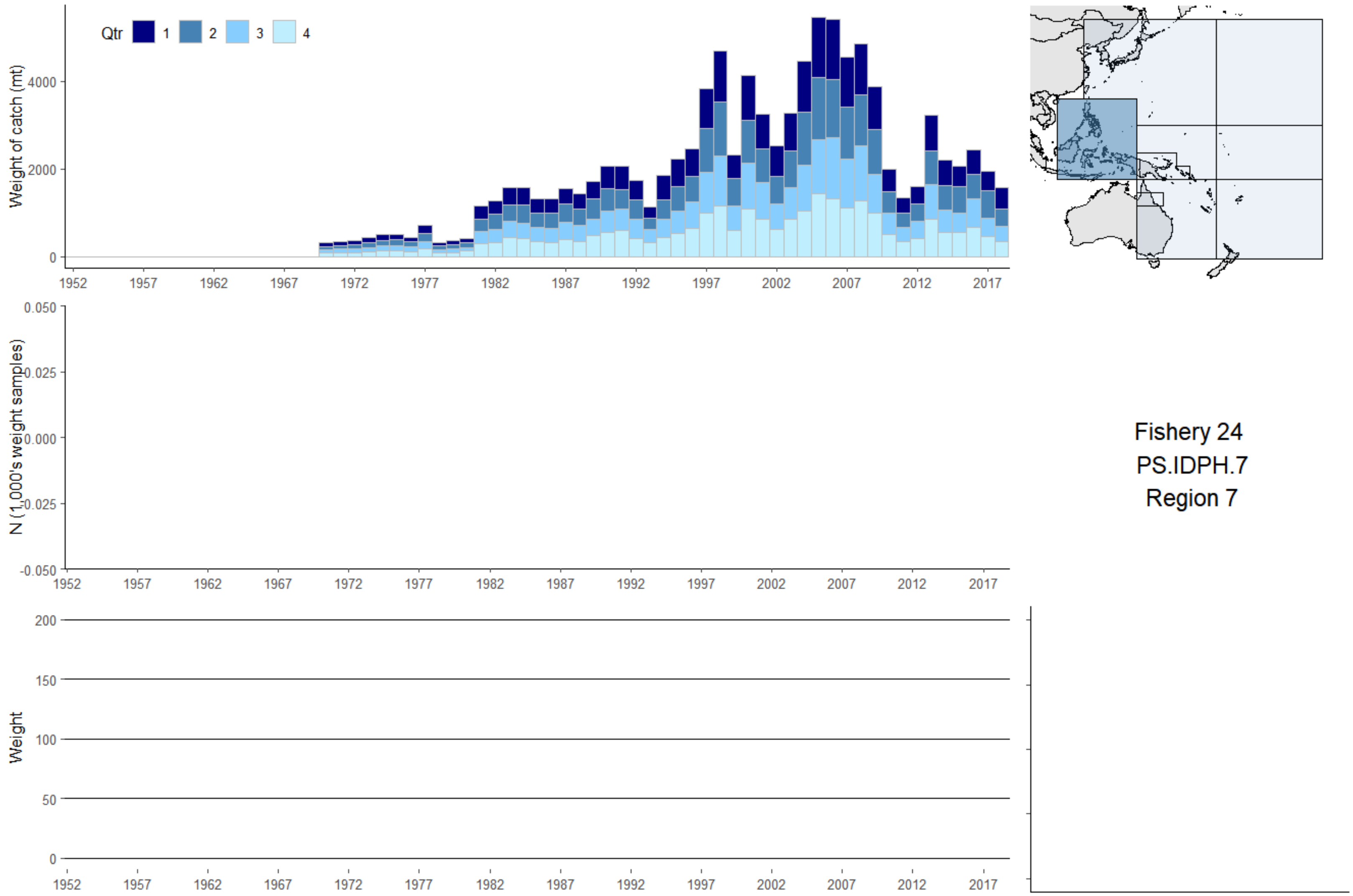

Figure 43: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 24.

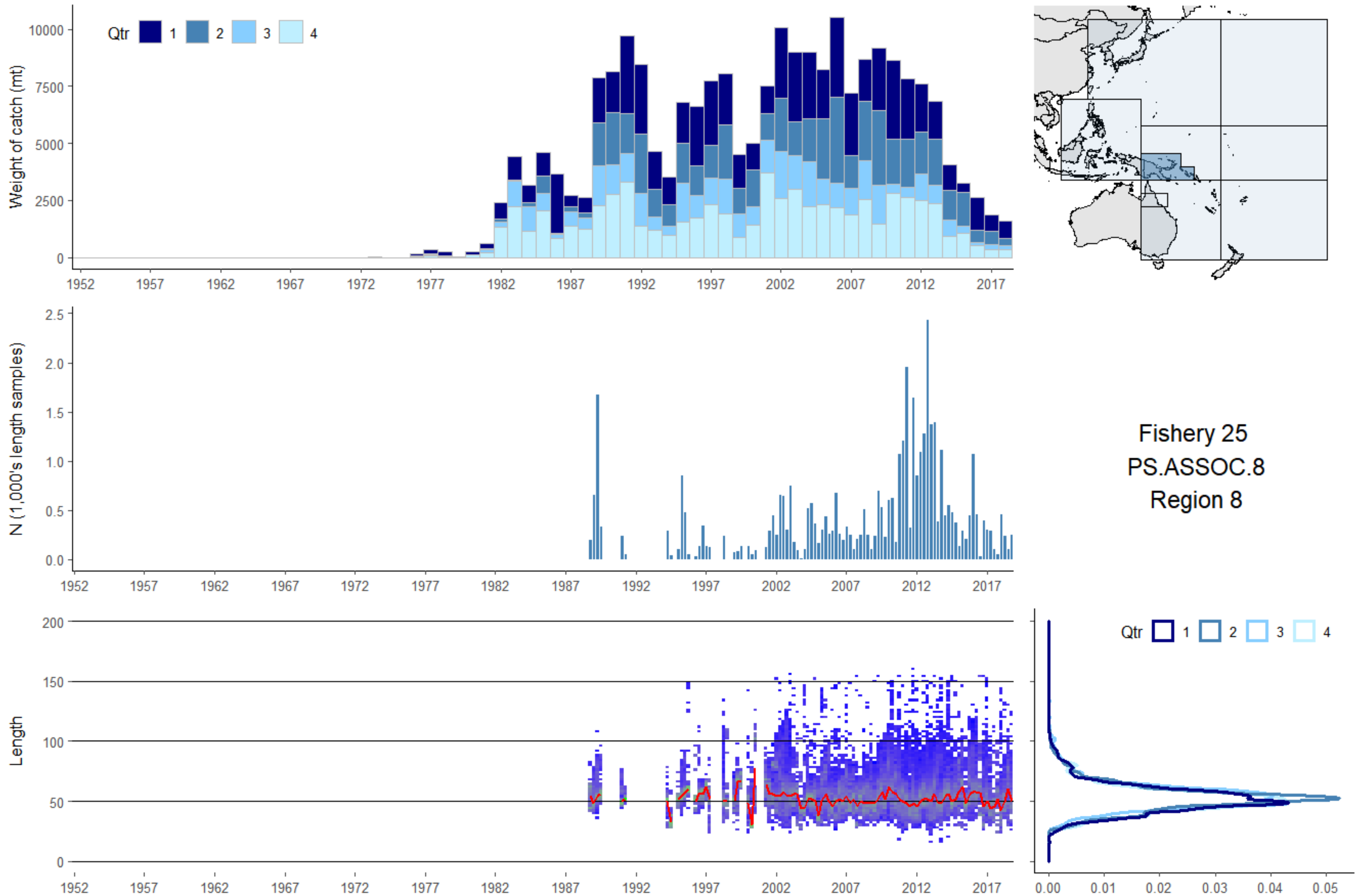

Figure 44: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 25.

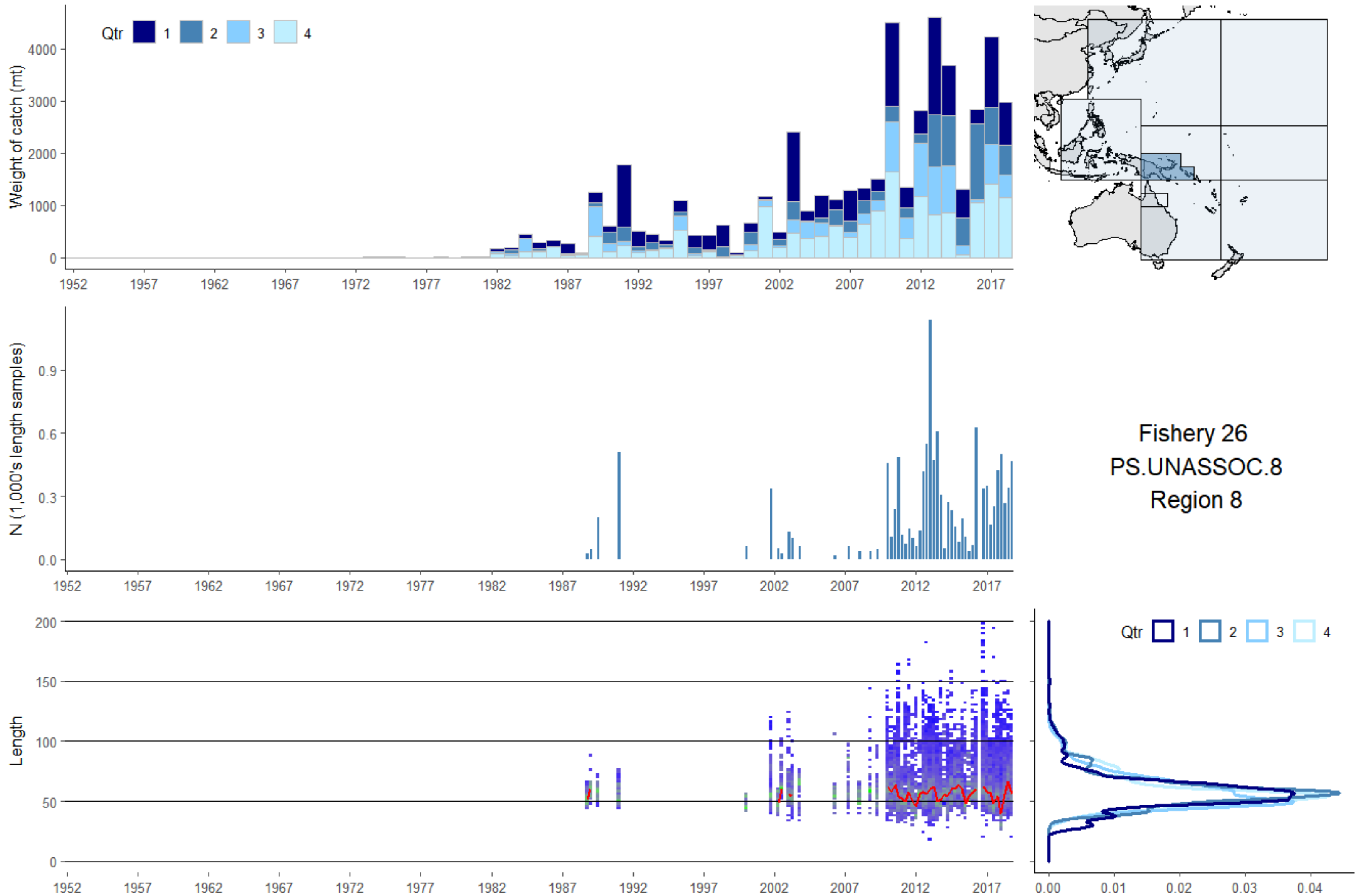

Figure 45: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 26.

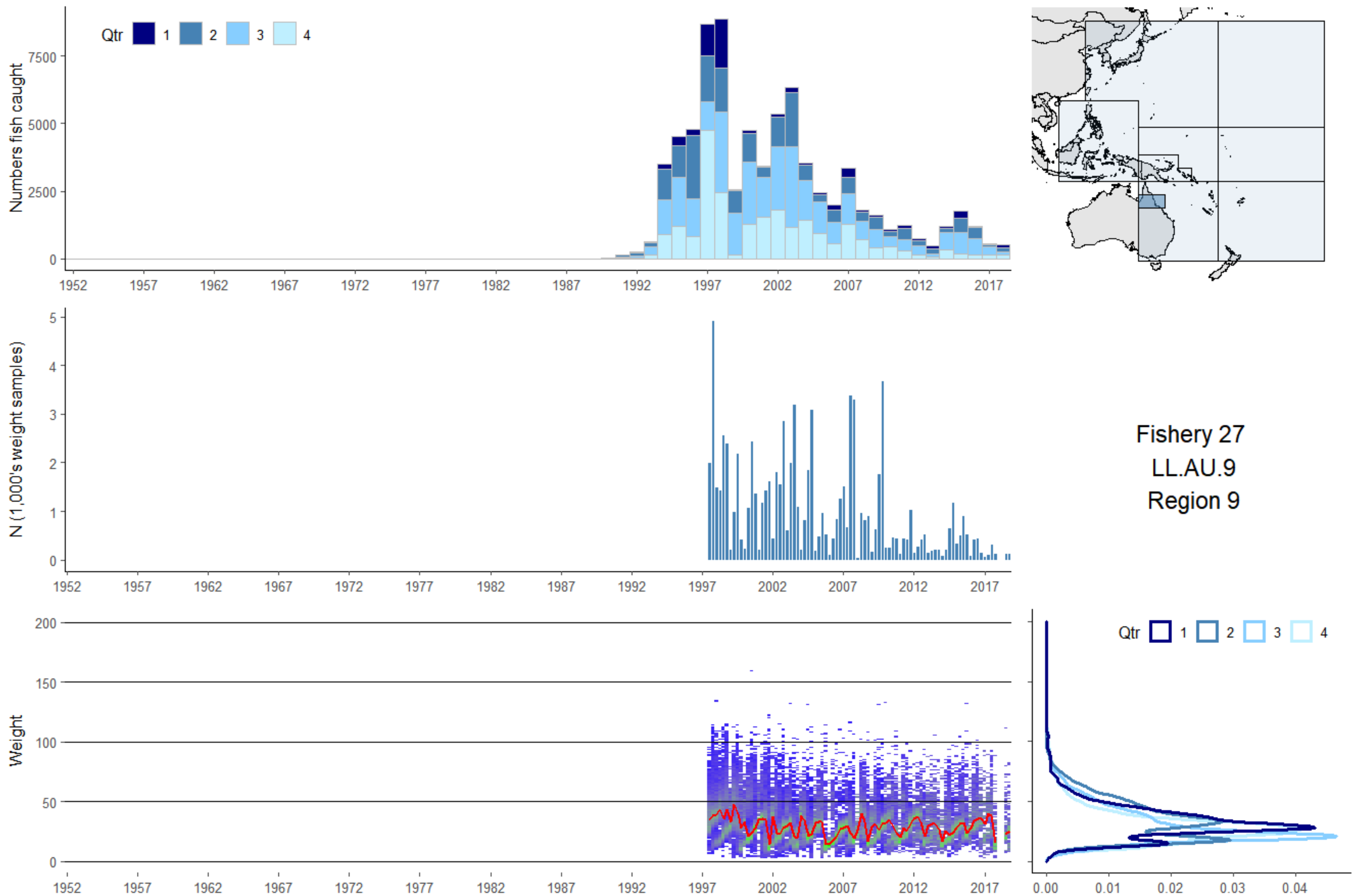

Figure 46: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 27.

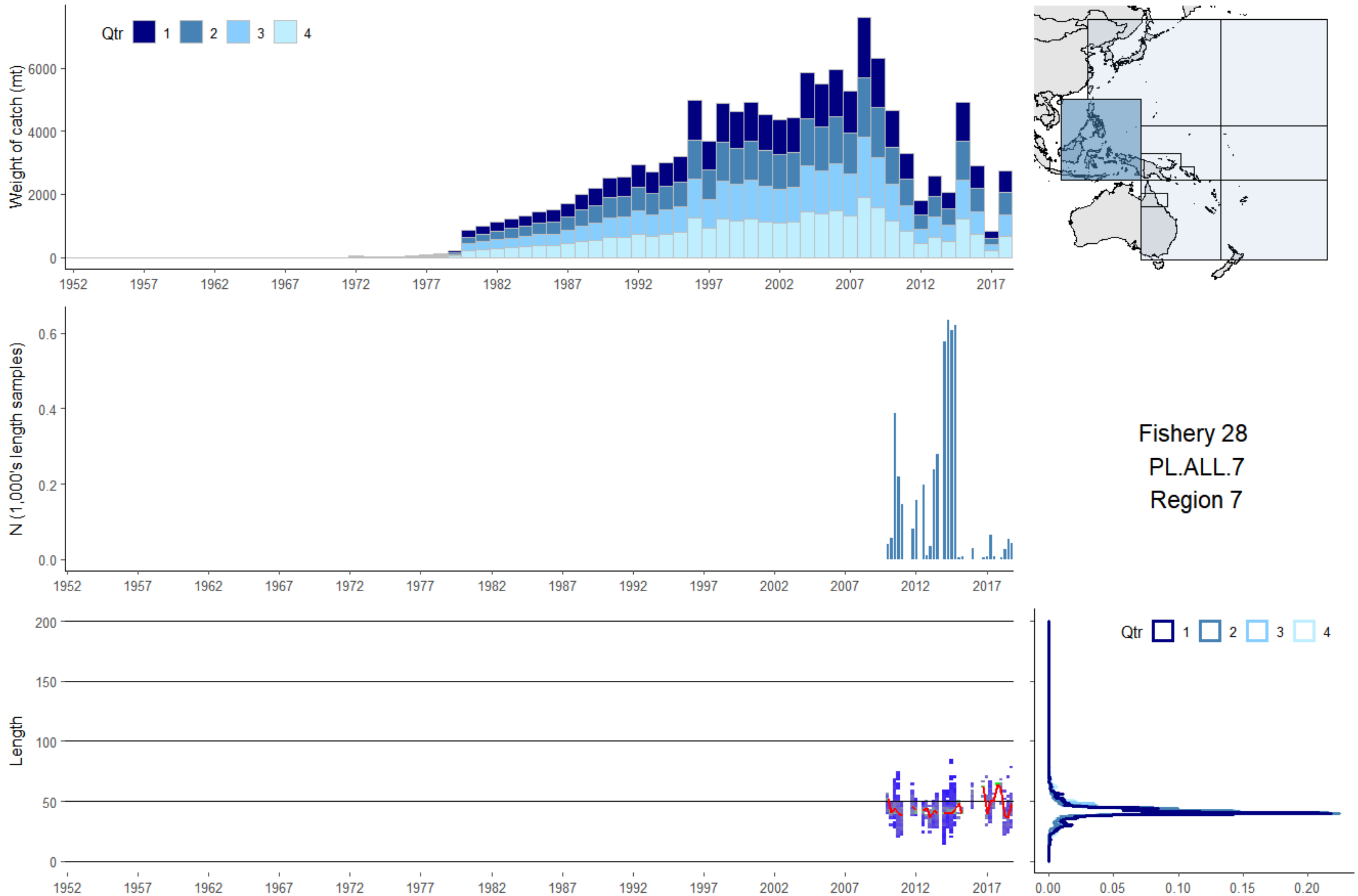

Figure 47: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 28.

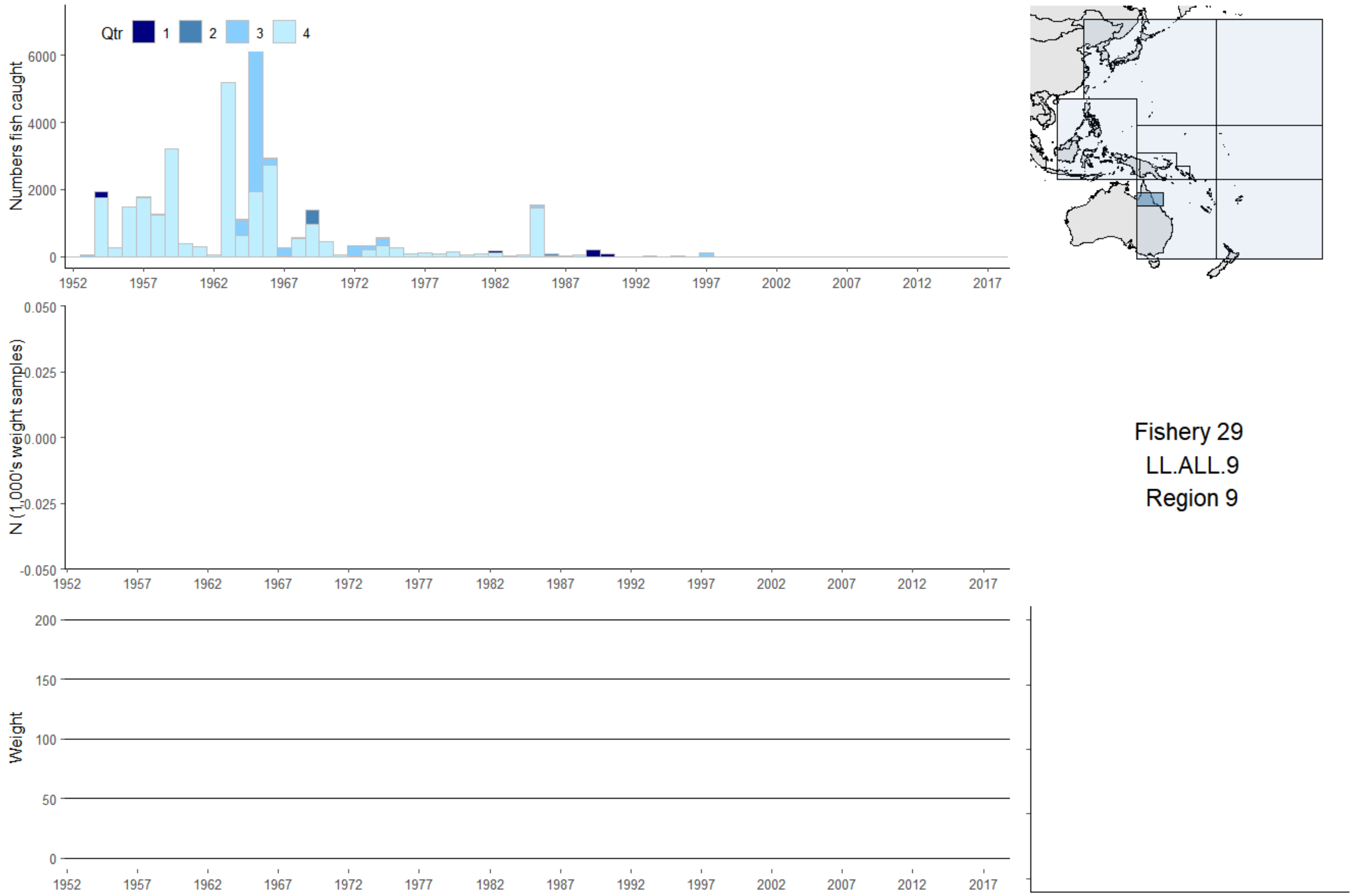

Figure 48: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 29.

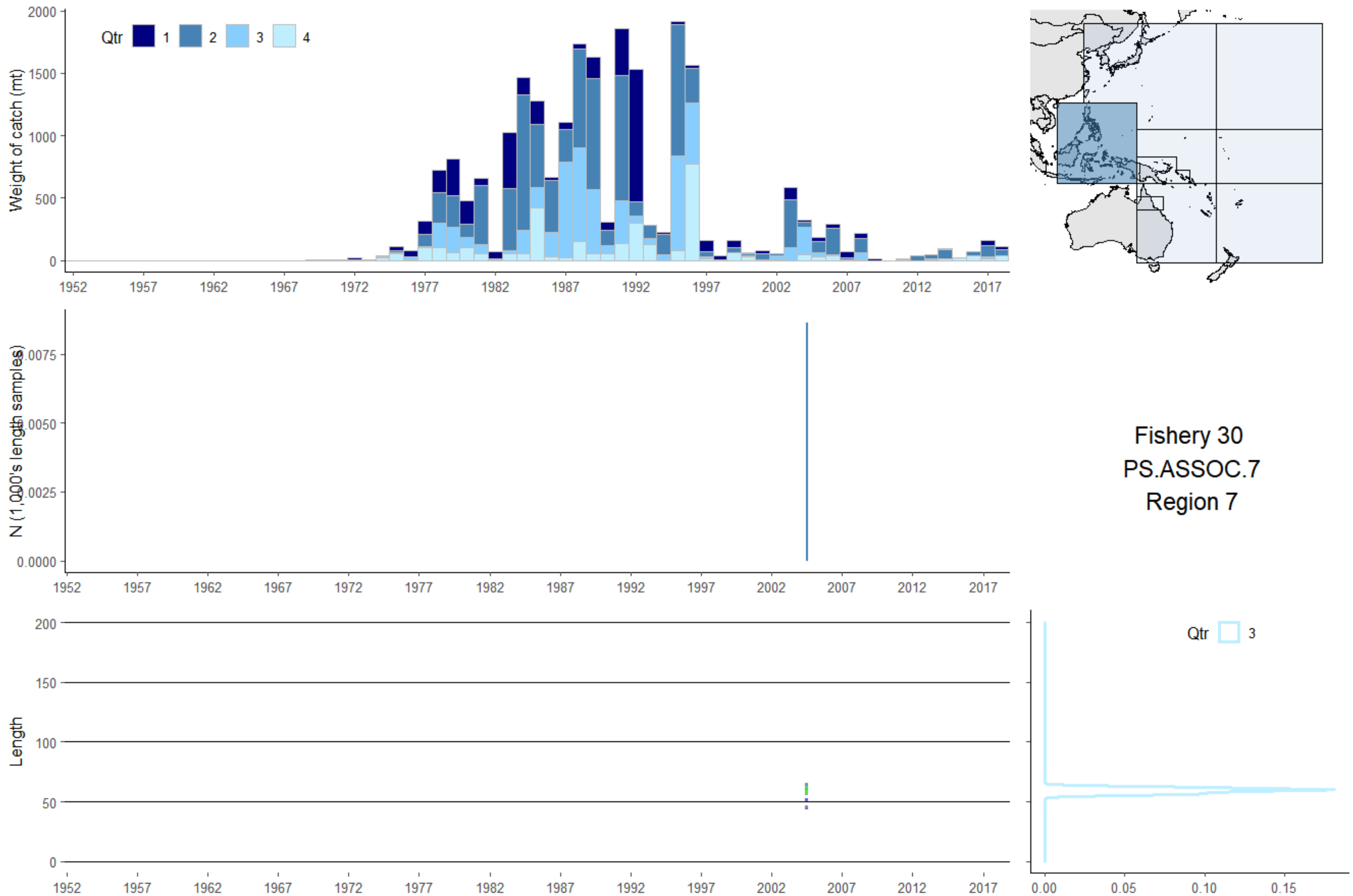

Figure 49: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 30.

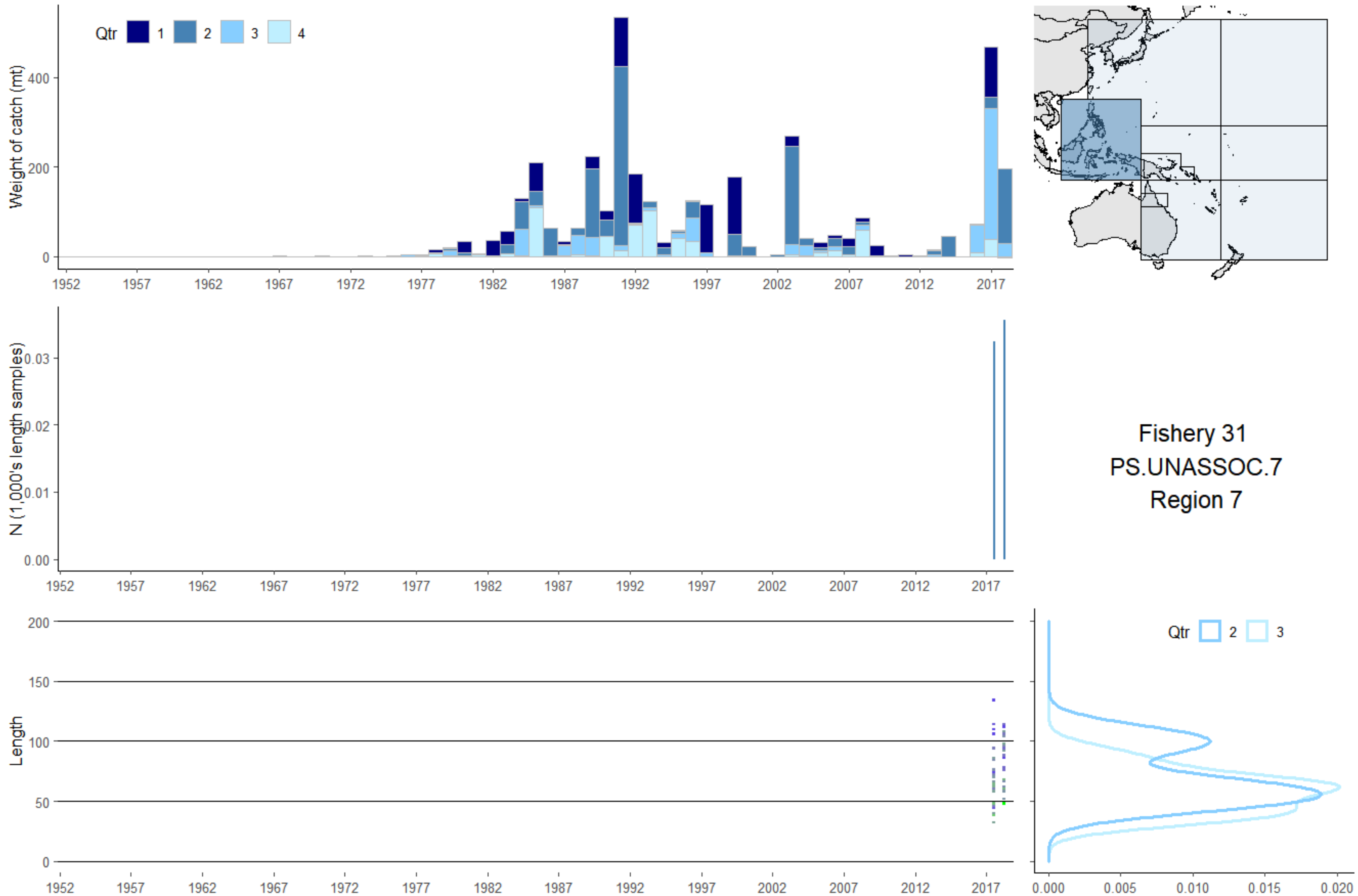

Figure 50: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 31.

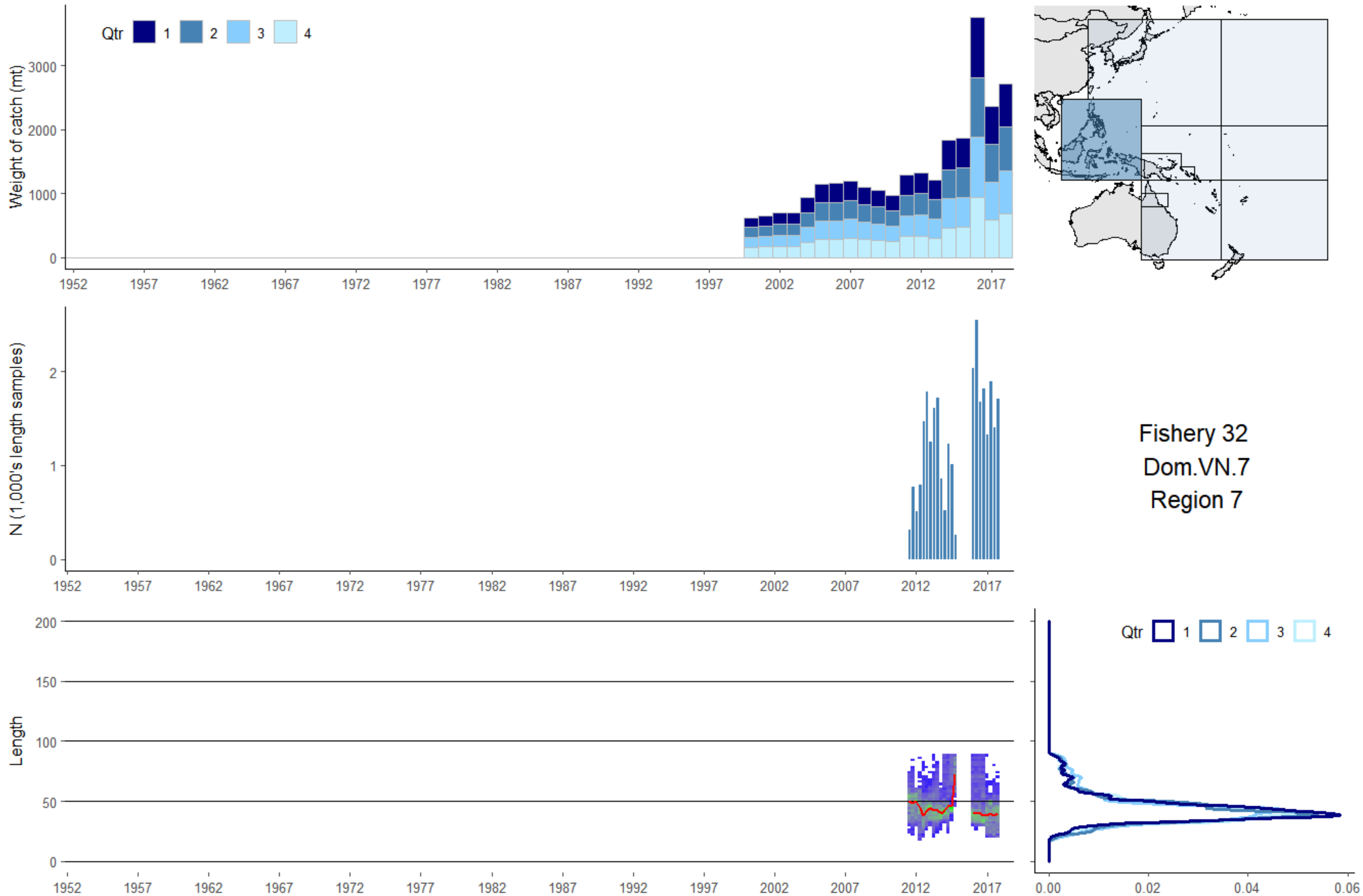

Figure 51: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 32.

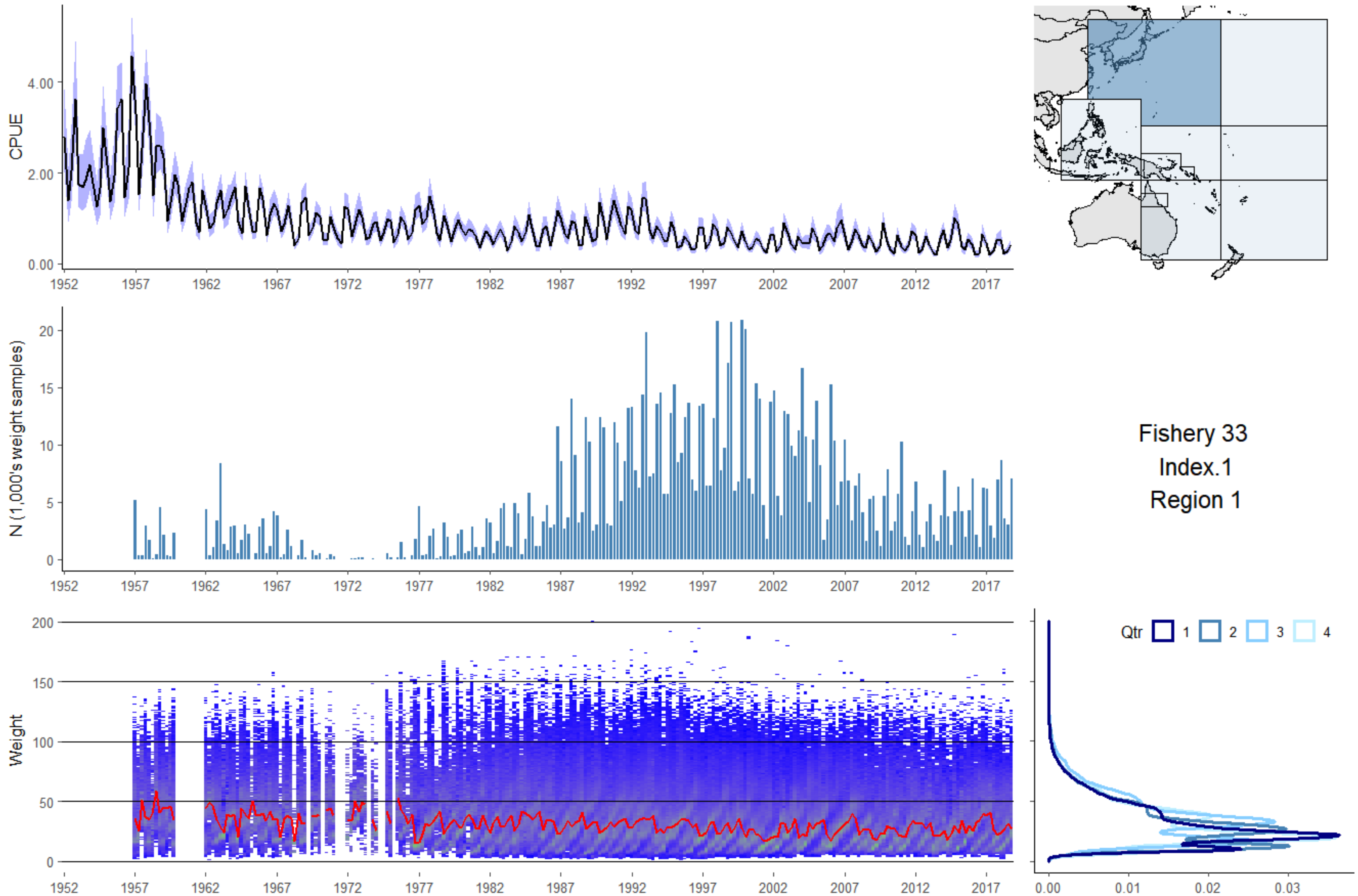

Figure 52: Summary plot of catch of bigeye tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 33.

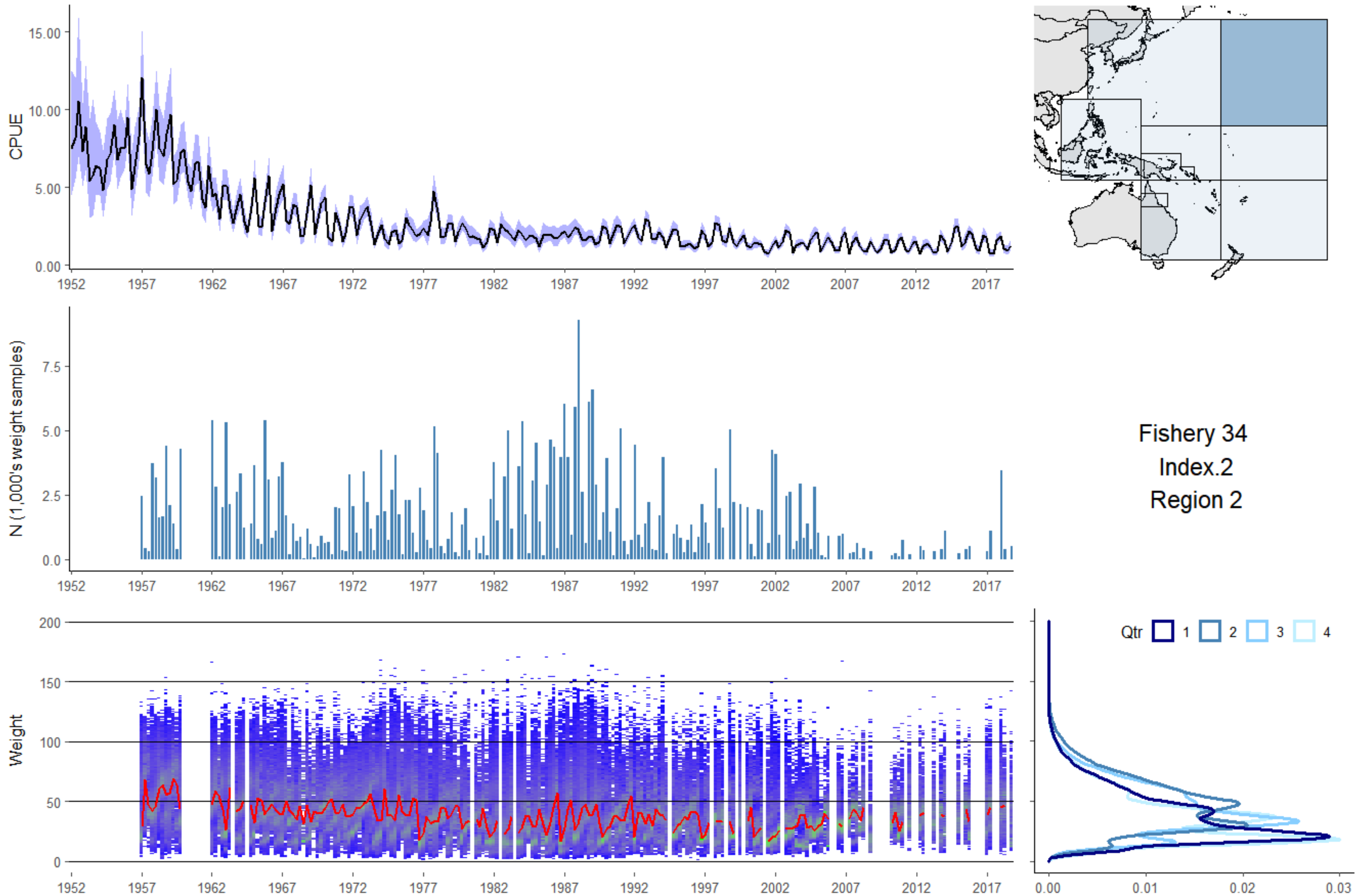

Figure 53: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 34.

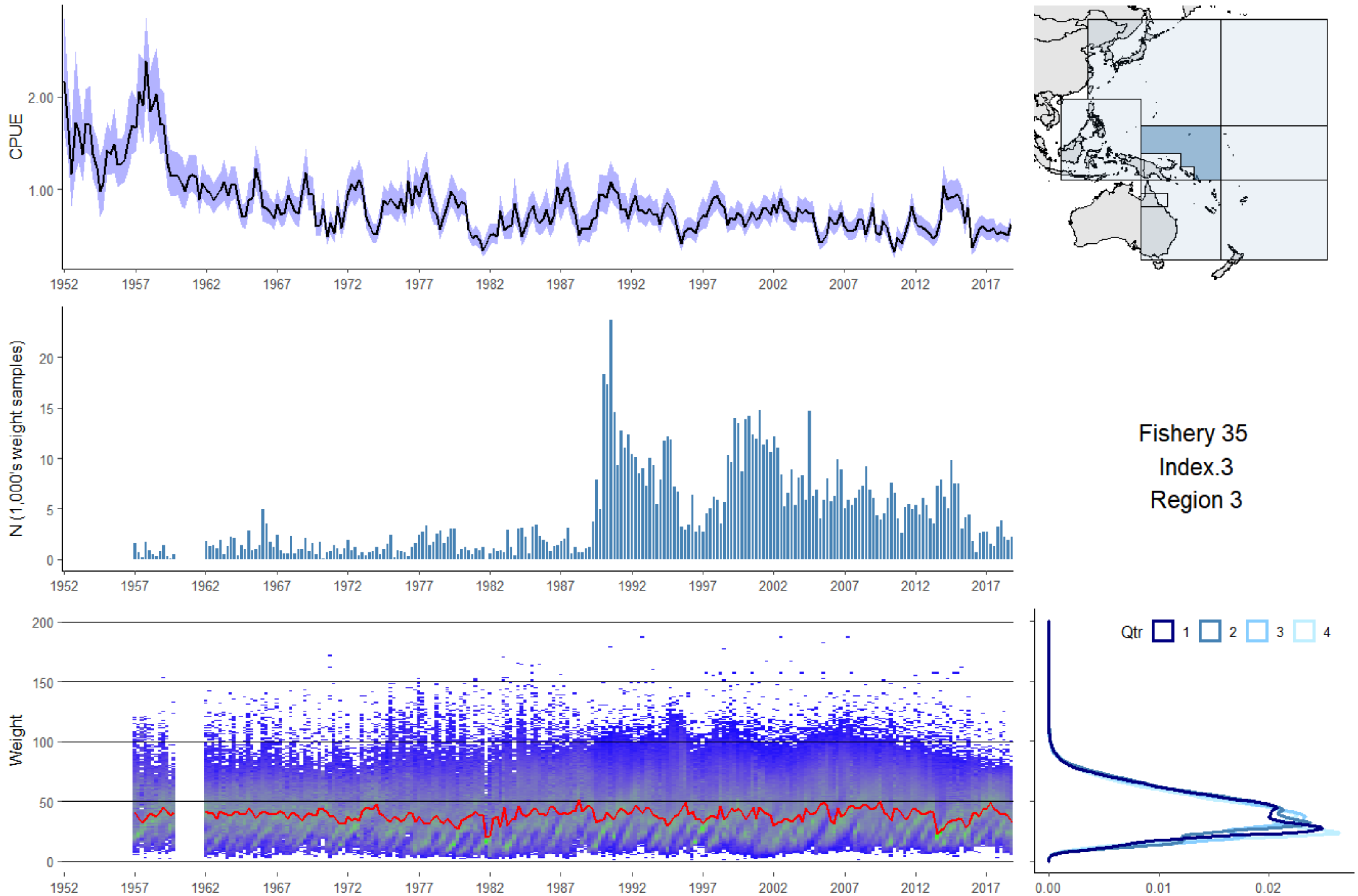

Figure 54: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 35.

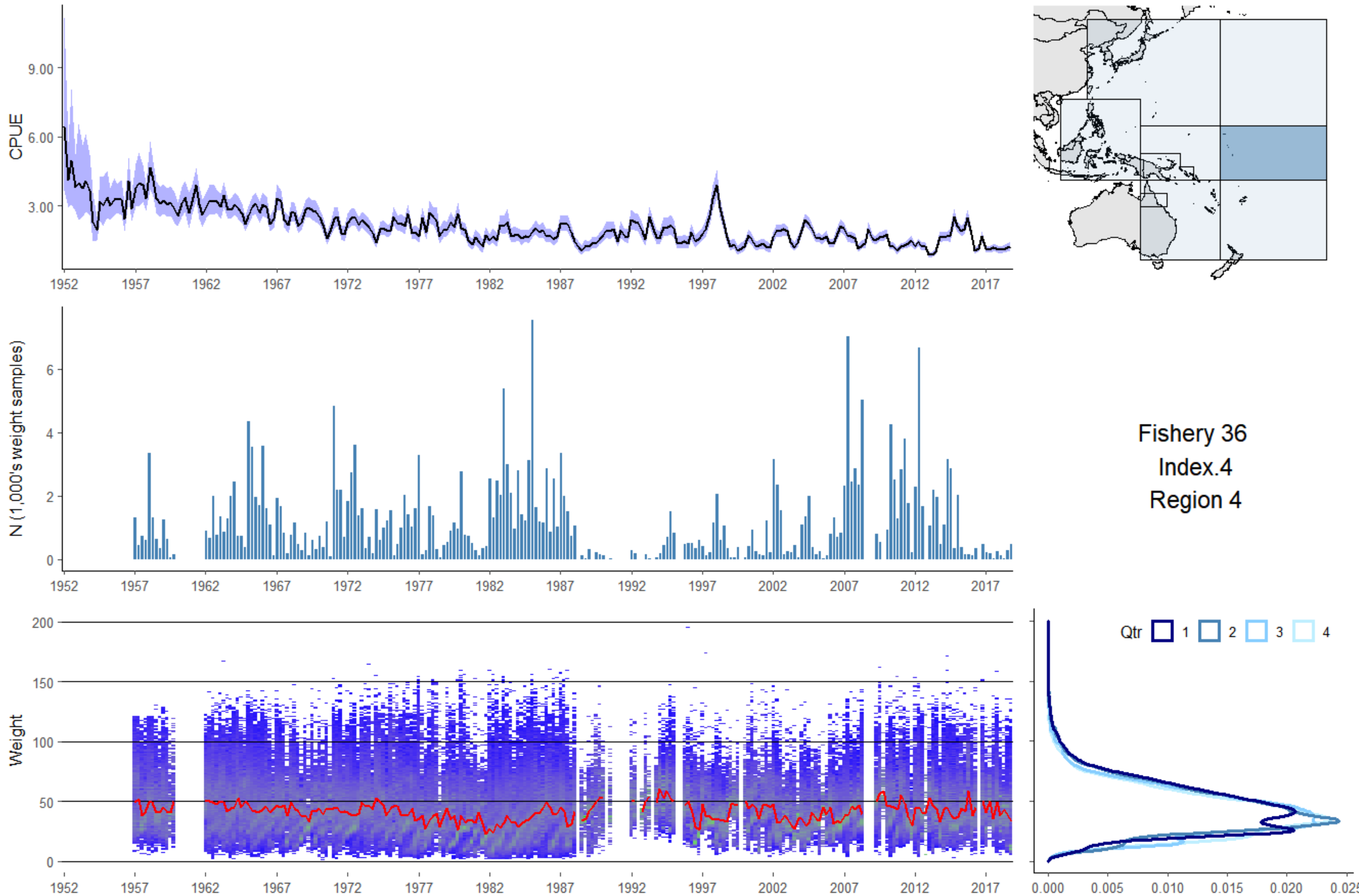

Figure 55: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 36.

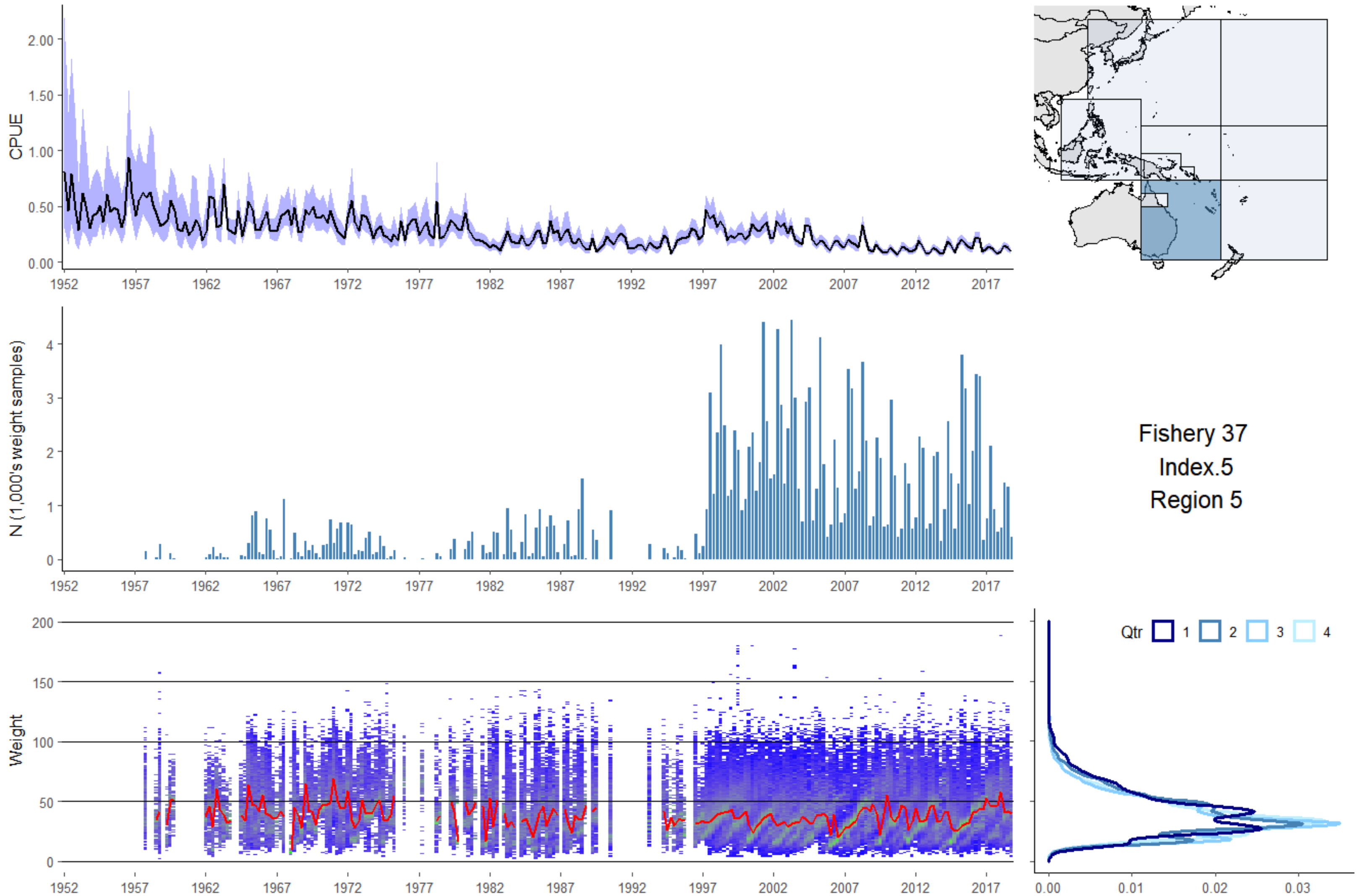

Figure 56: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 37.

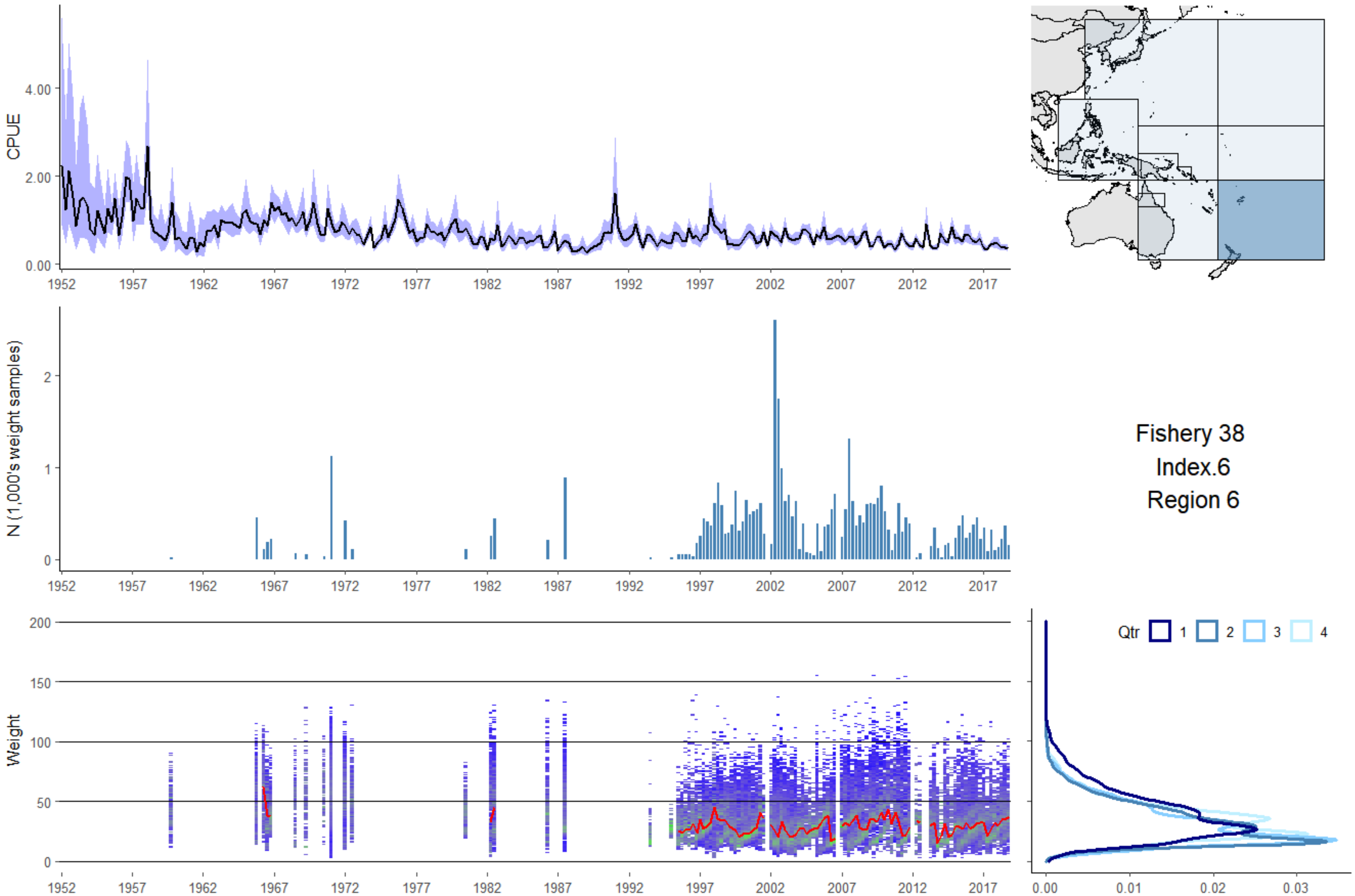

Figure 57: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 38.

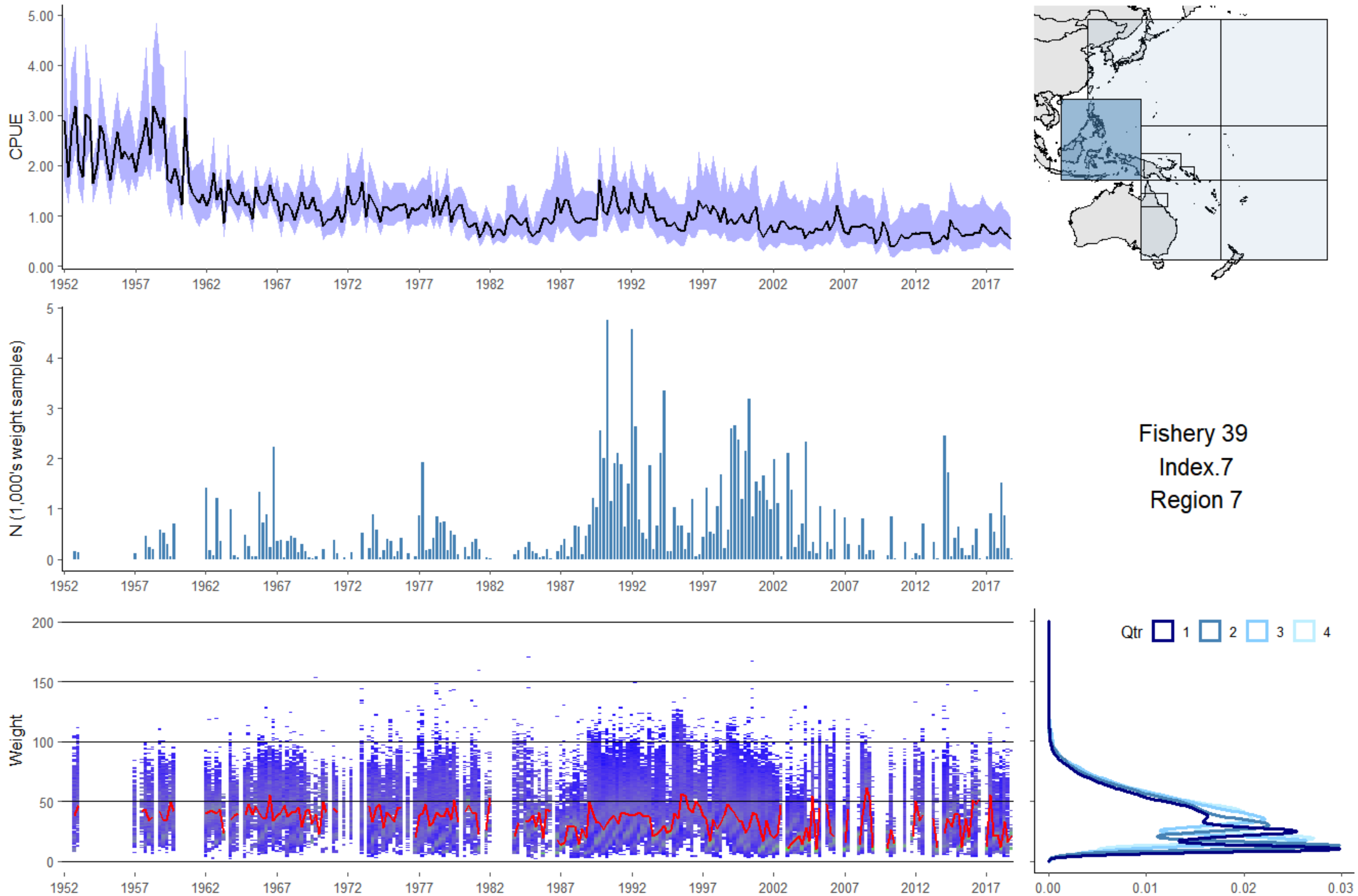

Figure 58: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 39.

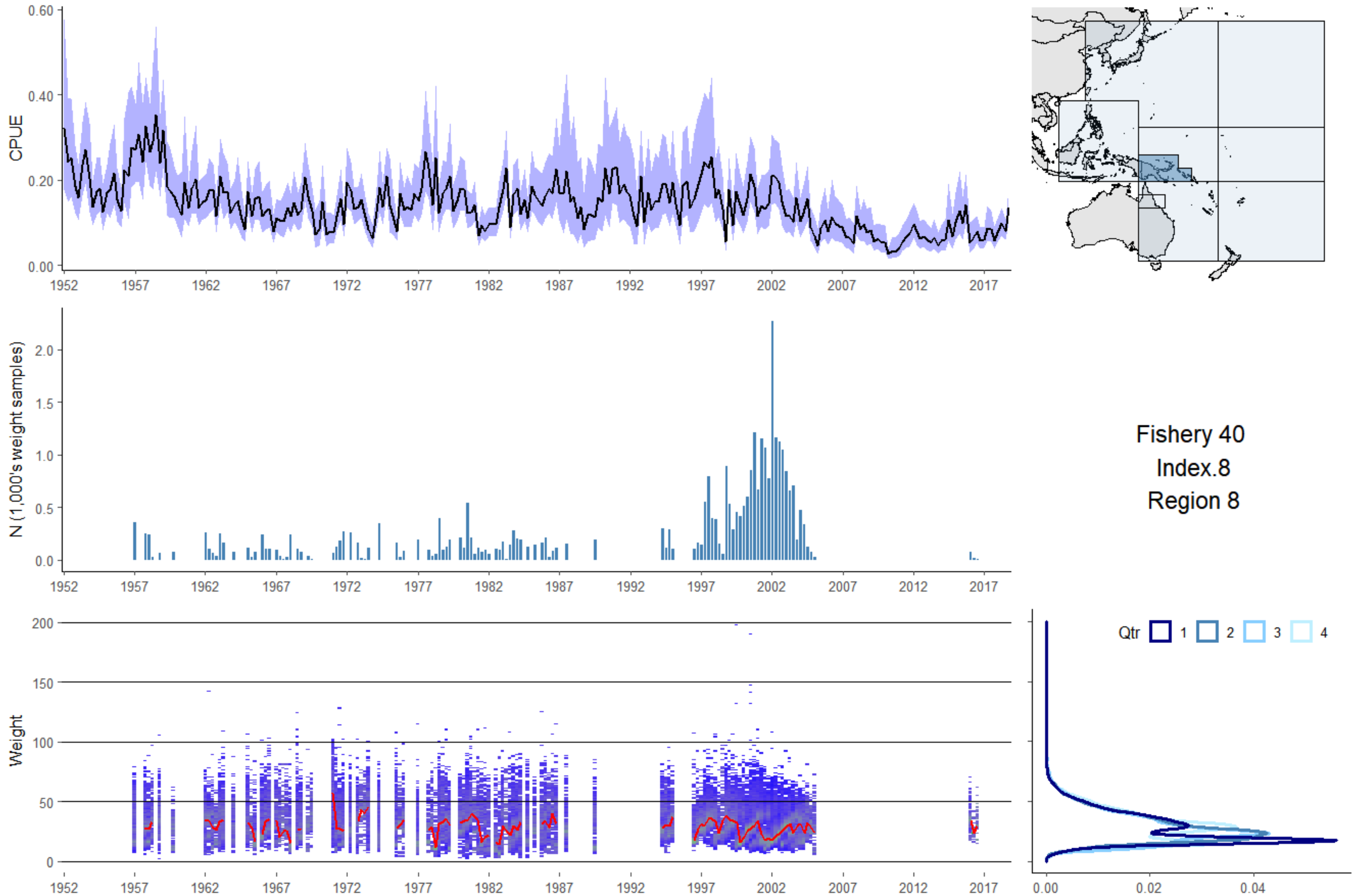

Figure 59: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 40.

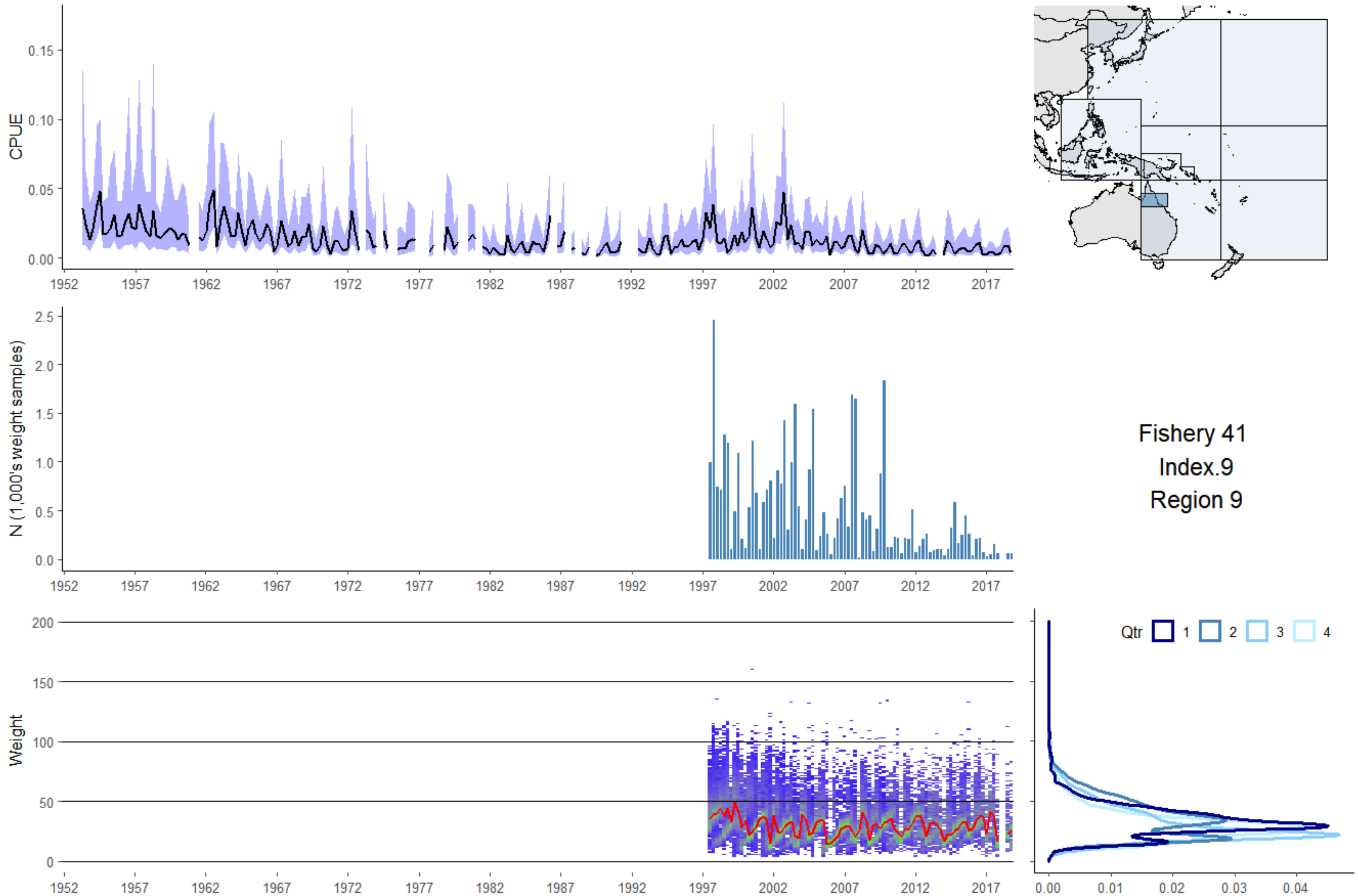

Figure 60: Summary plot of CPUE of bigeye tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 41.

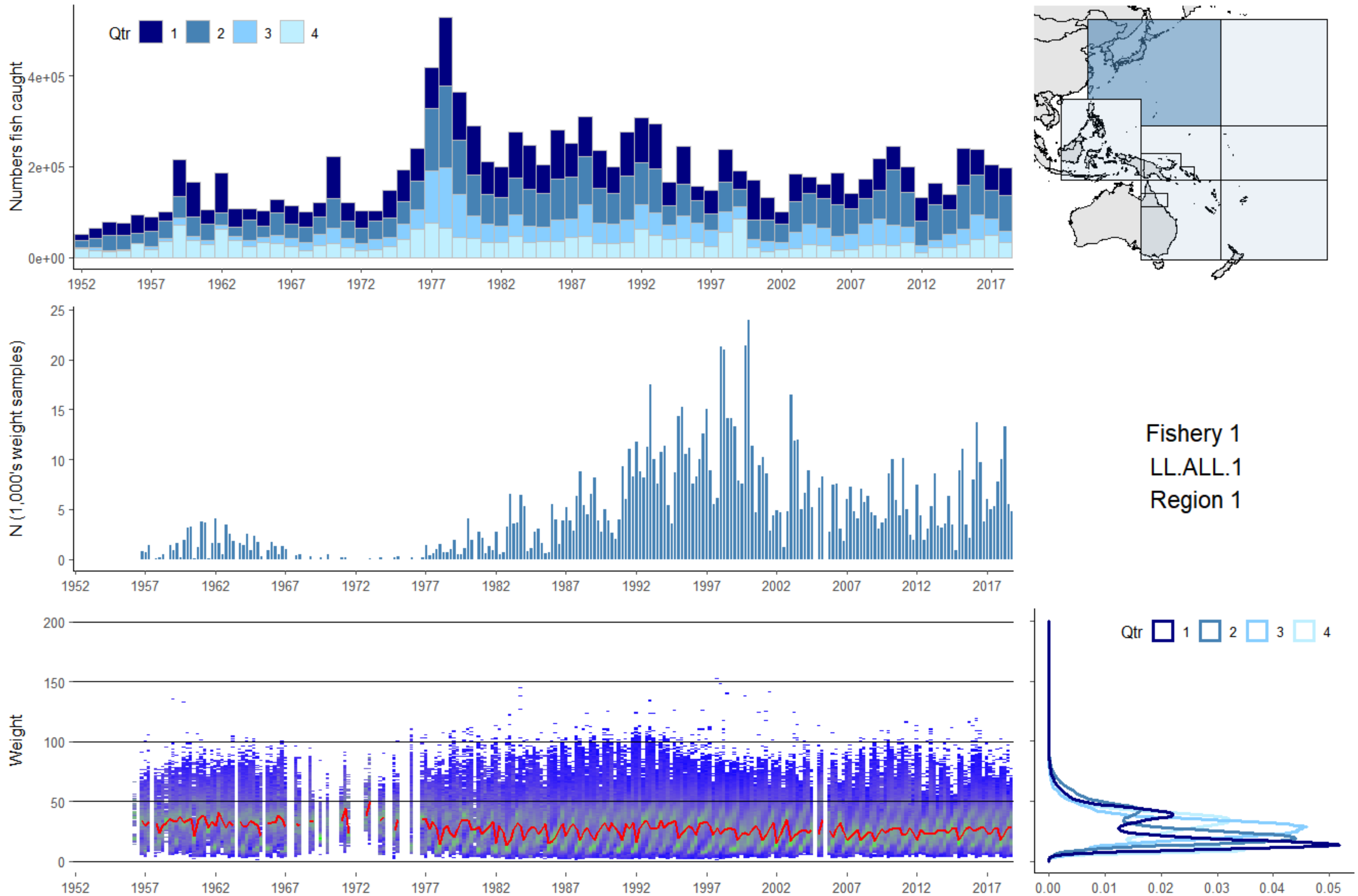

Figure 61: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 1.

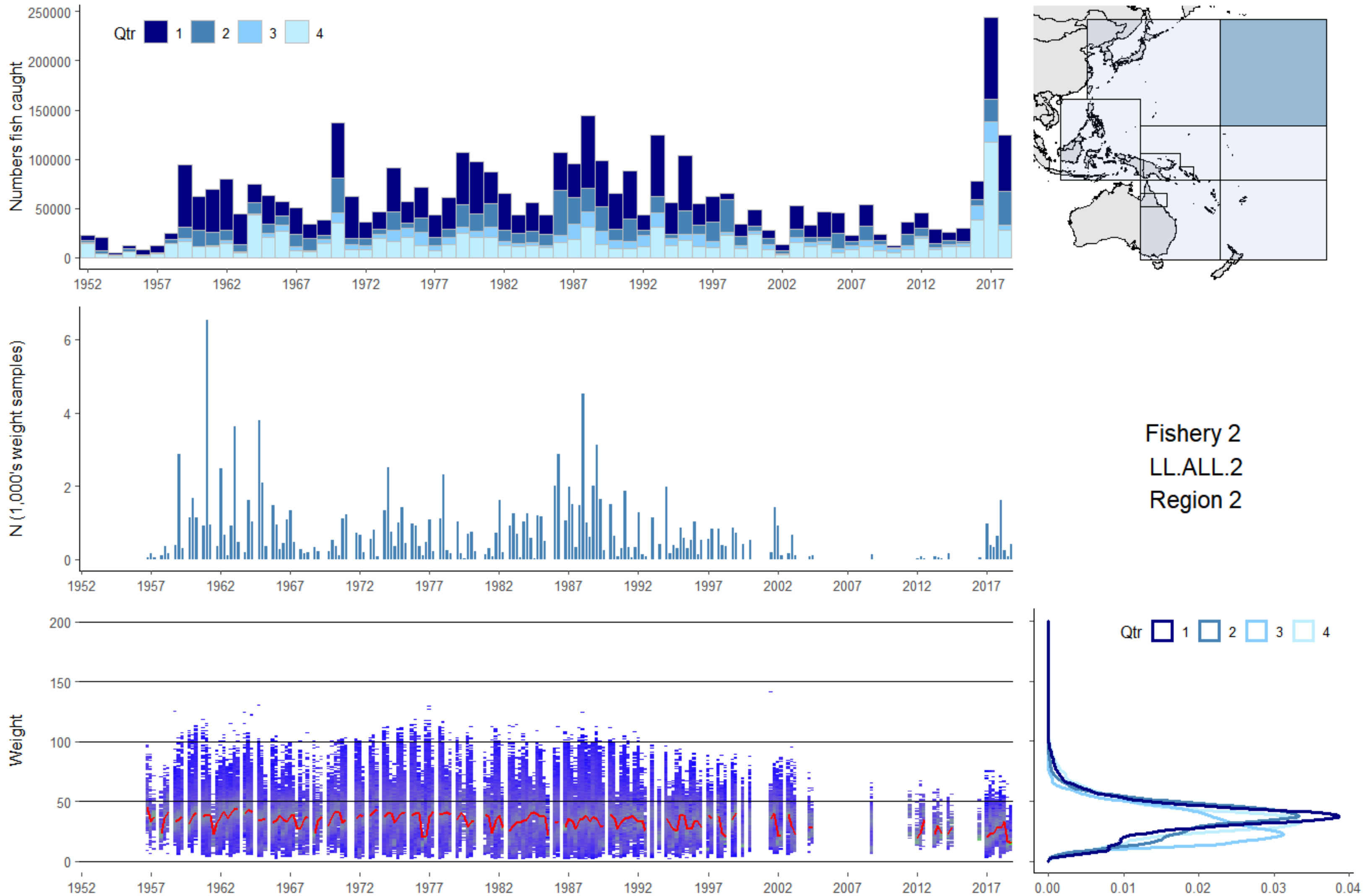

Figure 62: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 2.

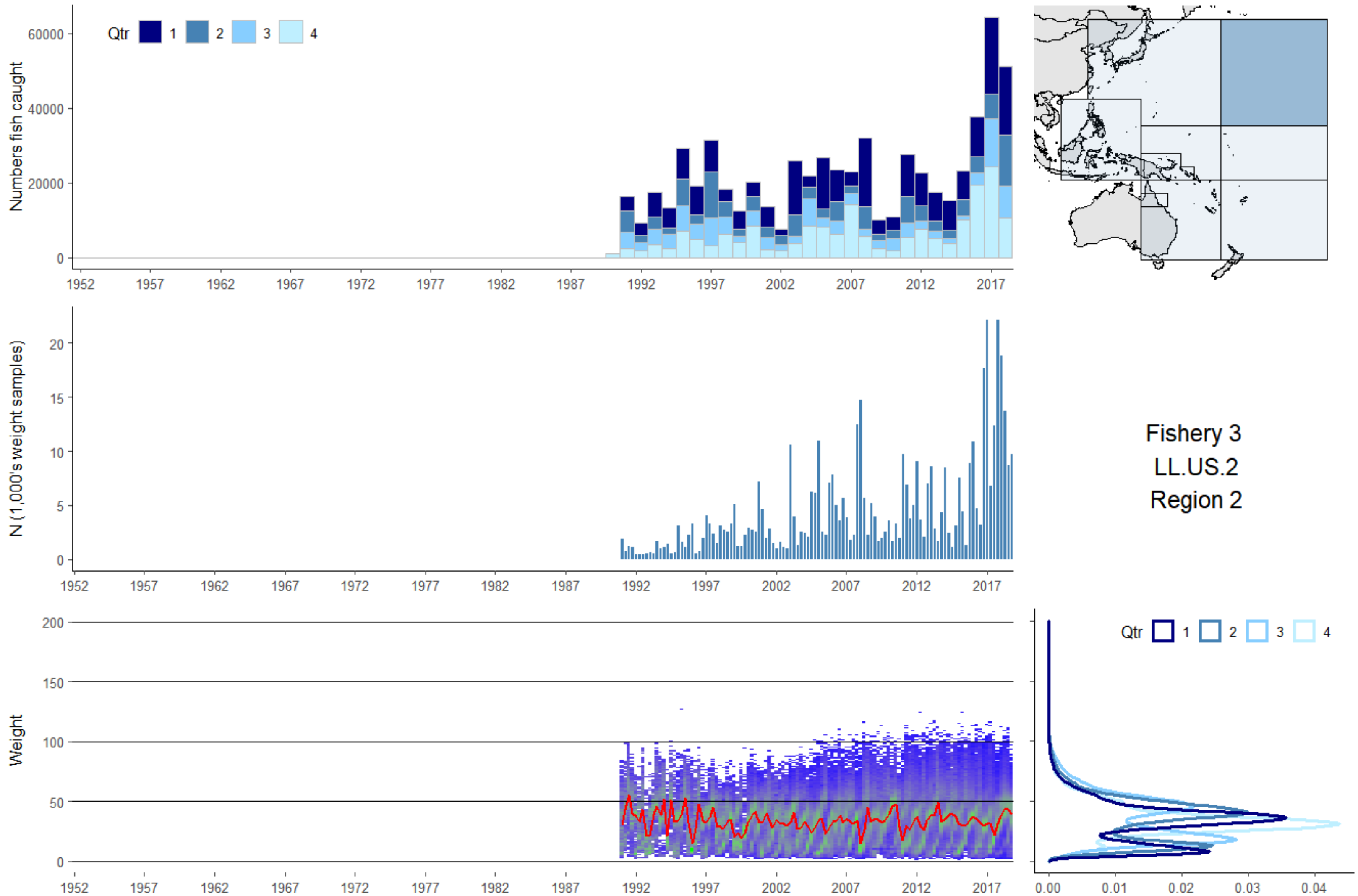

Figure 63: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 3.

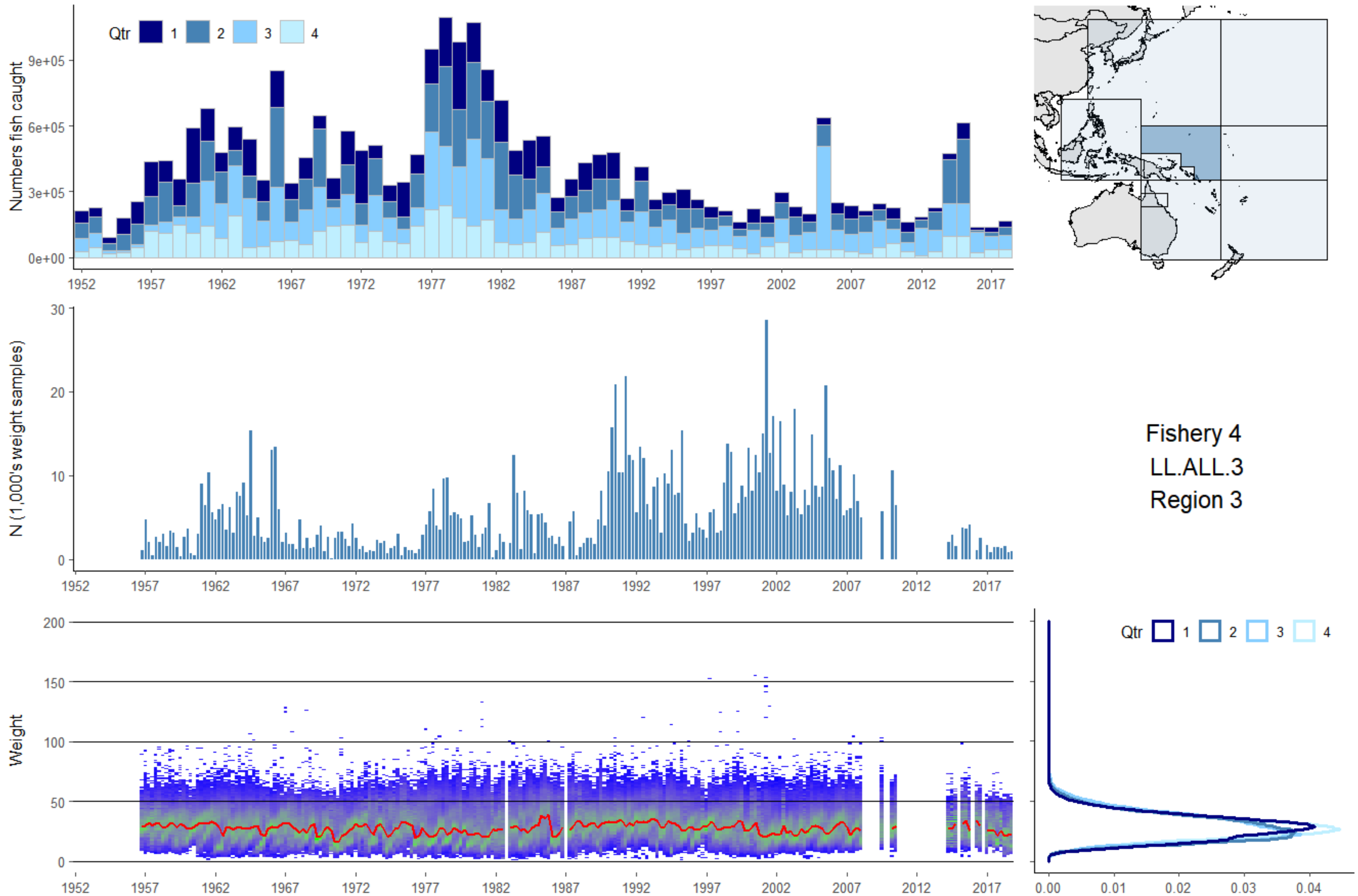

Figure 64: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 4.

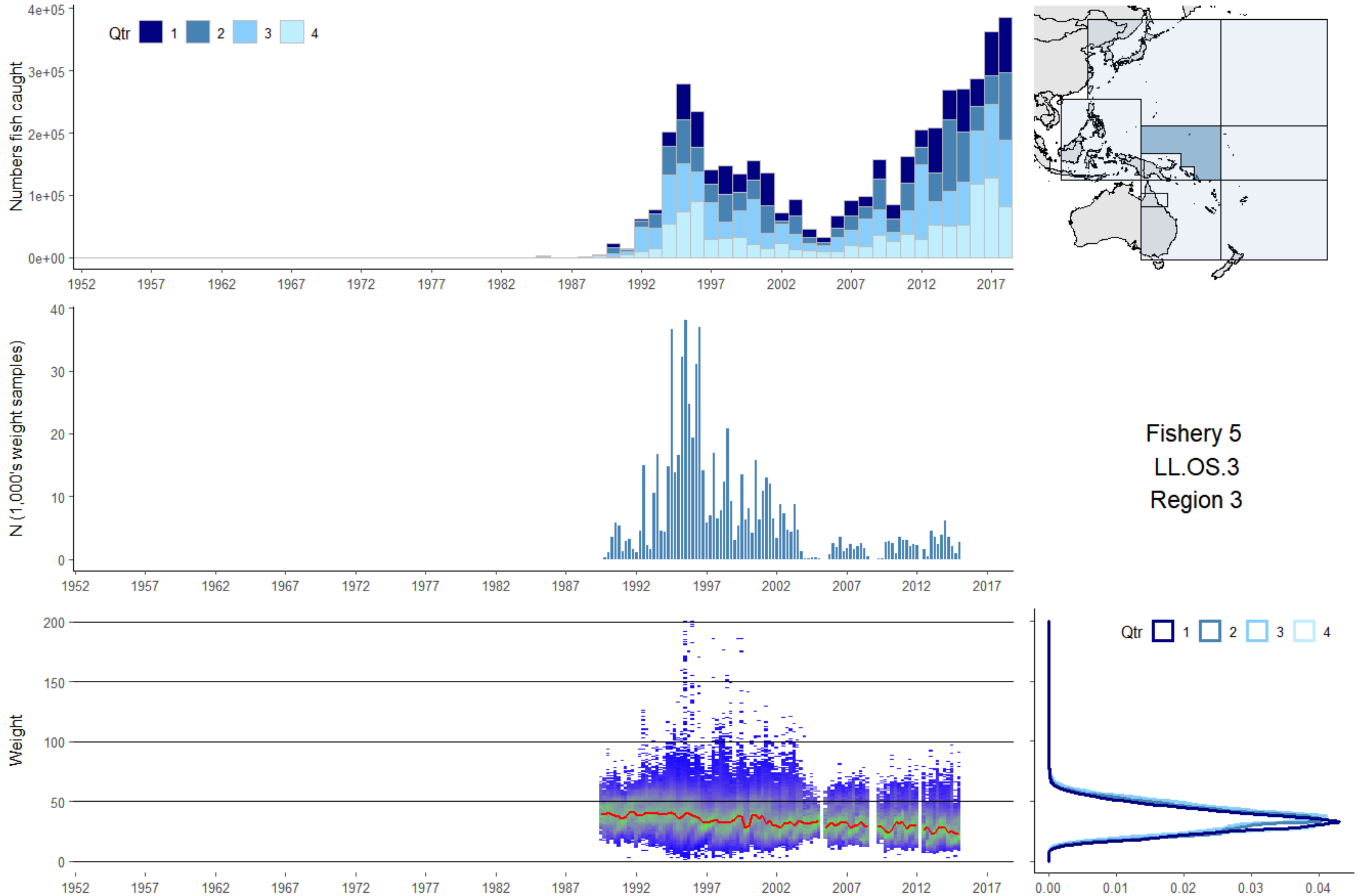

Figure 65: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 5.

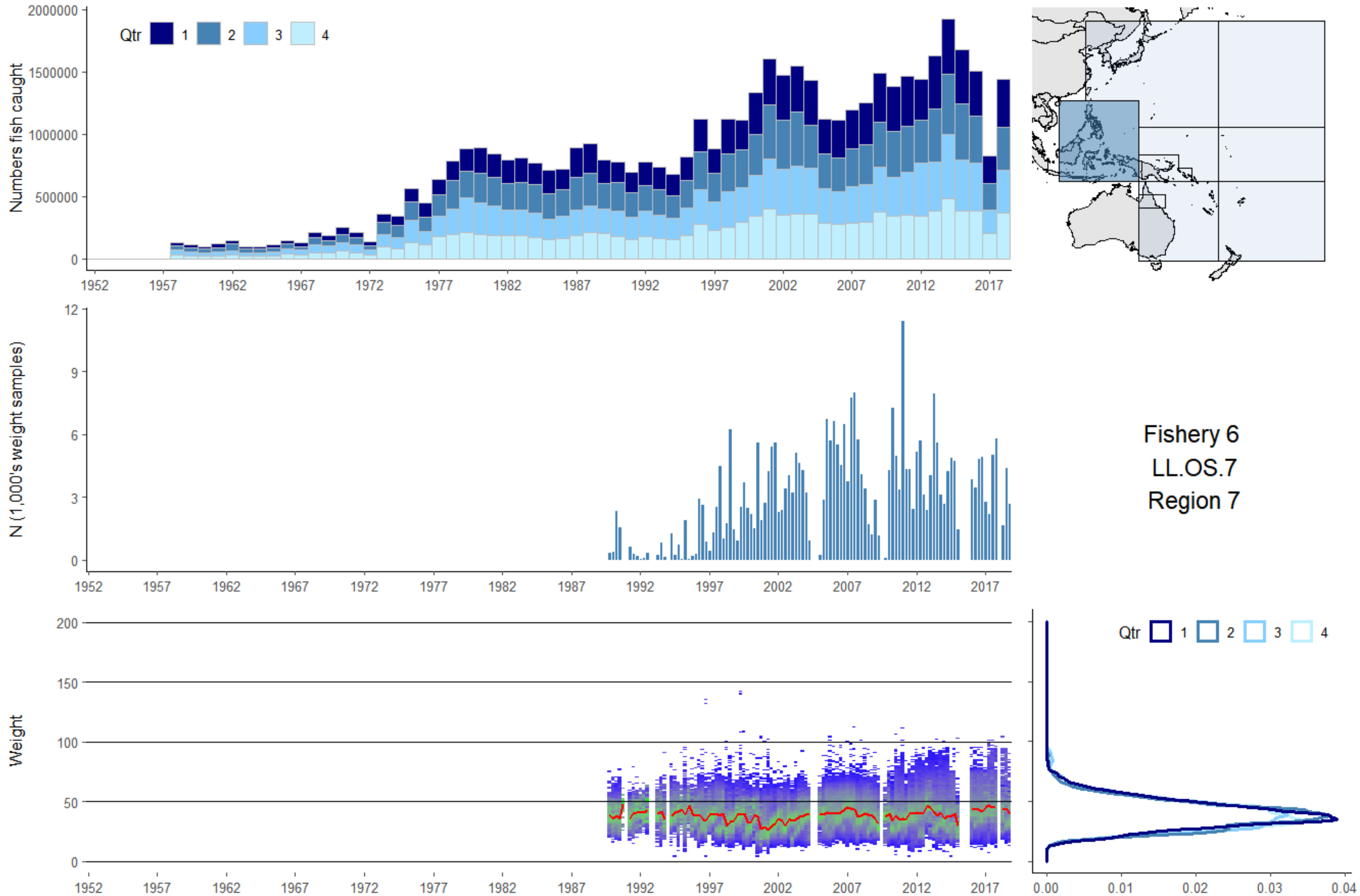

Figure 66: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 6.

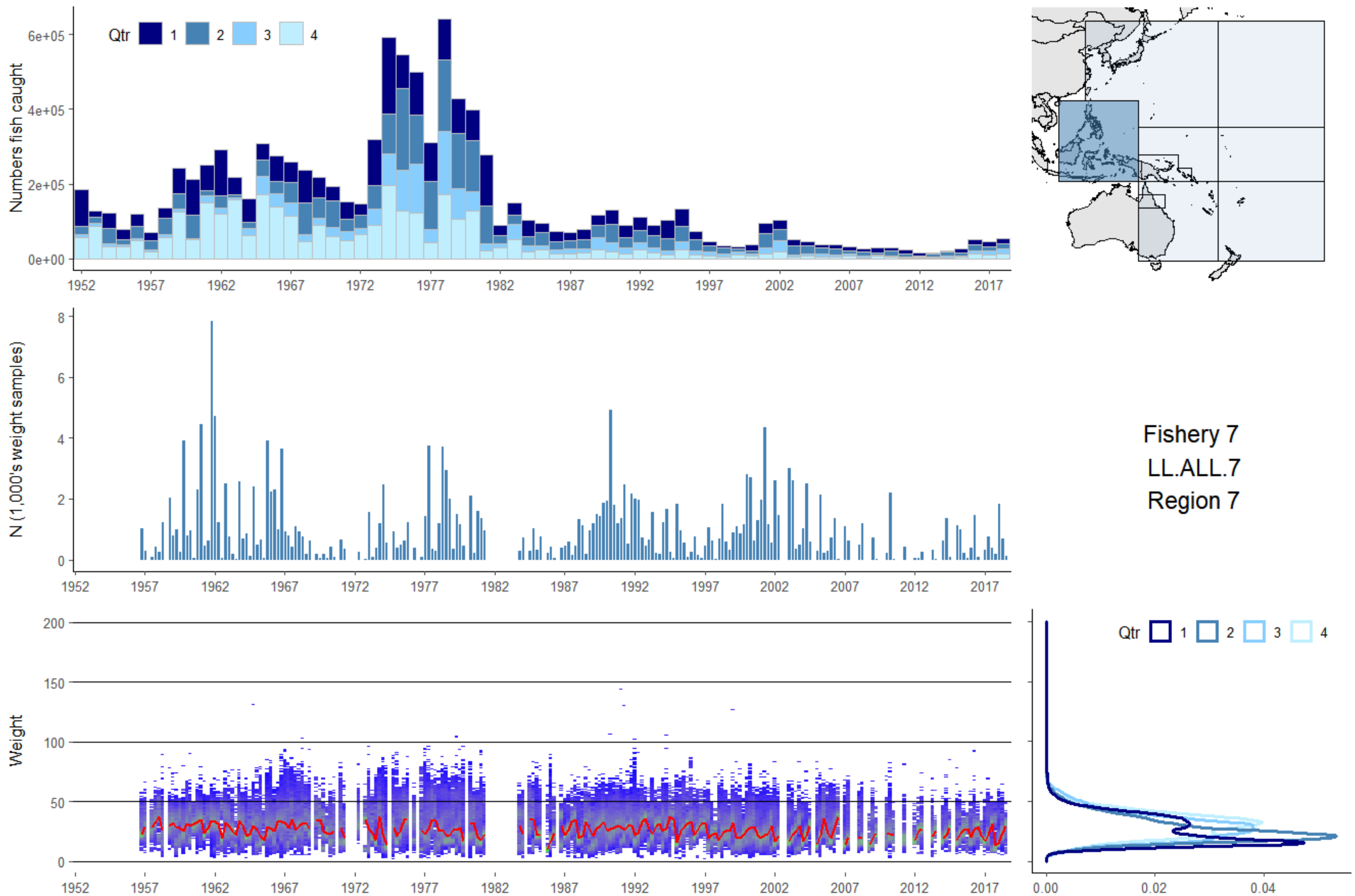

Figure 67: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 7.

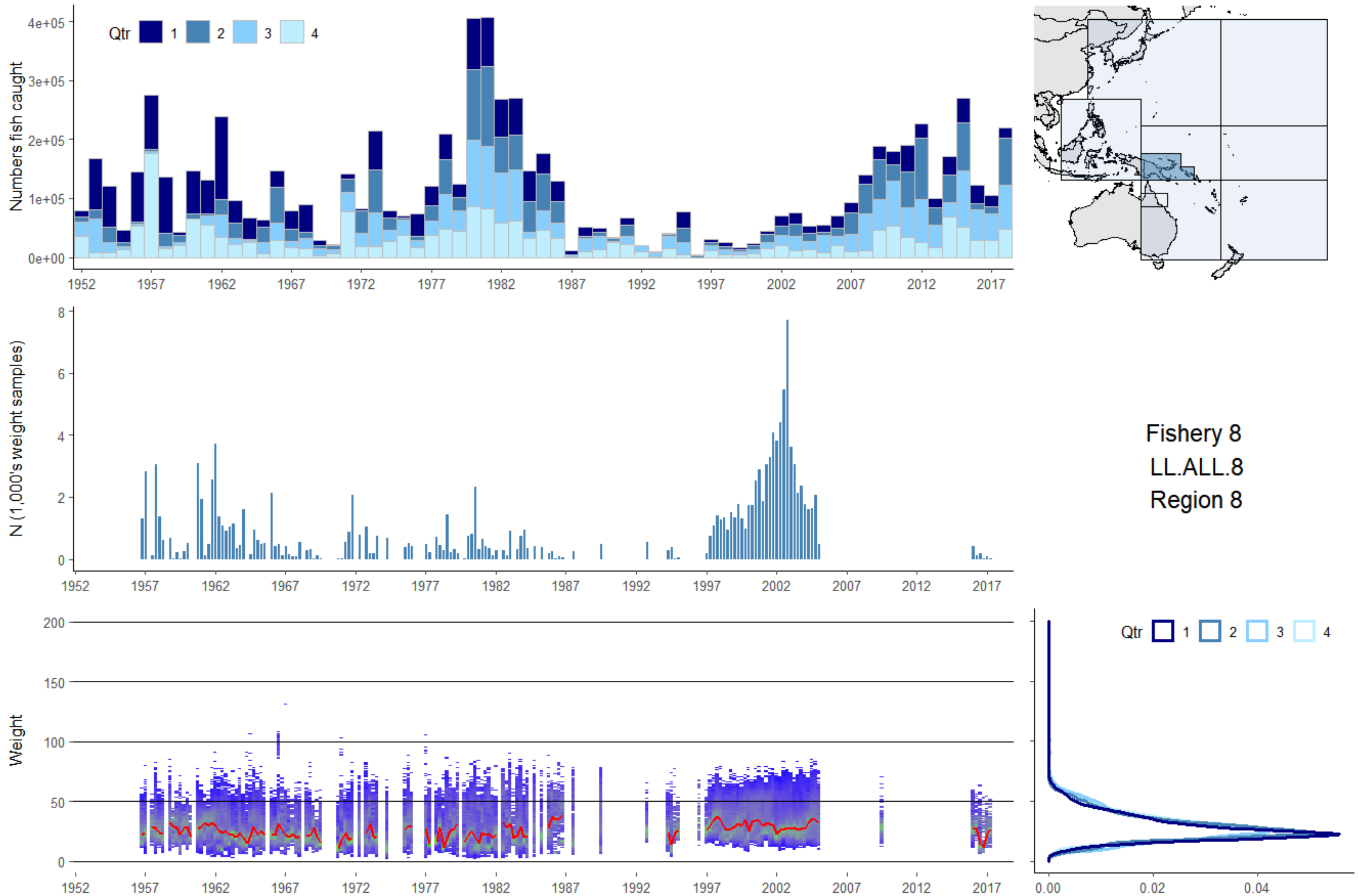

Figure 68: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 8.

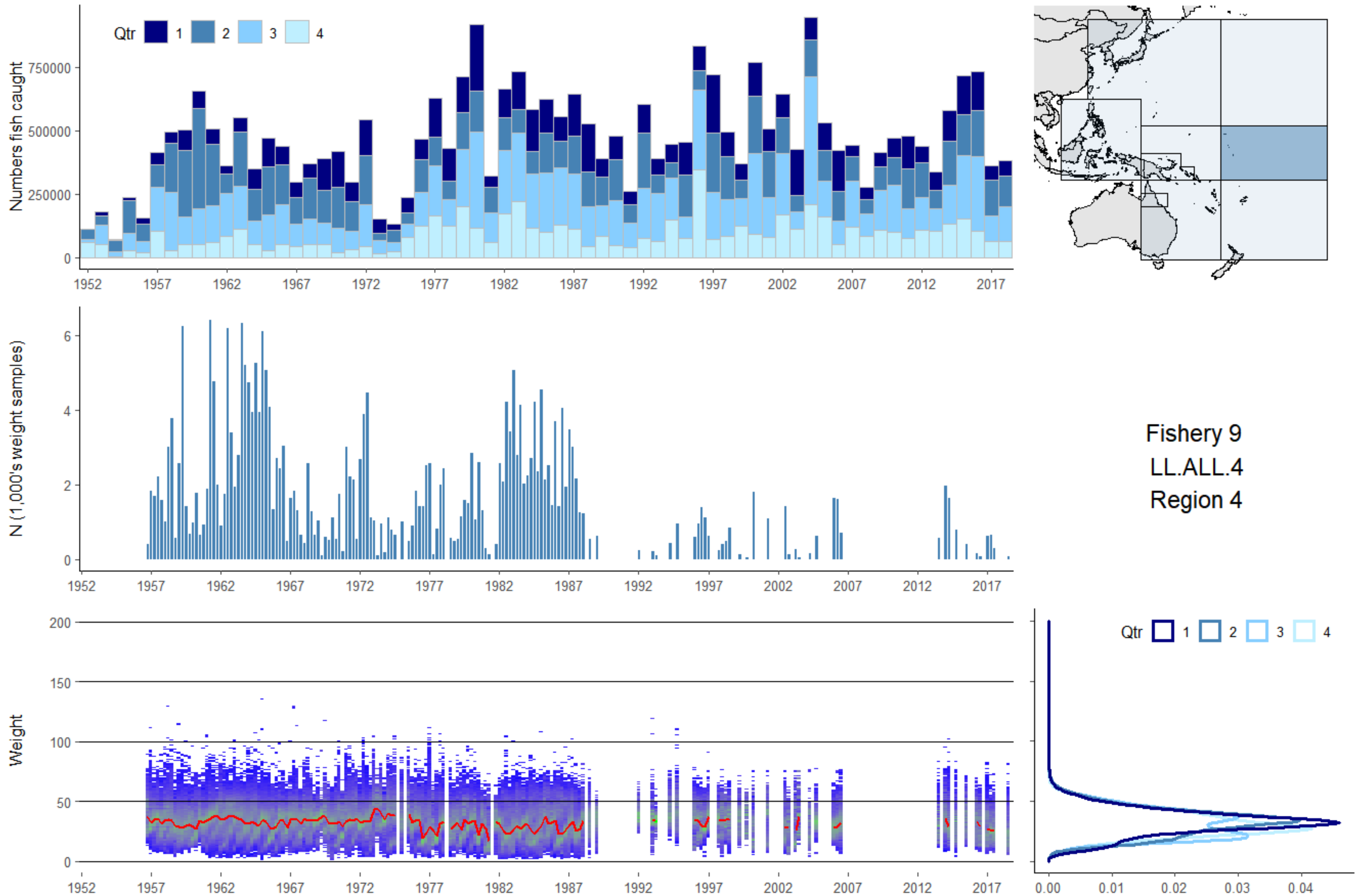

Figure 69: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 9.

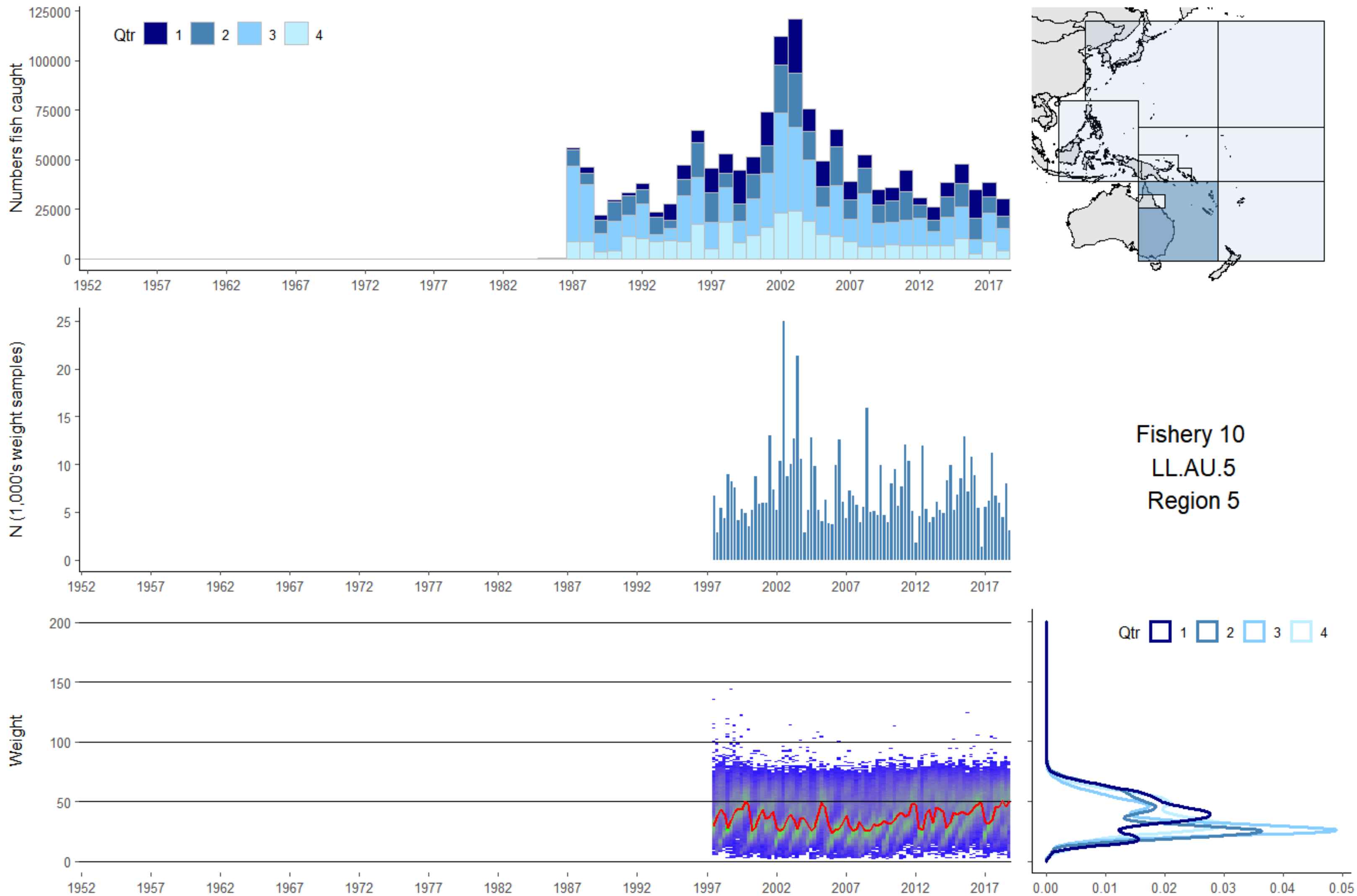

Figure 70: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 10.

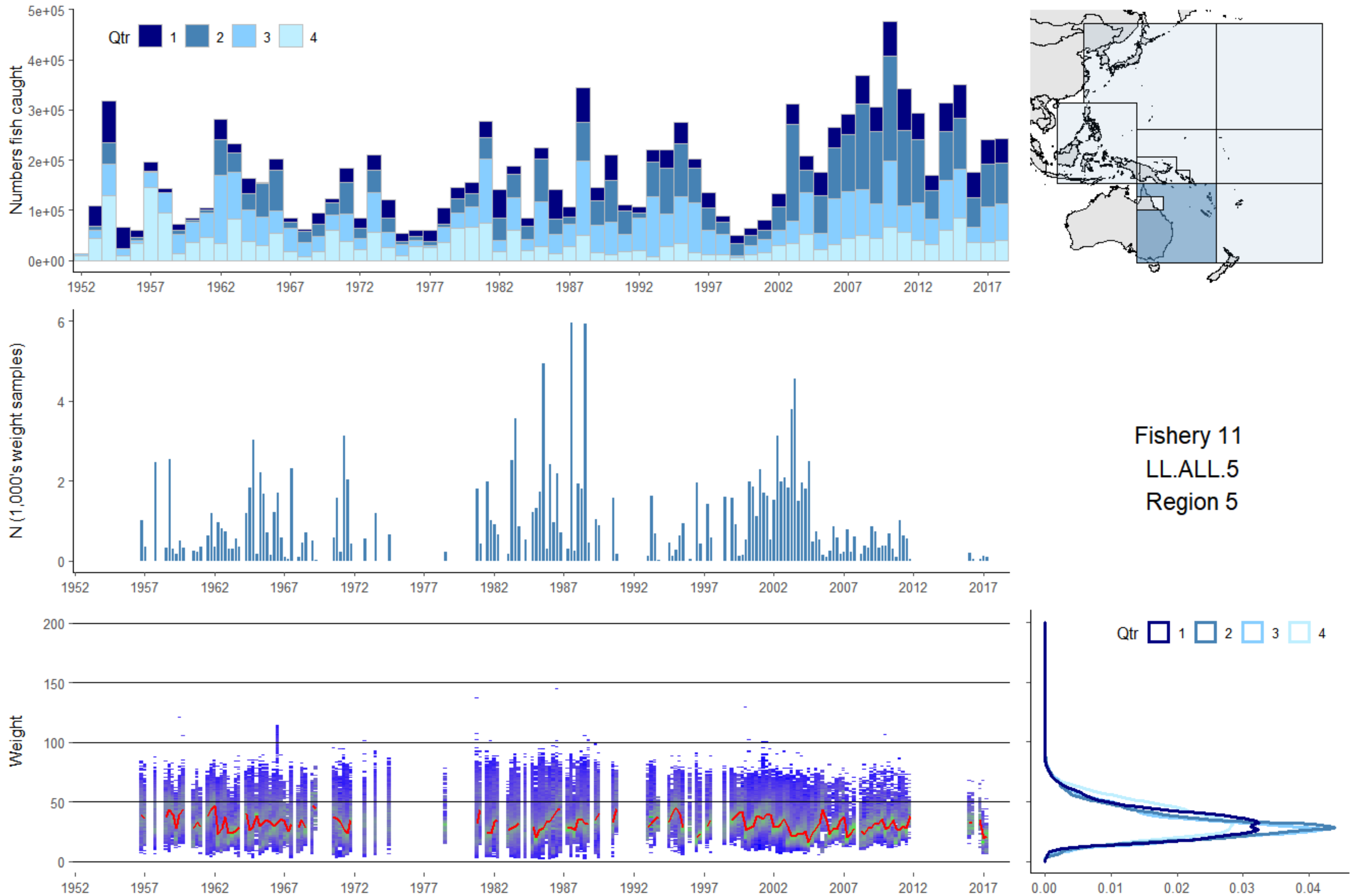

Figure 71: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 11.

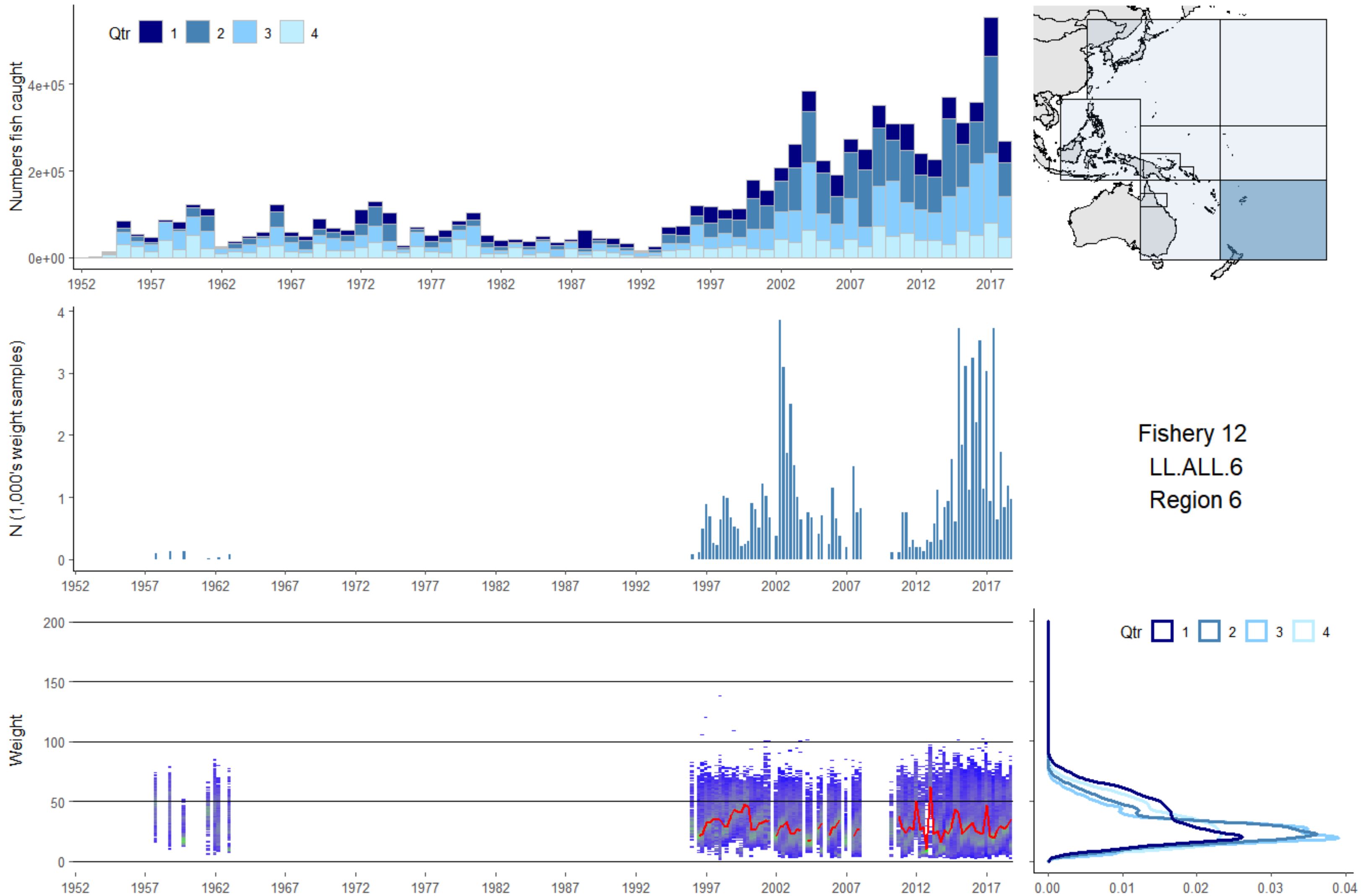

Figure 72: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 12.

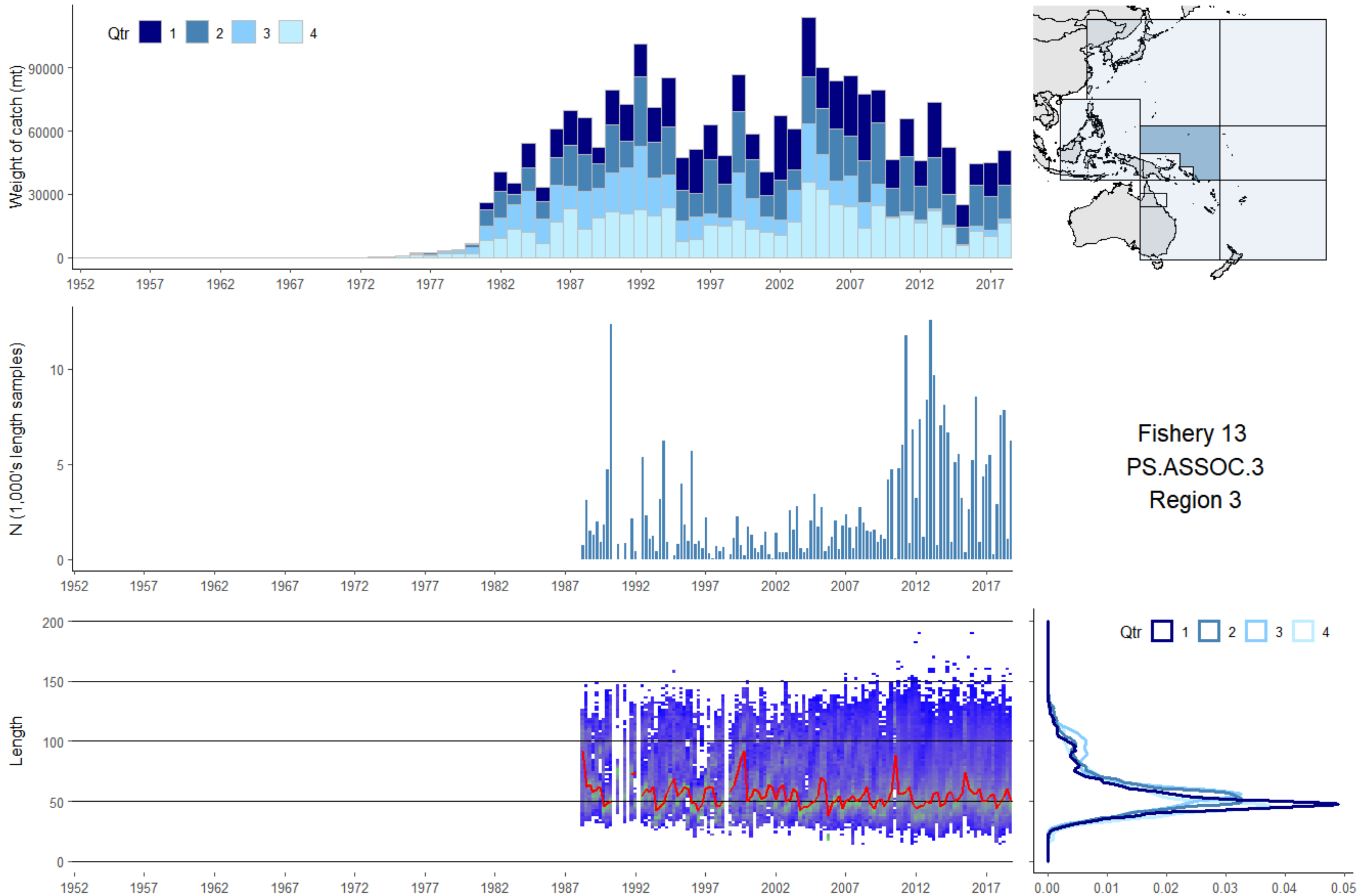

Figure 73: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 13.

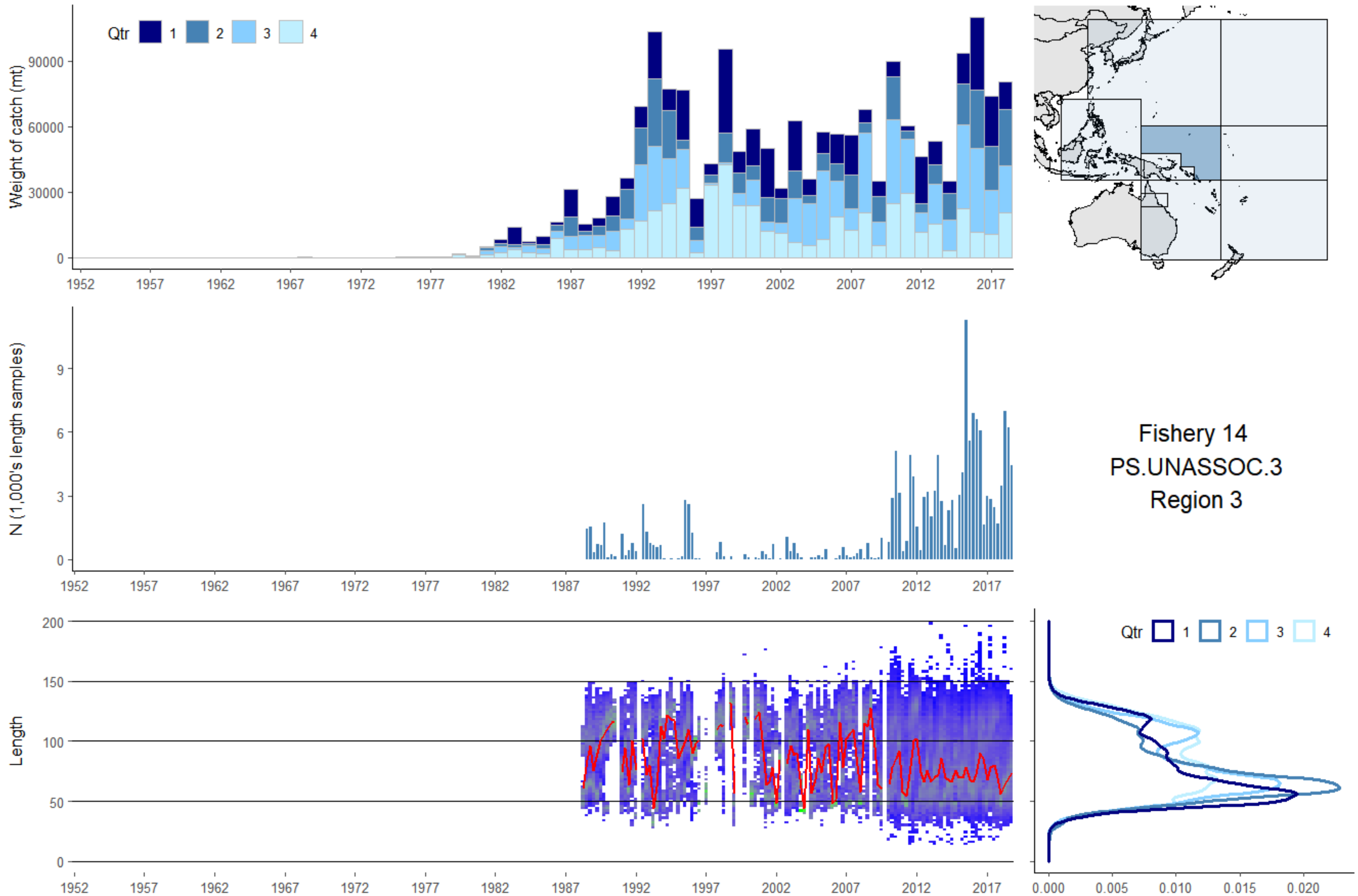

Figure 74: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 14.

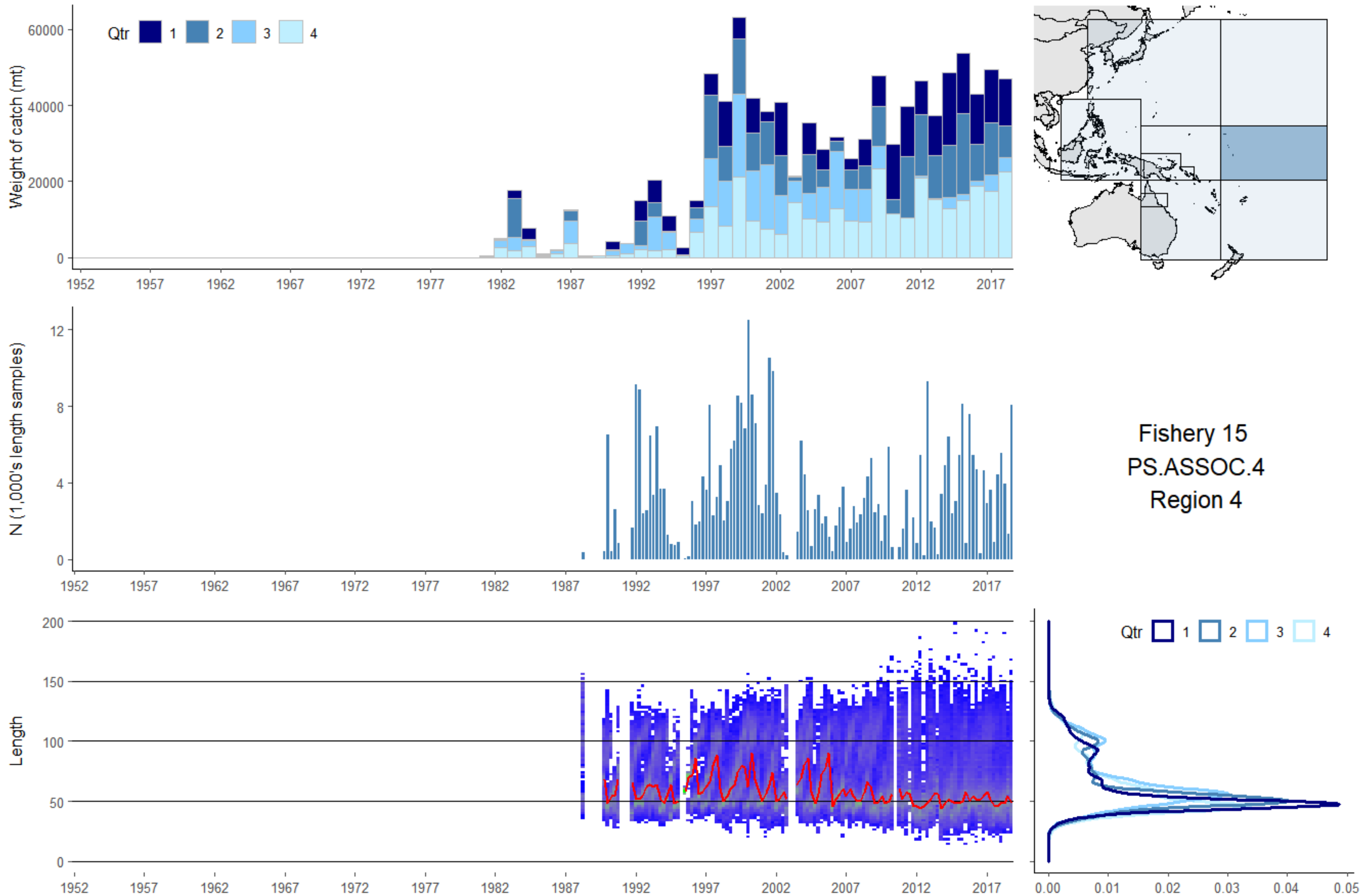

Figure 75: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 15.

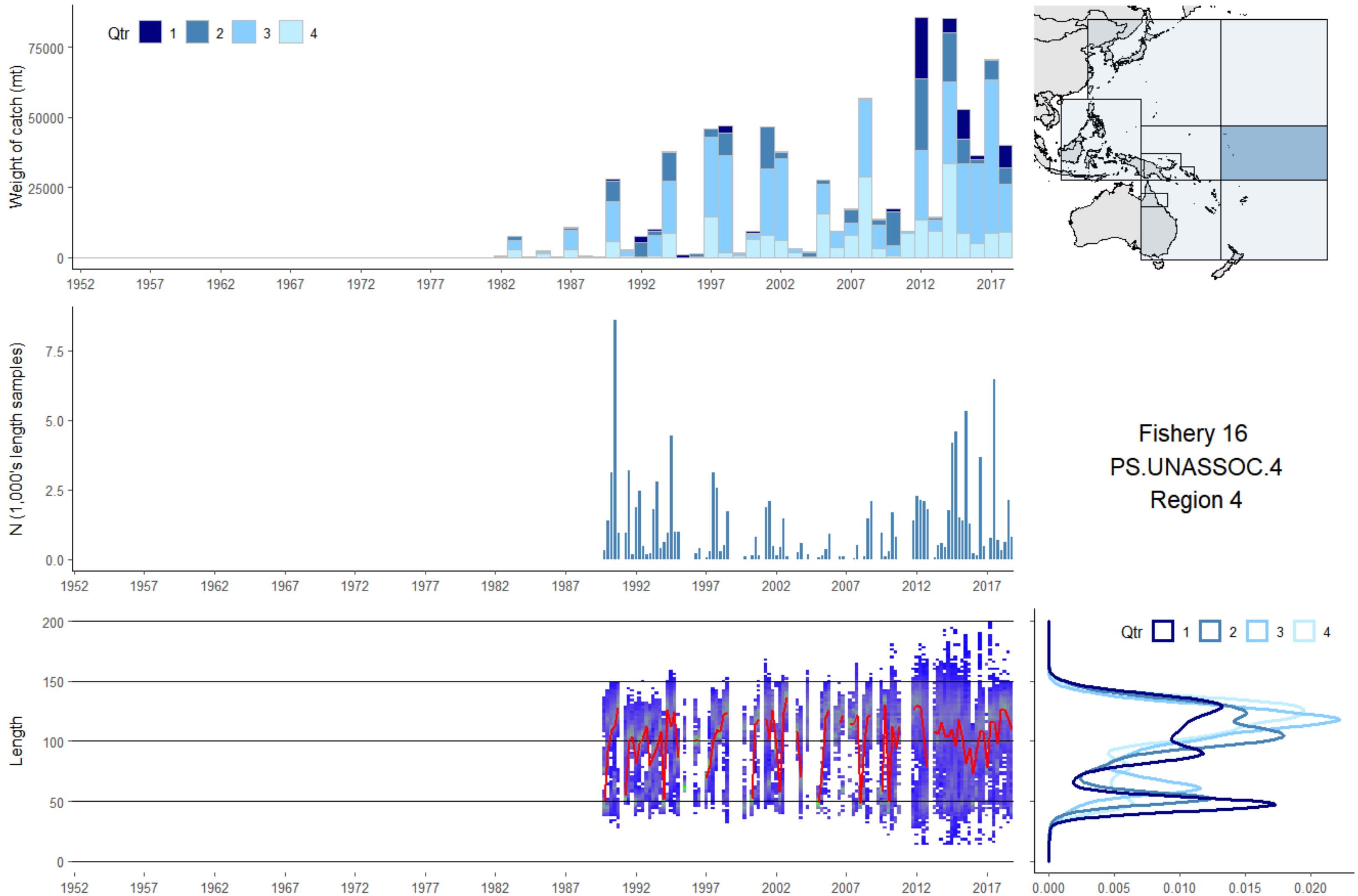

Figure 76: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 16.

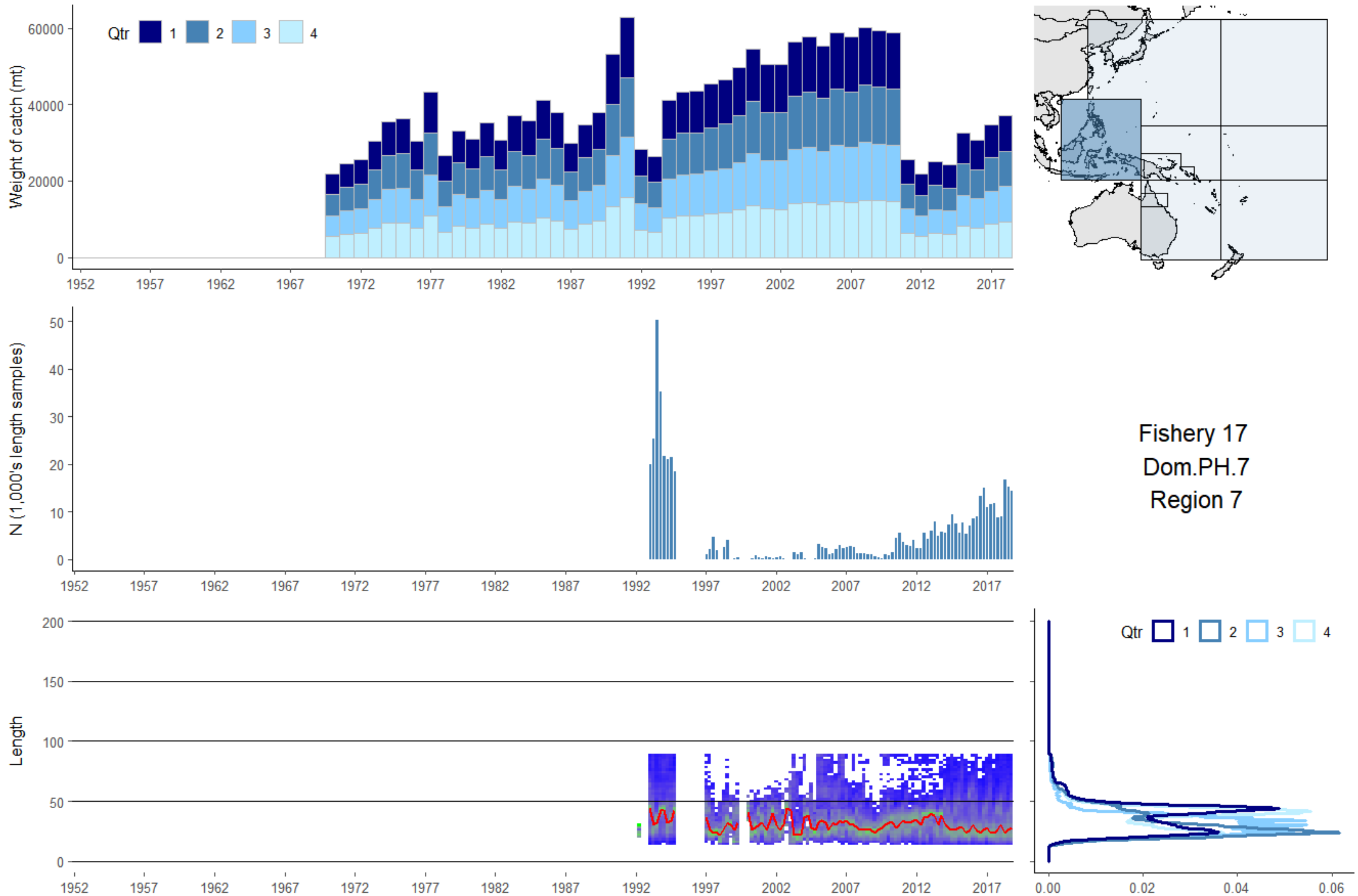

Figure 77: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 17.

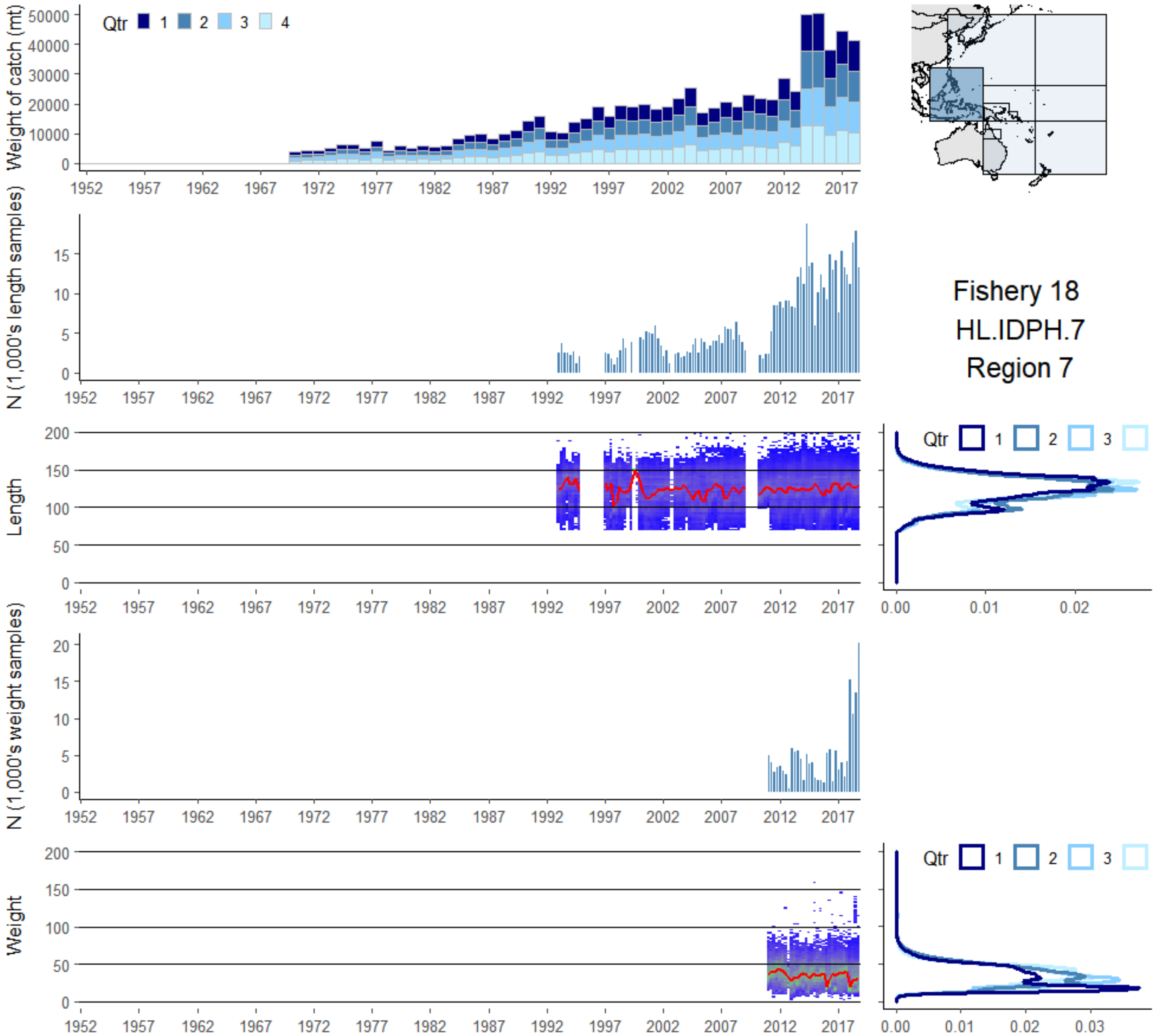

Figure 78: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 18.

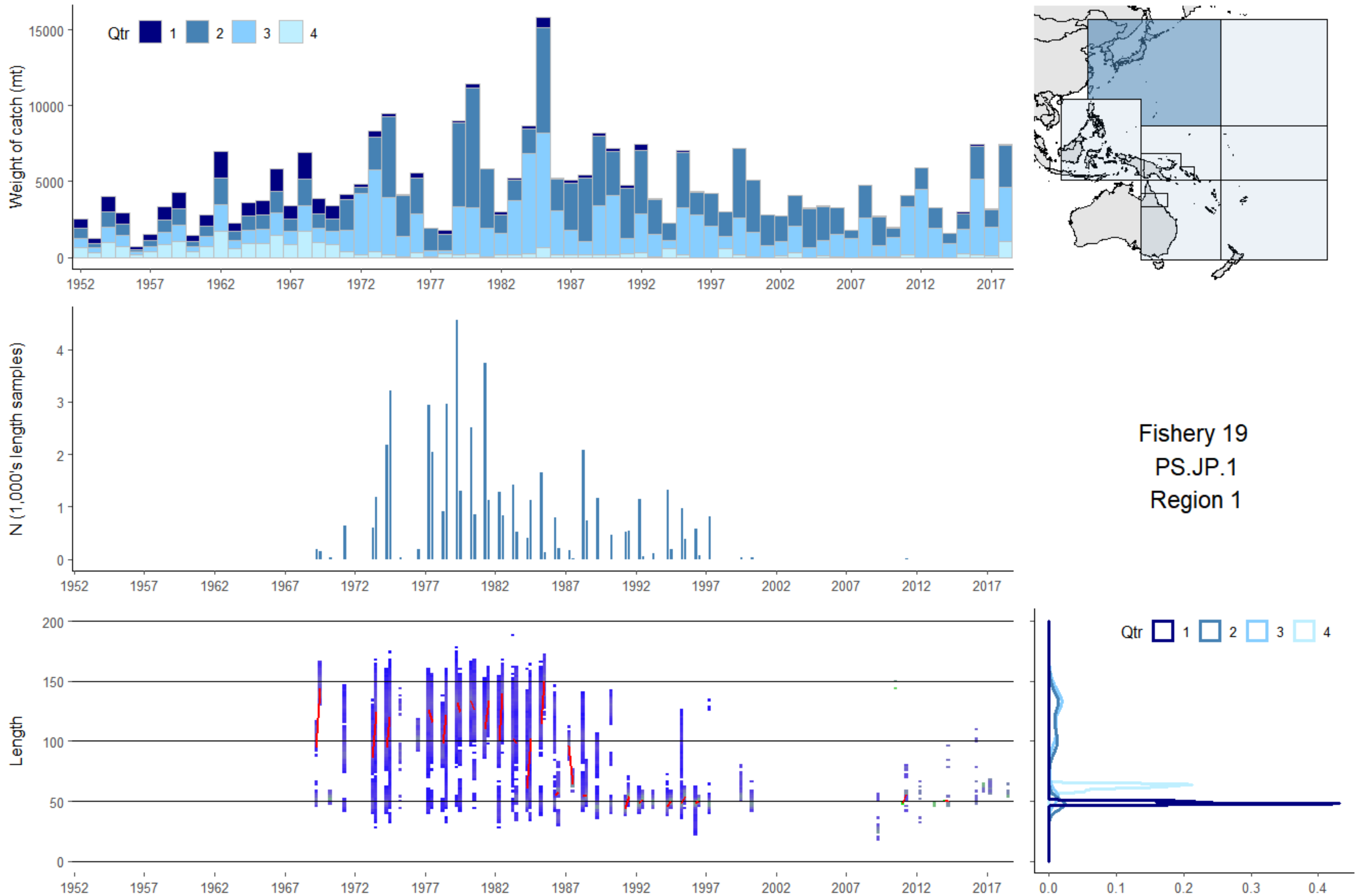

Figure 79: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 19.

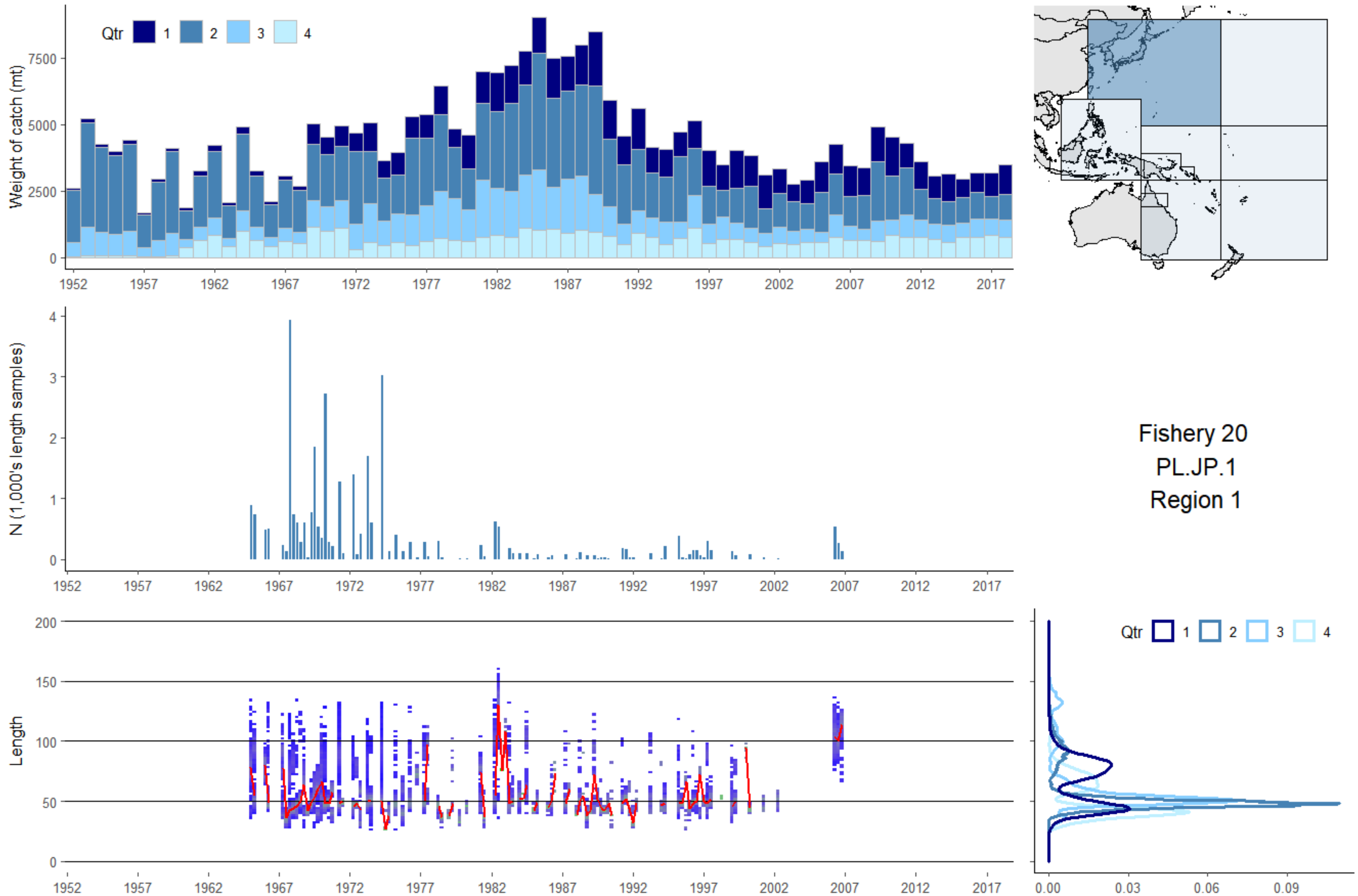

Figure 80: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 20.

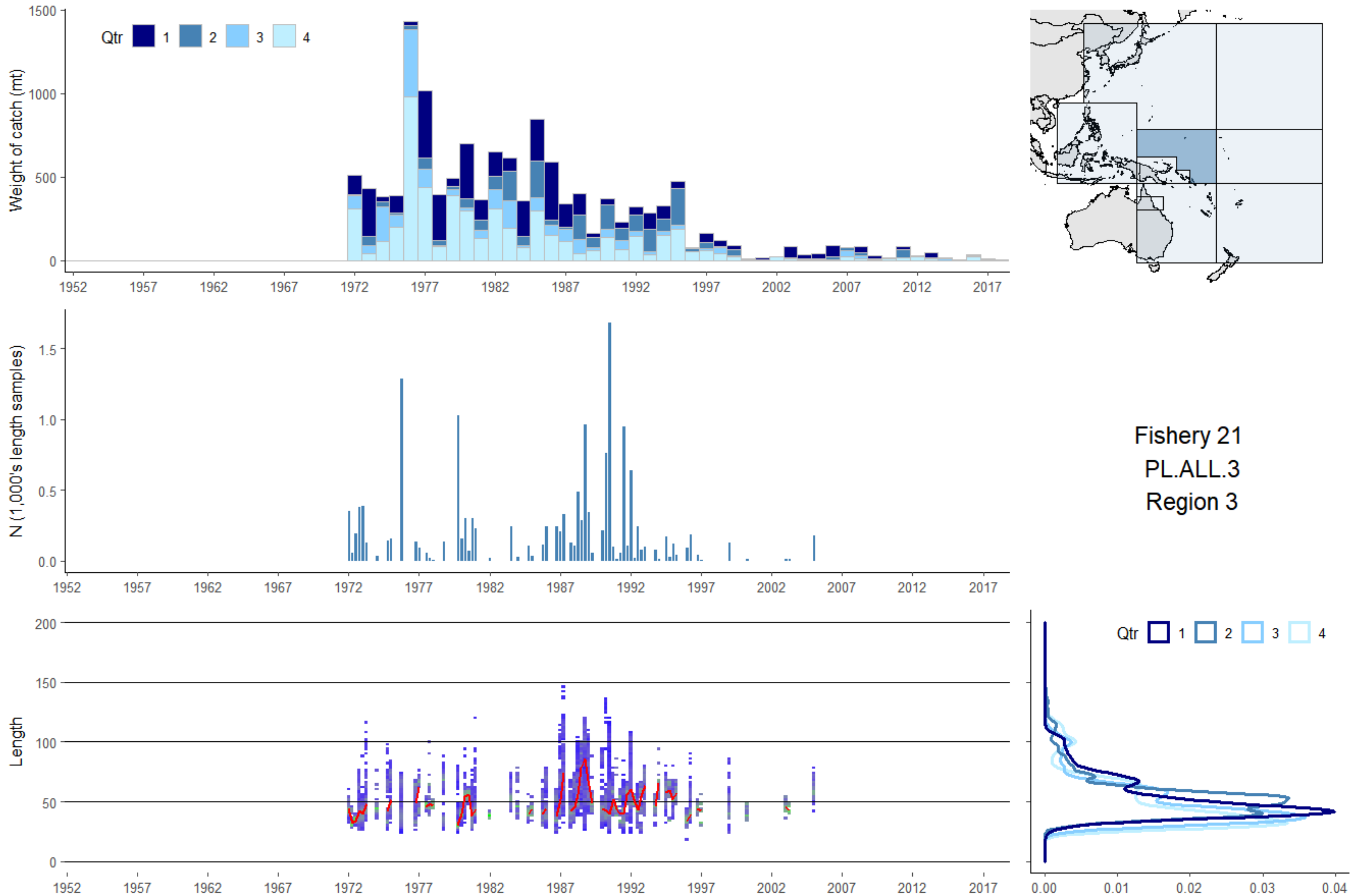

Figure 81: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 21.

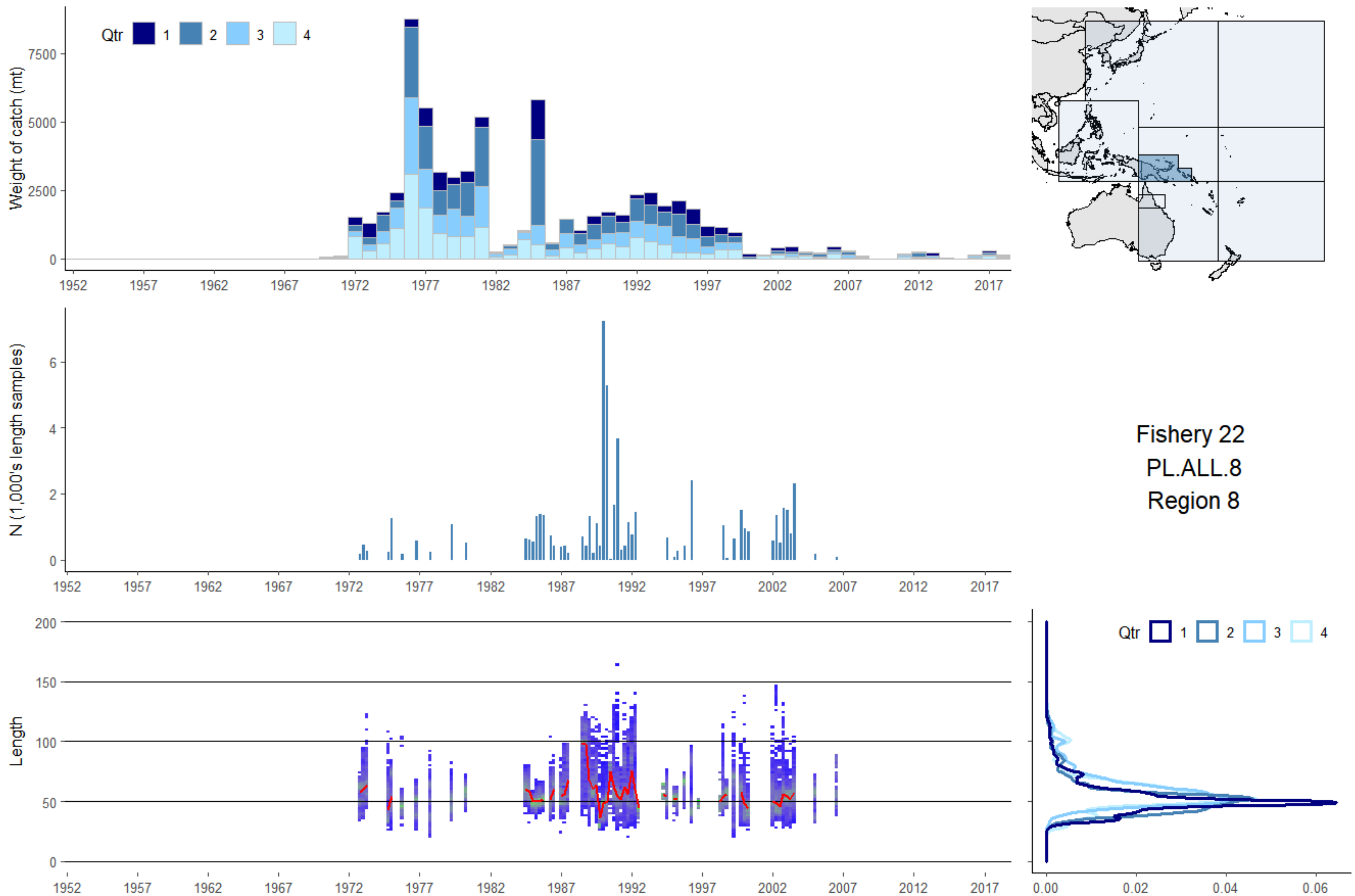

Figure 82: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 22.

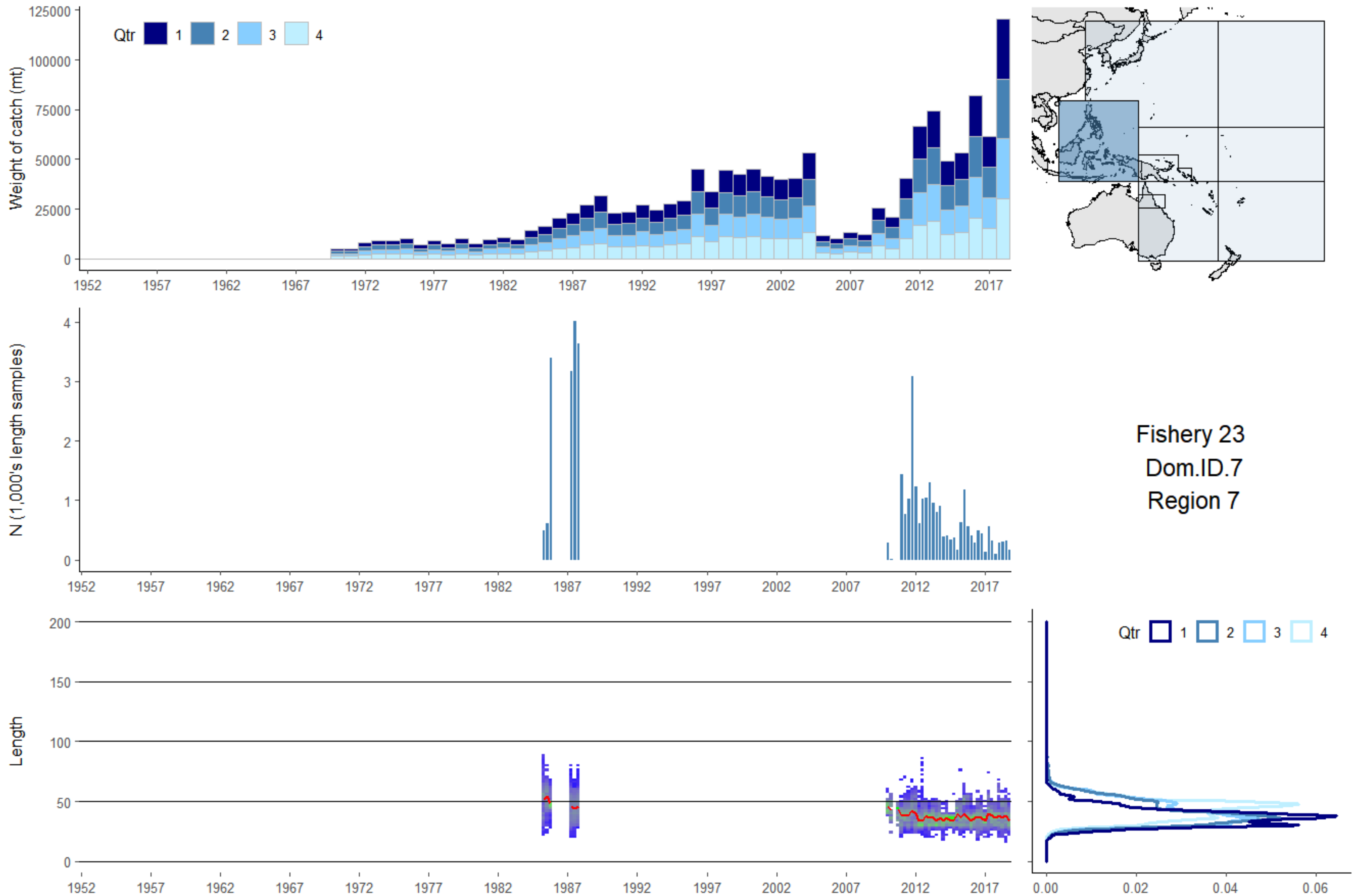

Figure 83: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 23.

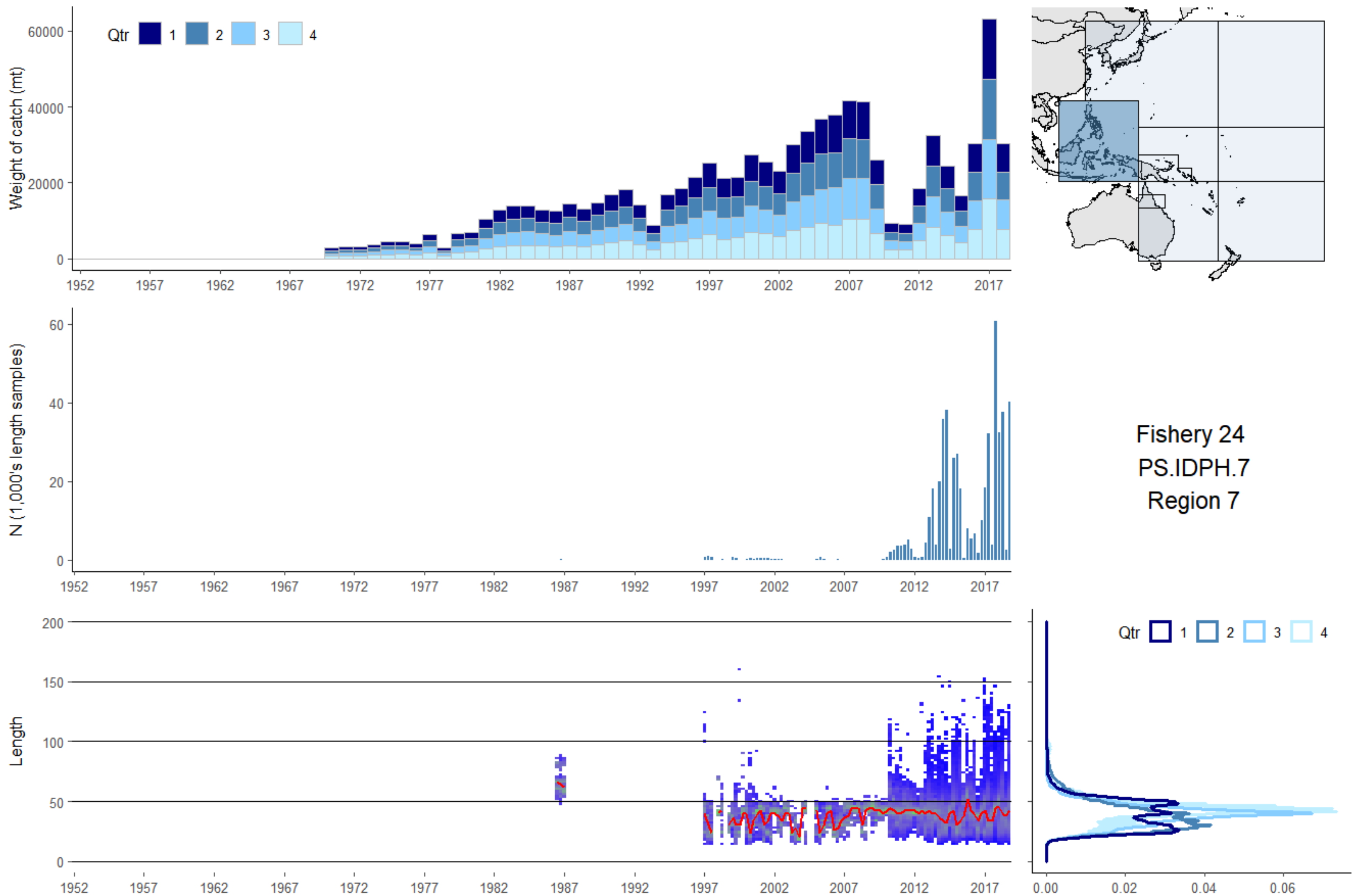

Figure 84: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 24.

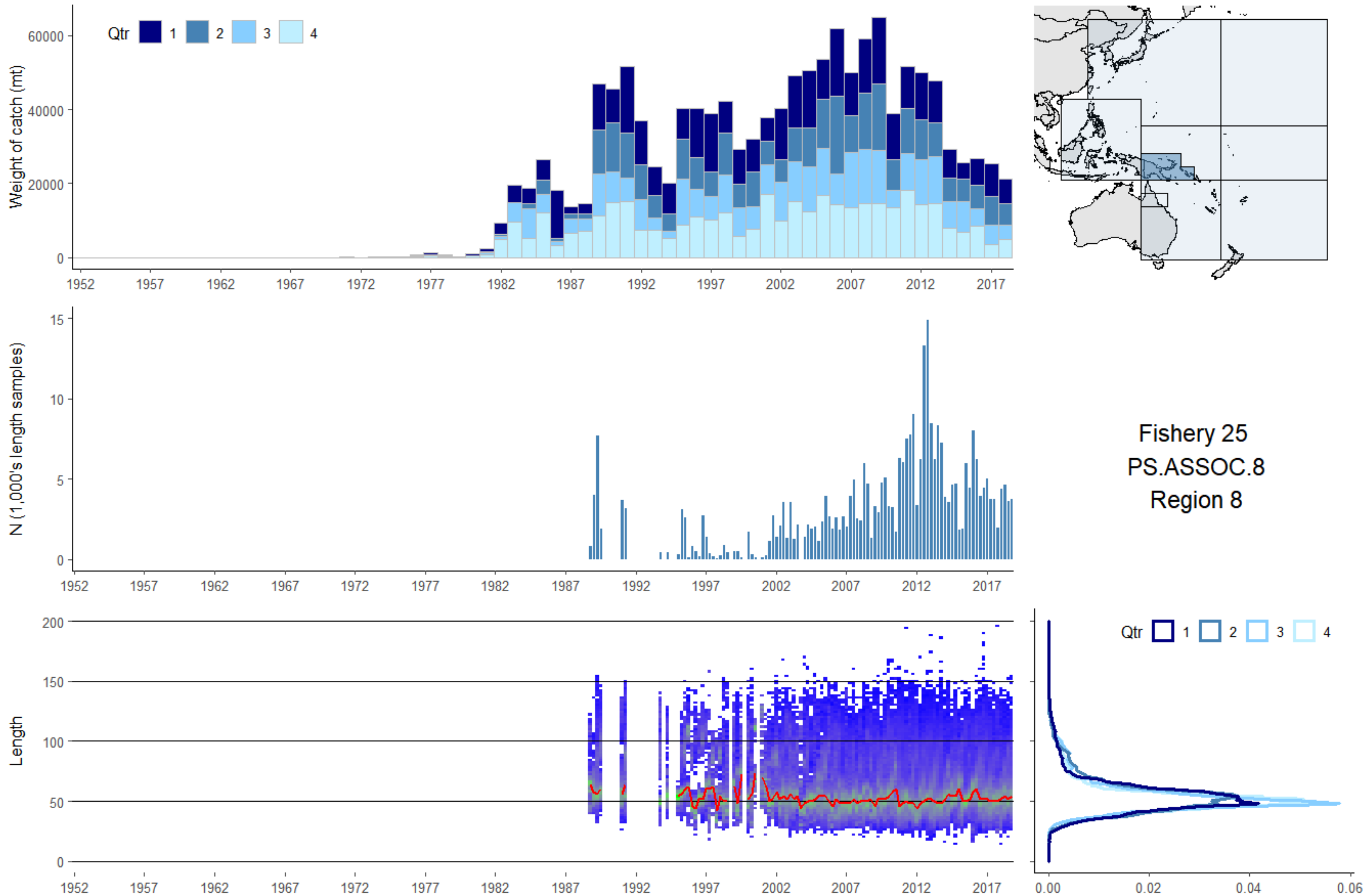

Figure 85: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 25.

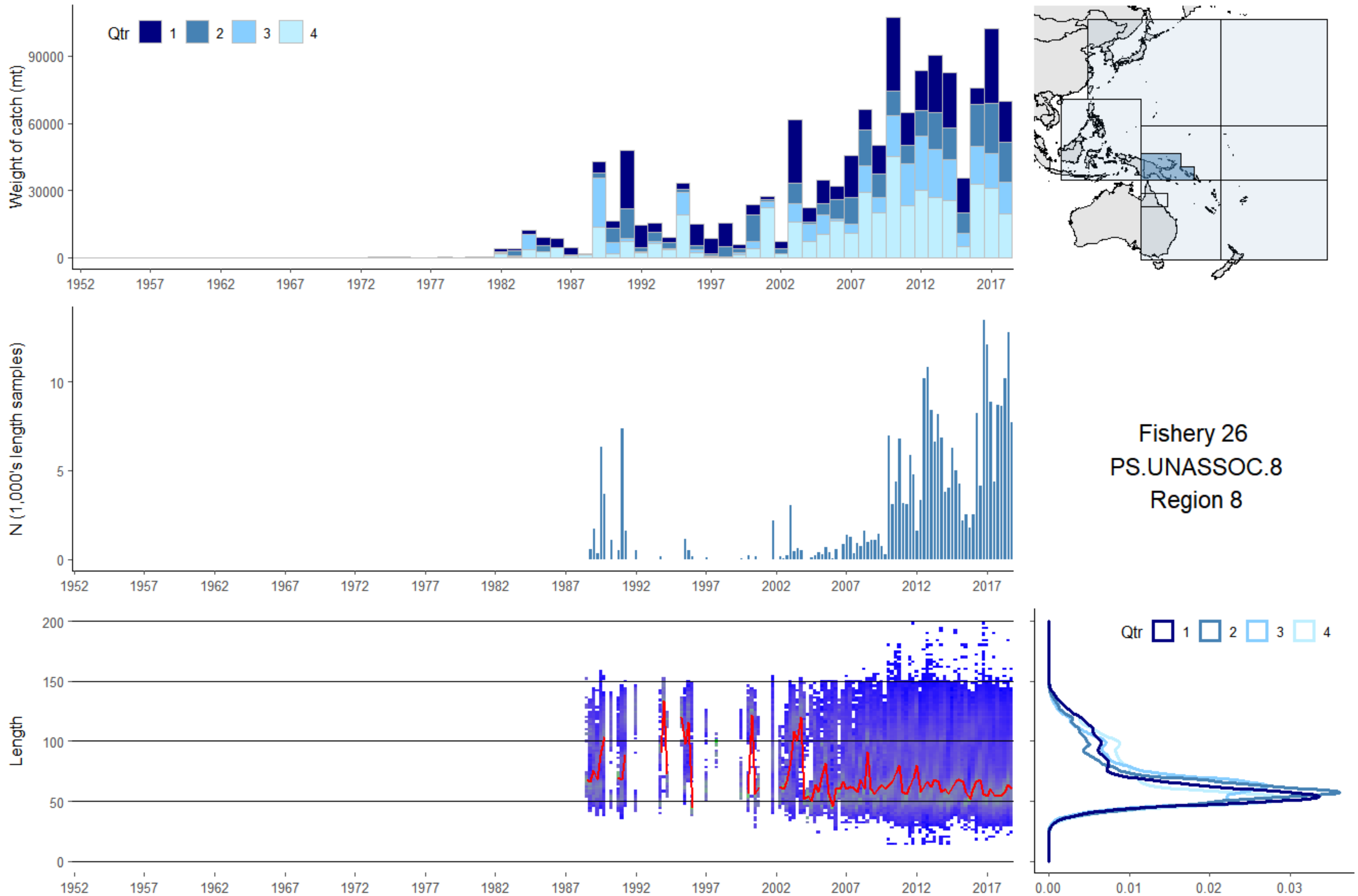

Figure 86: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 26.

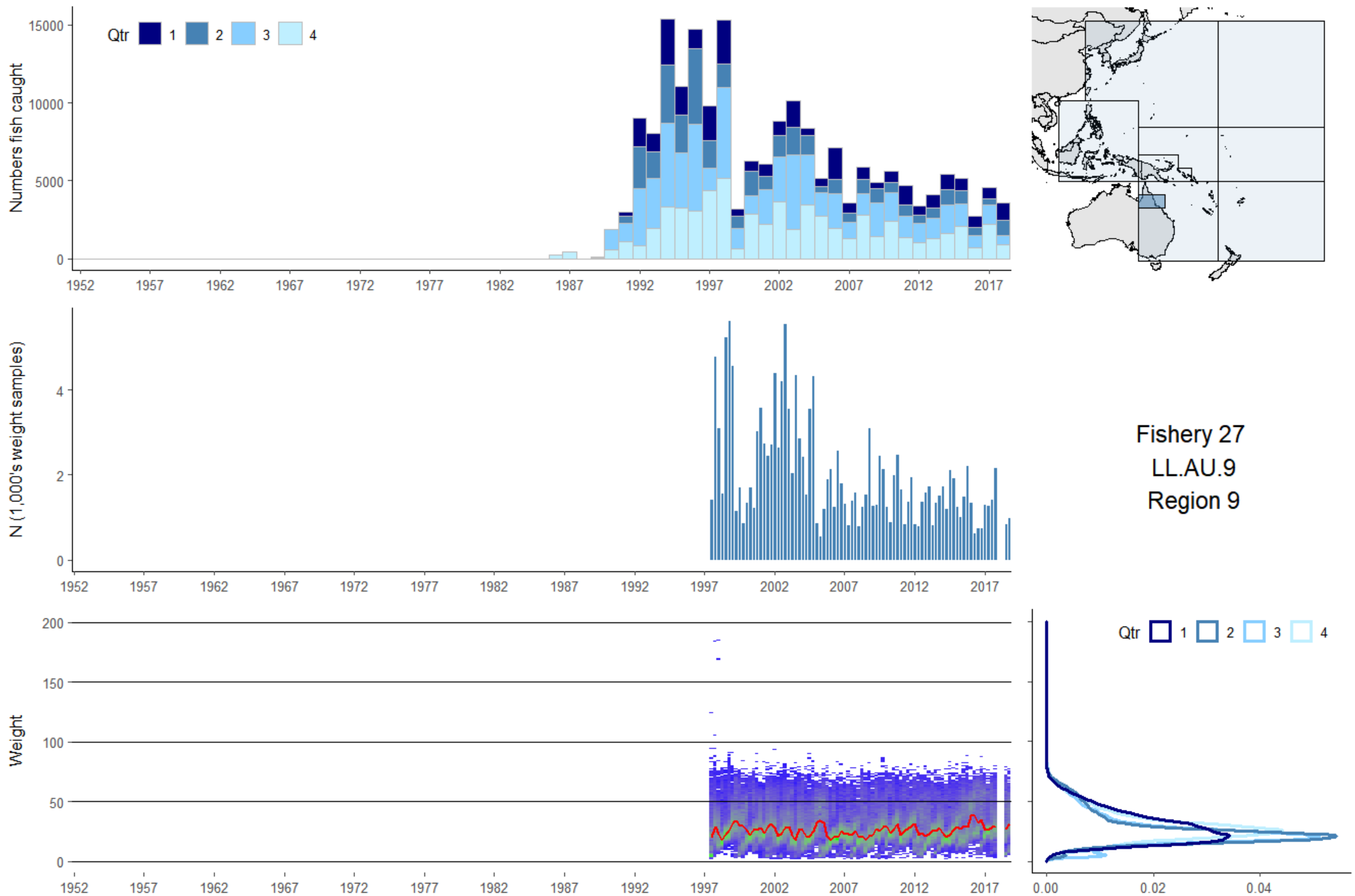

Figure 87: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 27.

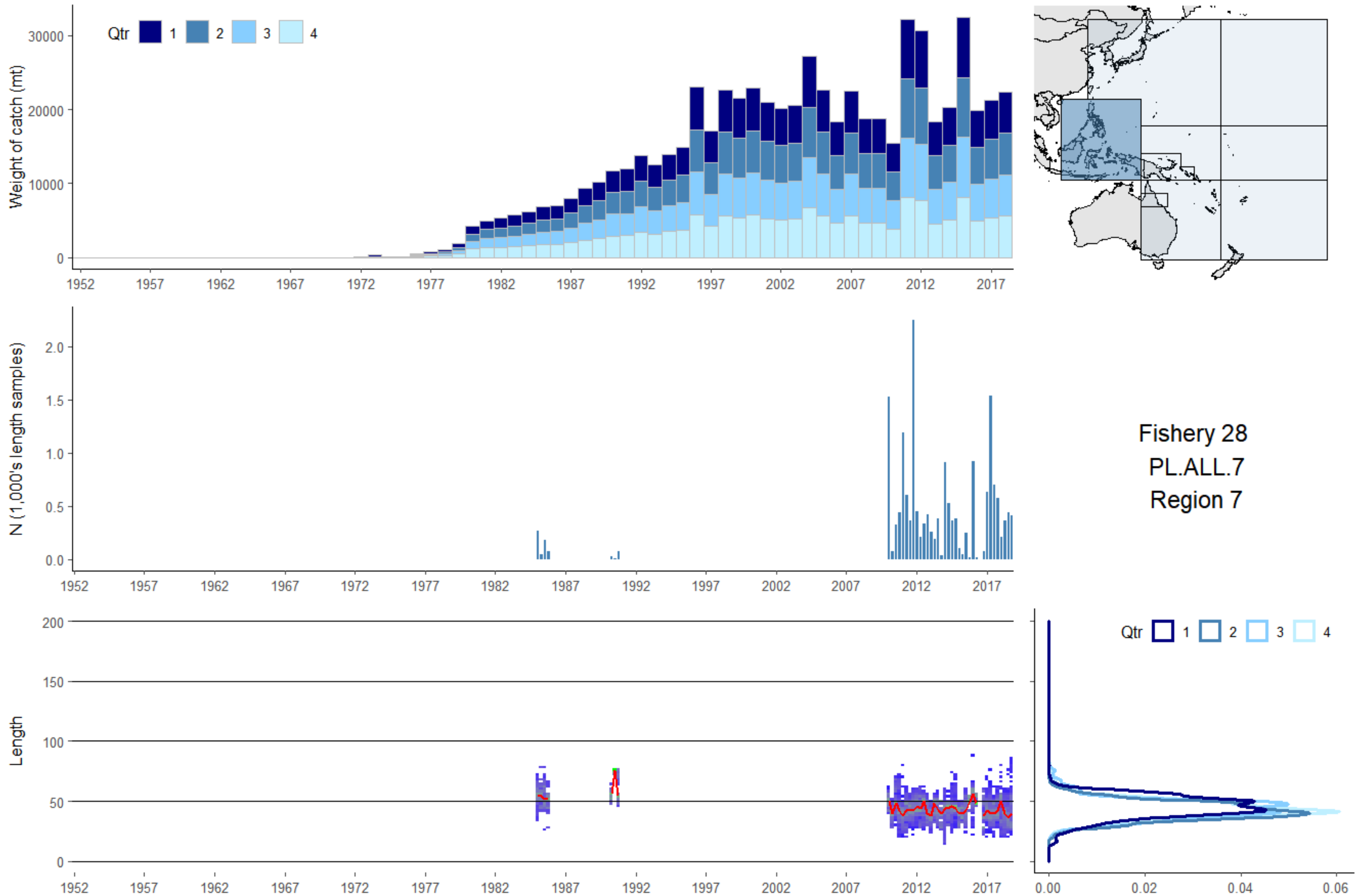

Figure 88: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 28.

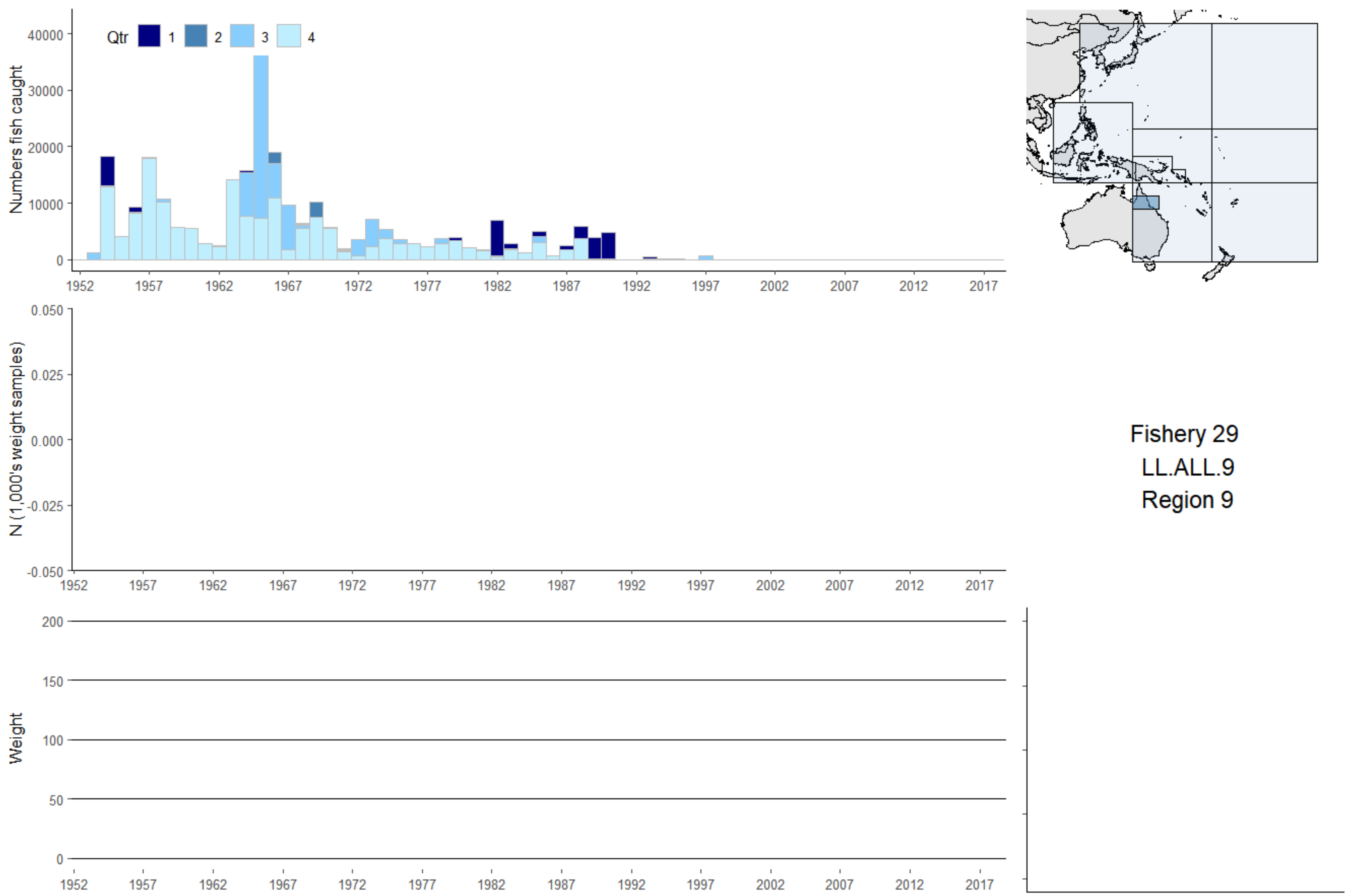

Figure 89: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 29.

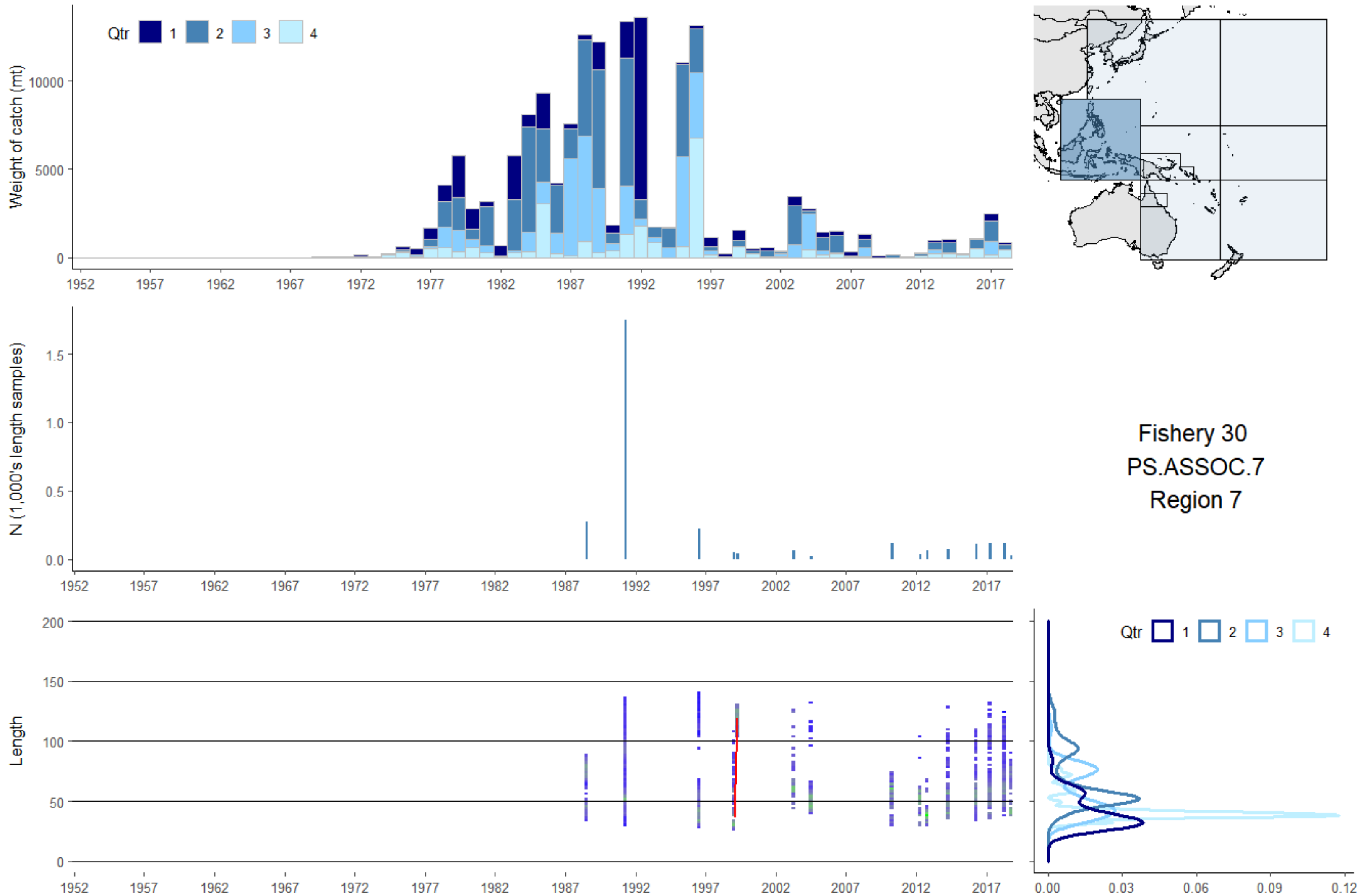

Figure 90: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 30.

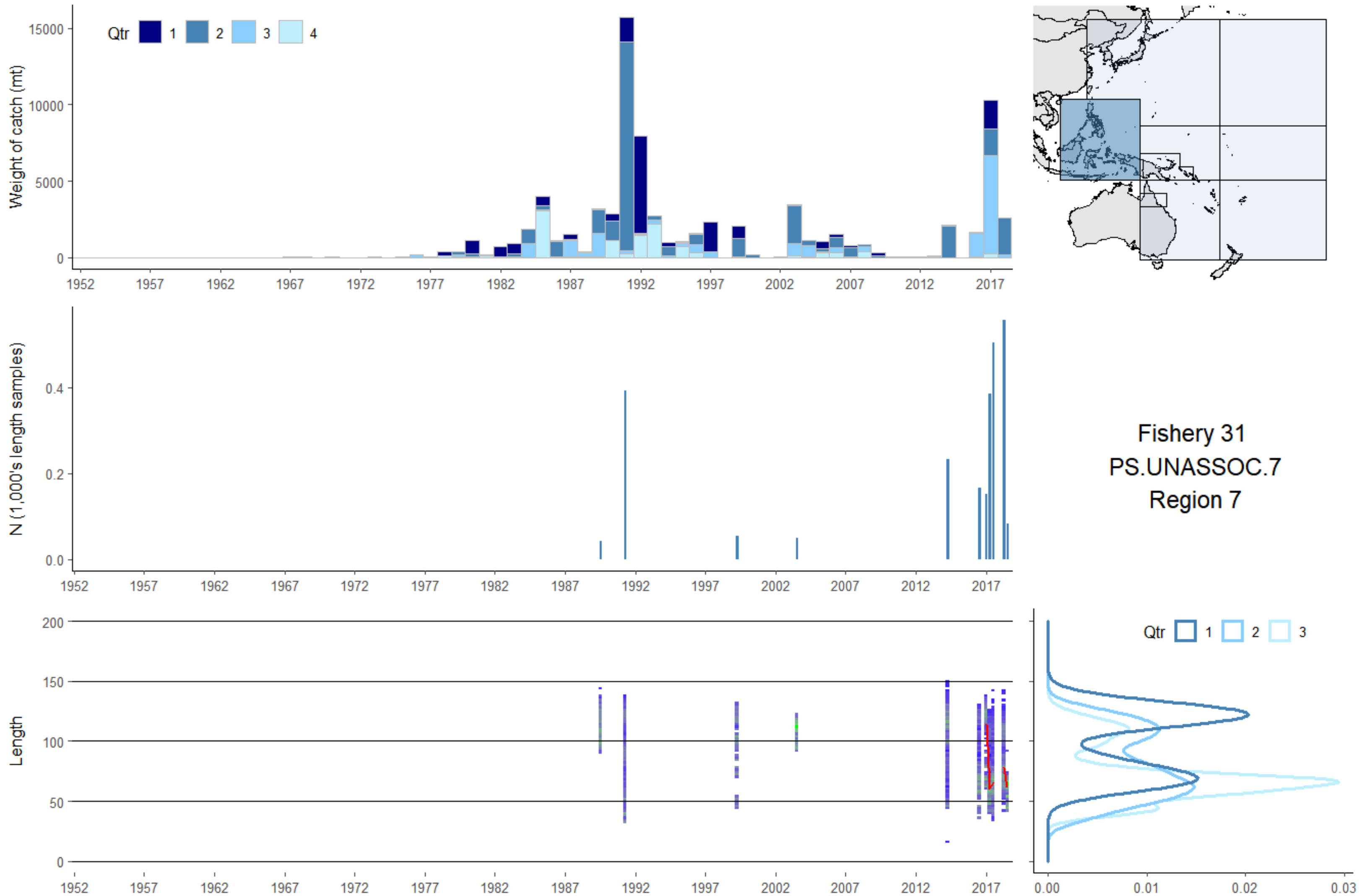

Figure 91: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 31.

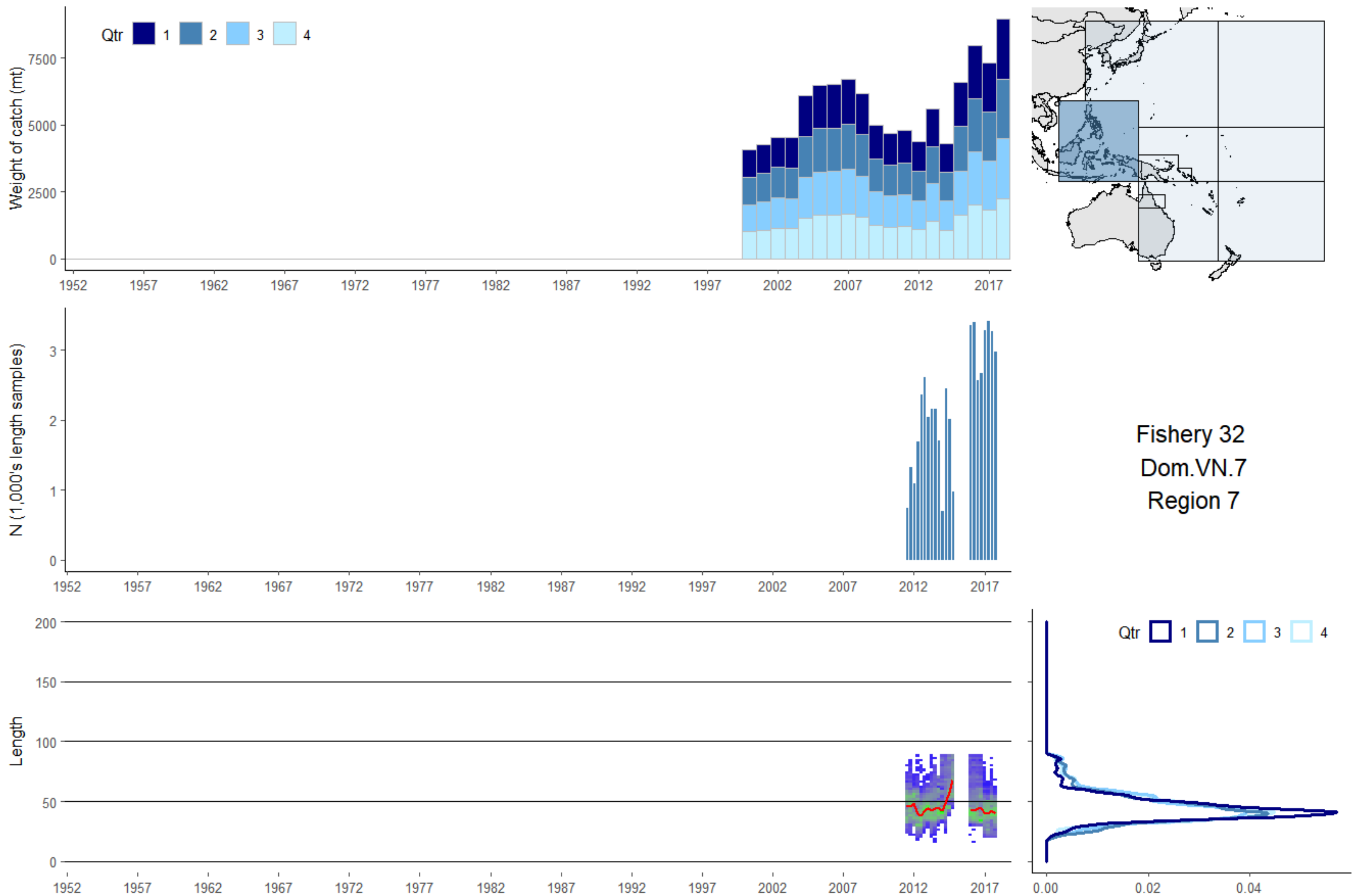

Figure 92: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 32.

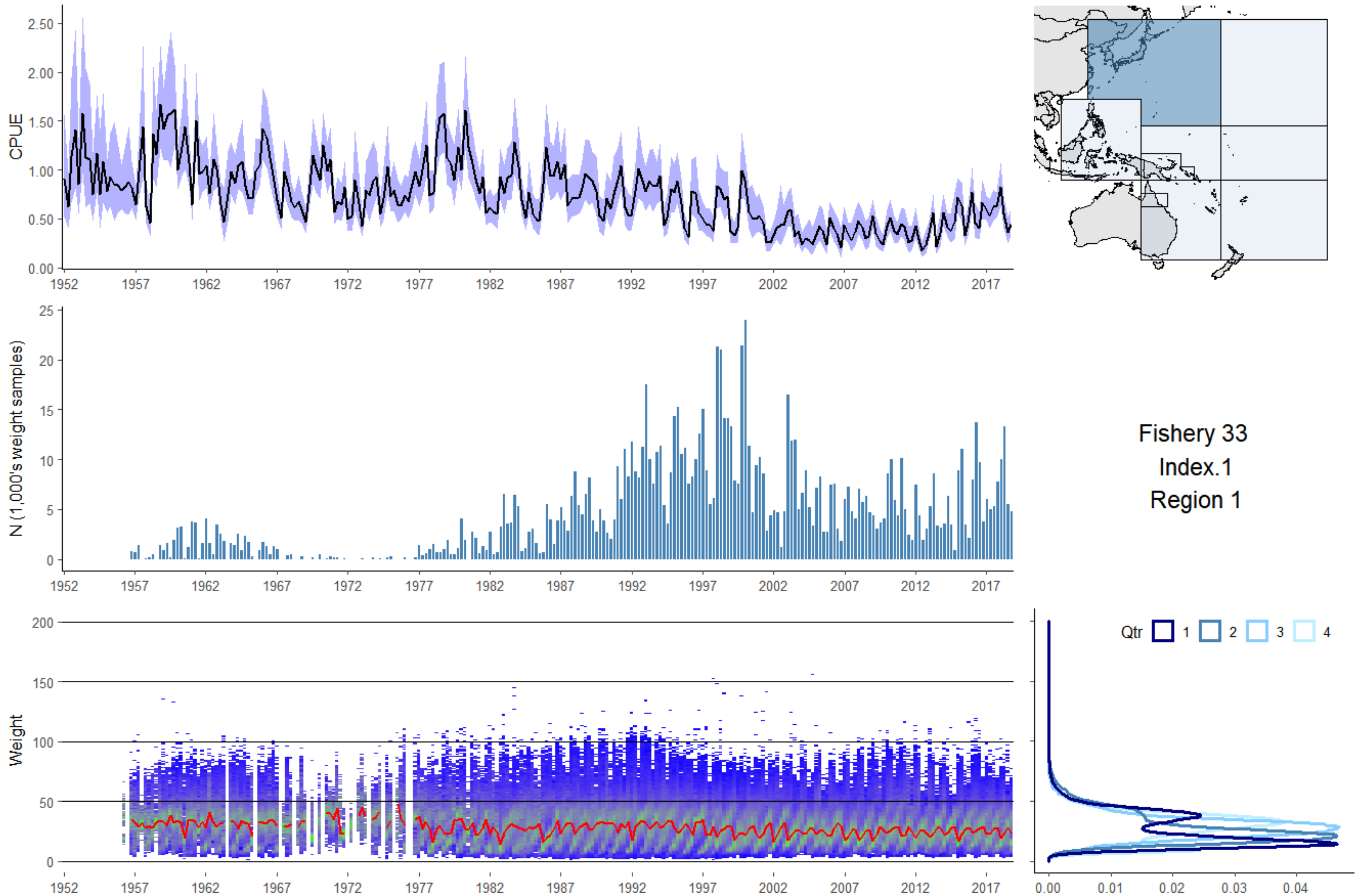

Figure 93: Summary plot of catch of yellowfin tuna (in numbers or weight), the number of size samples available, and the size distribution of fish measured or weighed, for fishery 33.

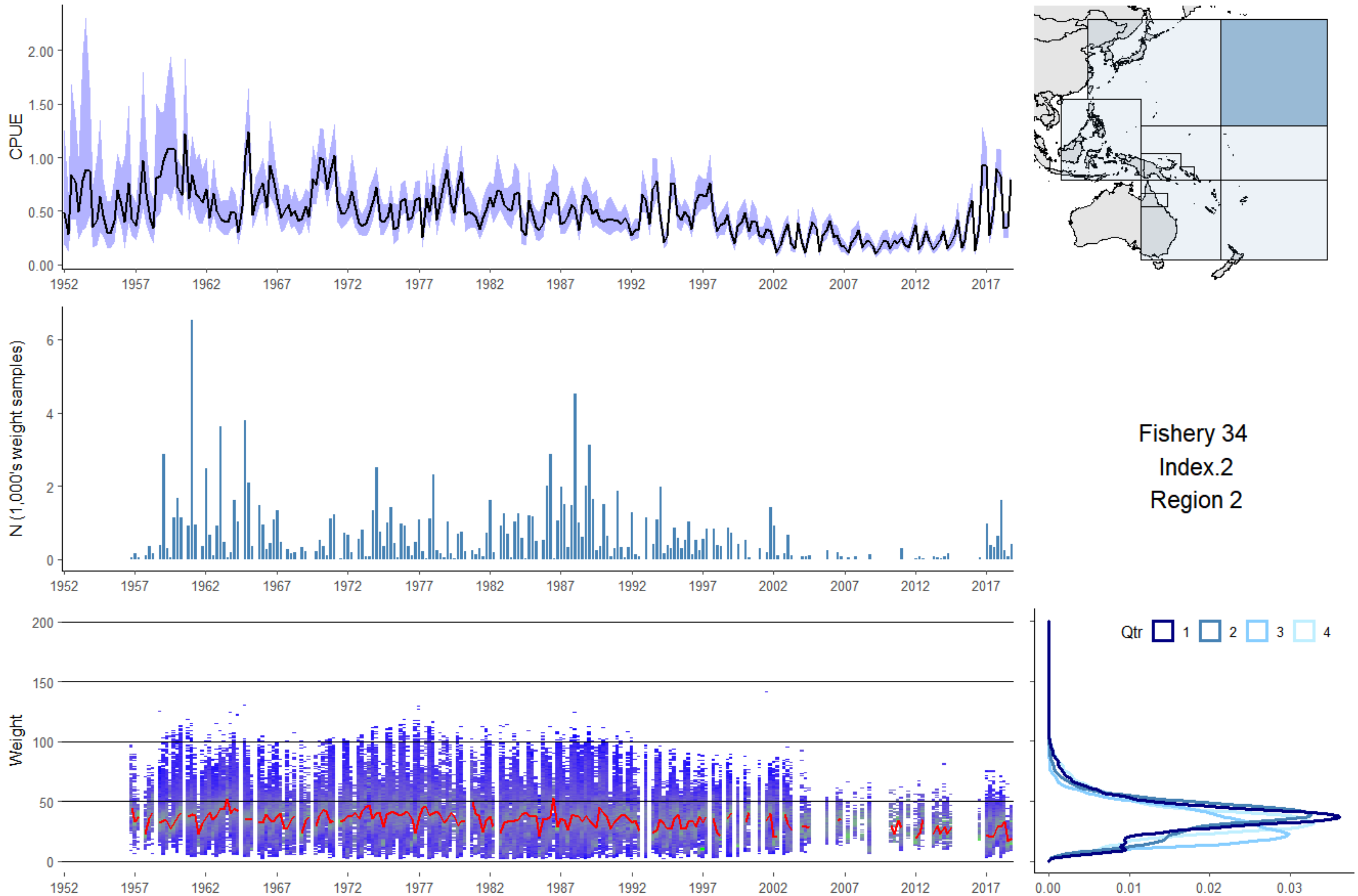

Figure 94: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 34.

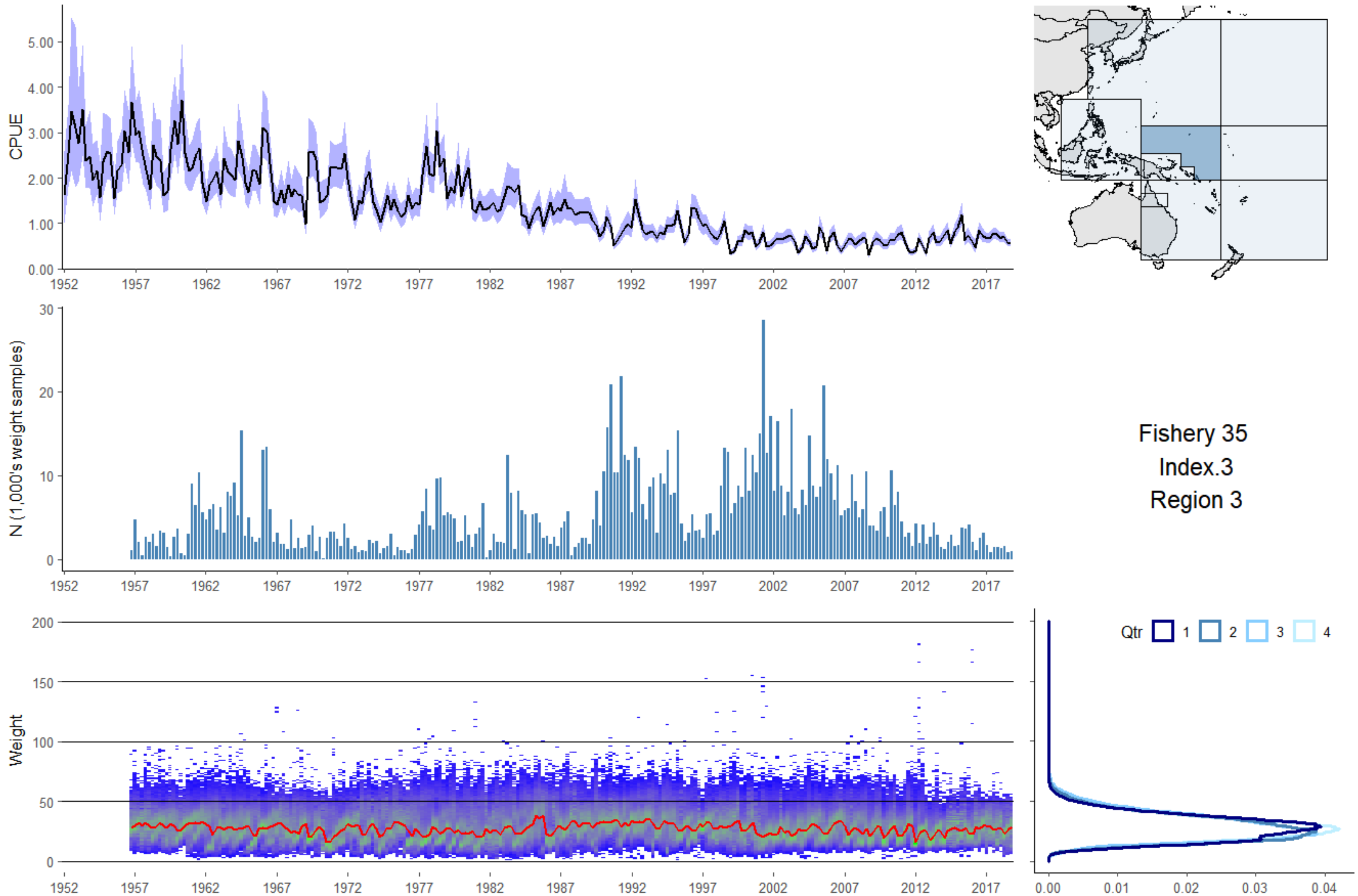

Figure 95: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 35.

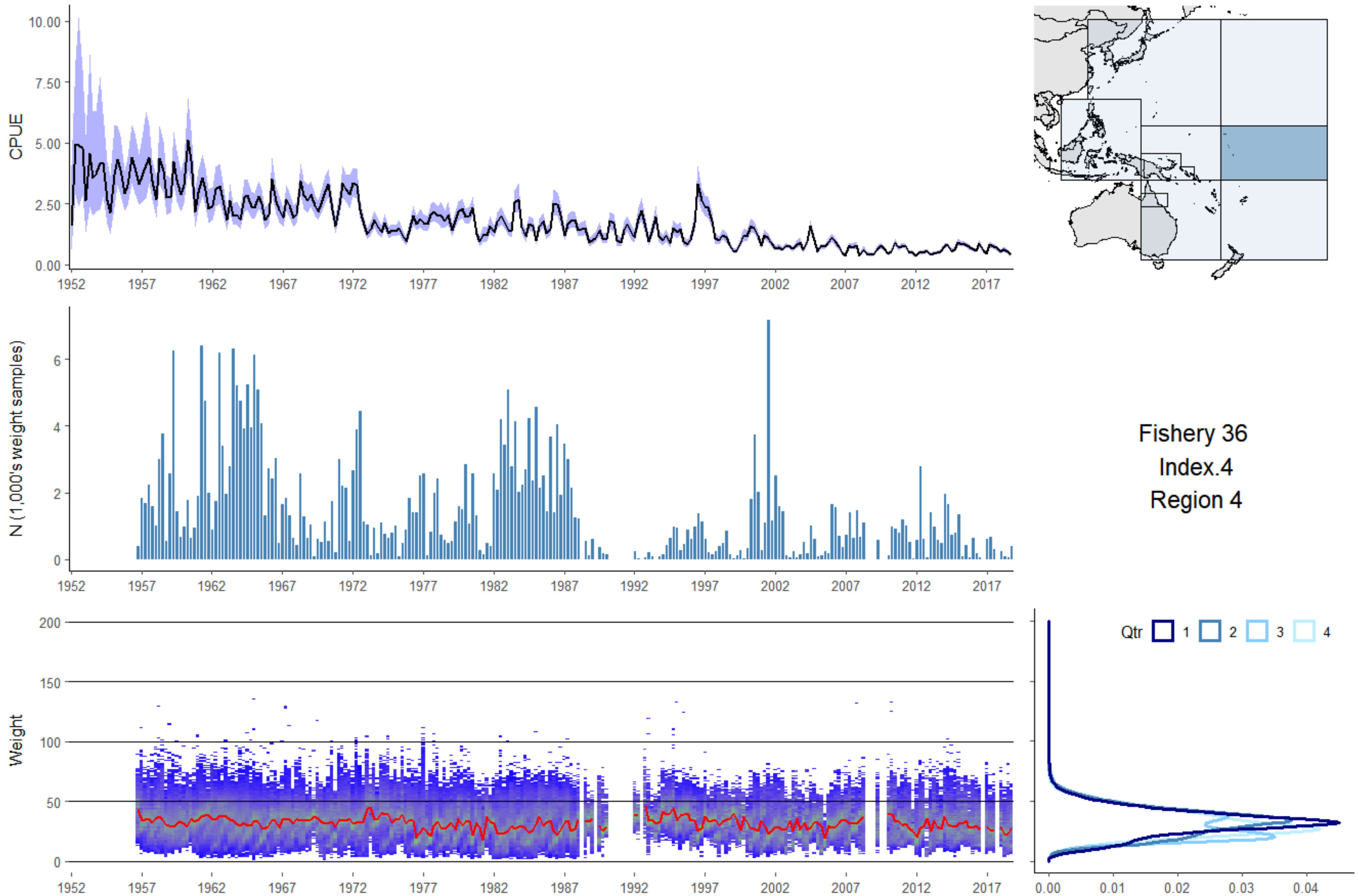

Figure 96: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 36.

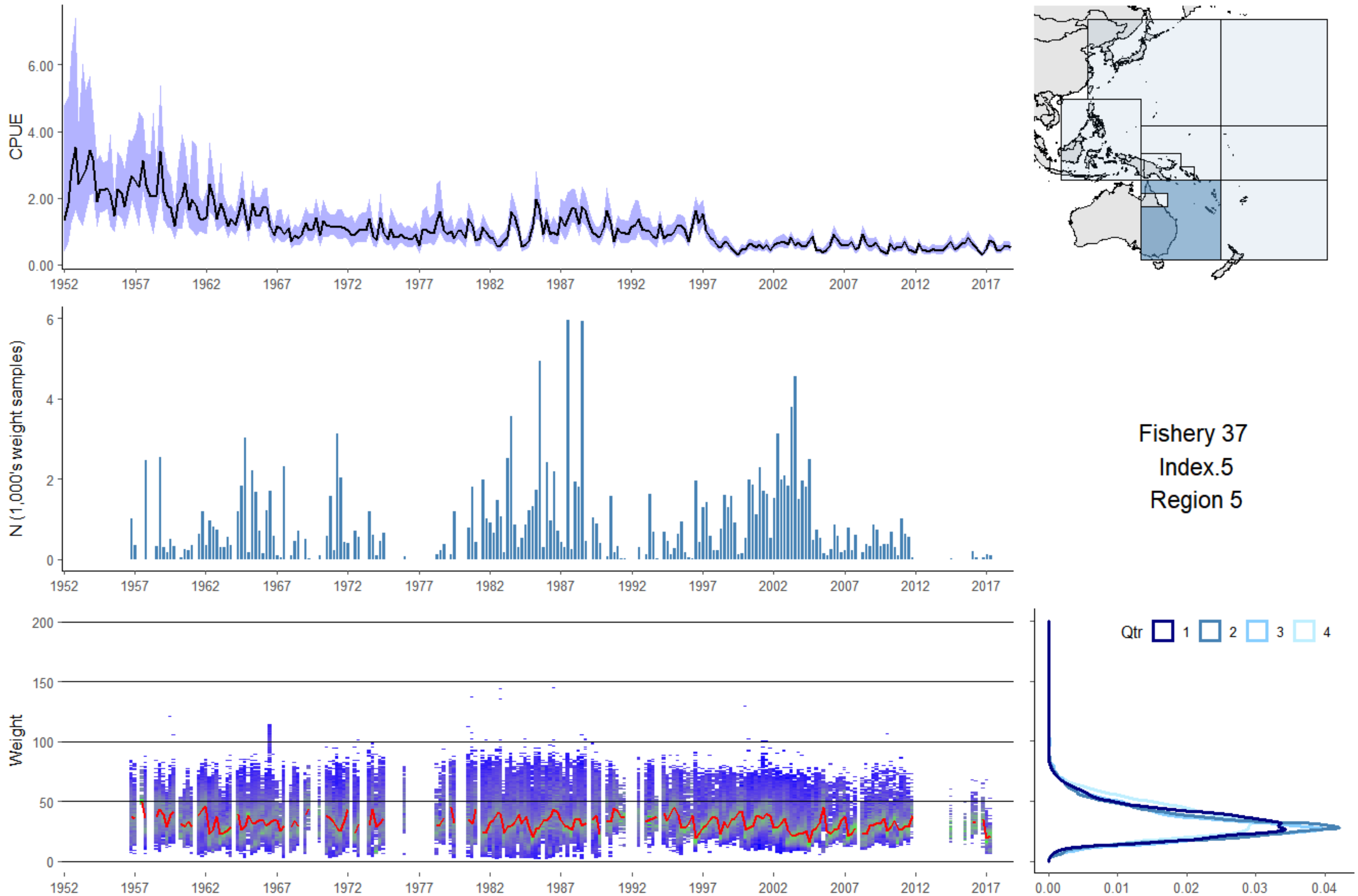

Figure 97: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 37.

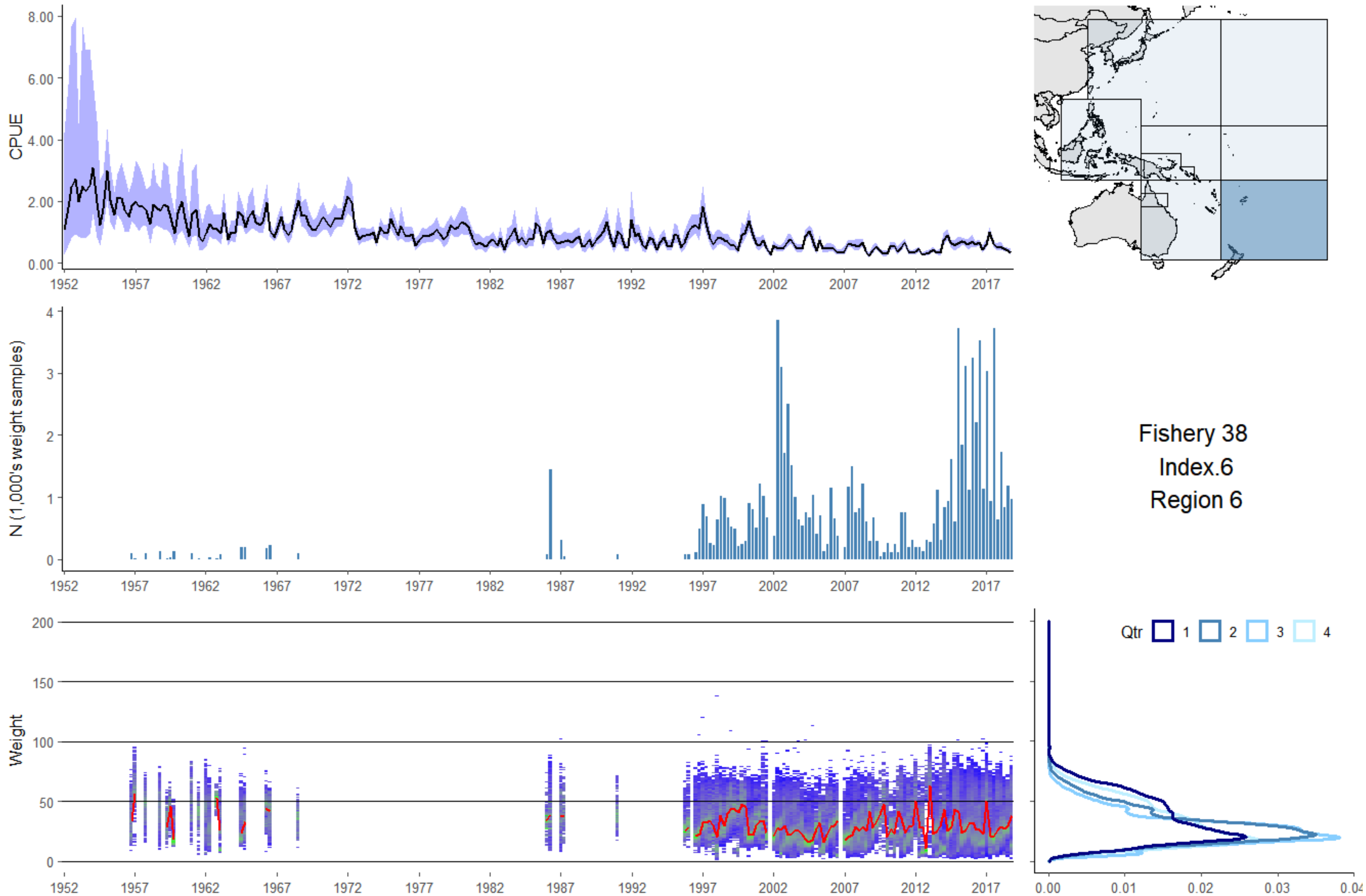

Figure 98: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 38.

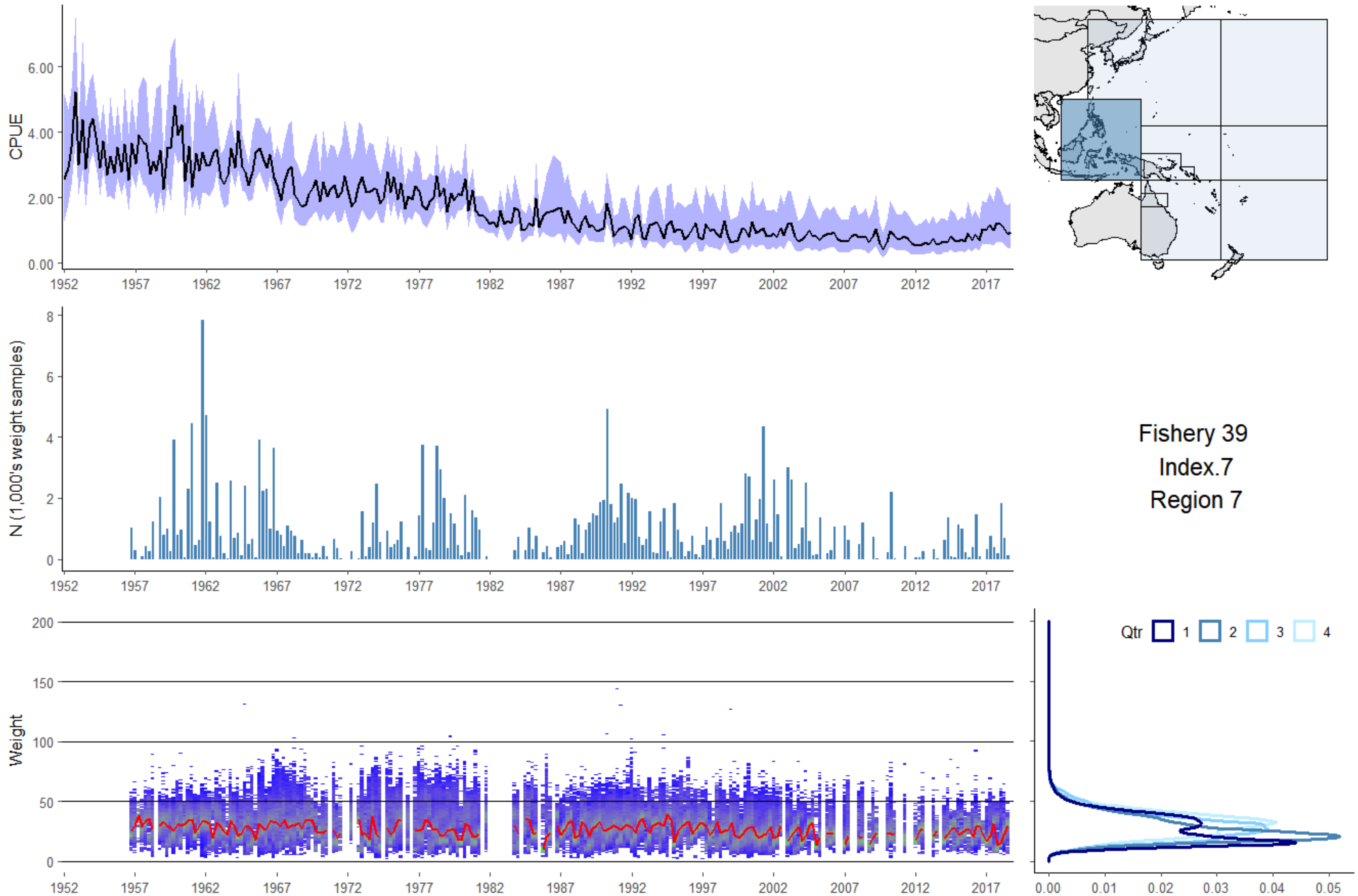

Figure 99: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 39.

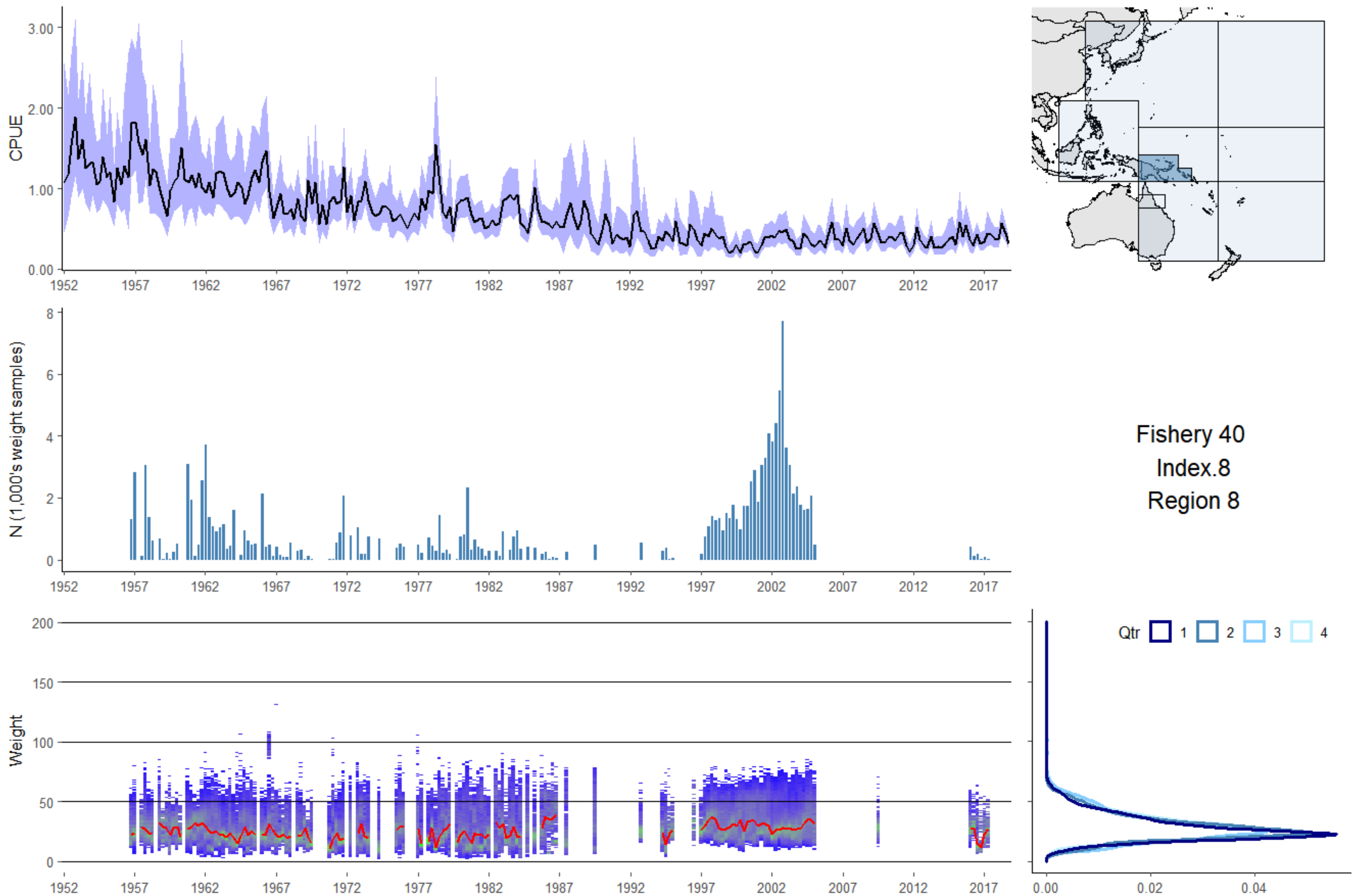

Figure 100: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 40.

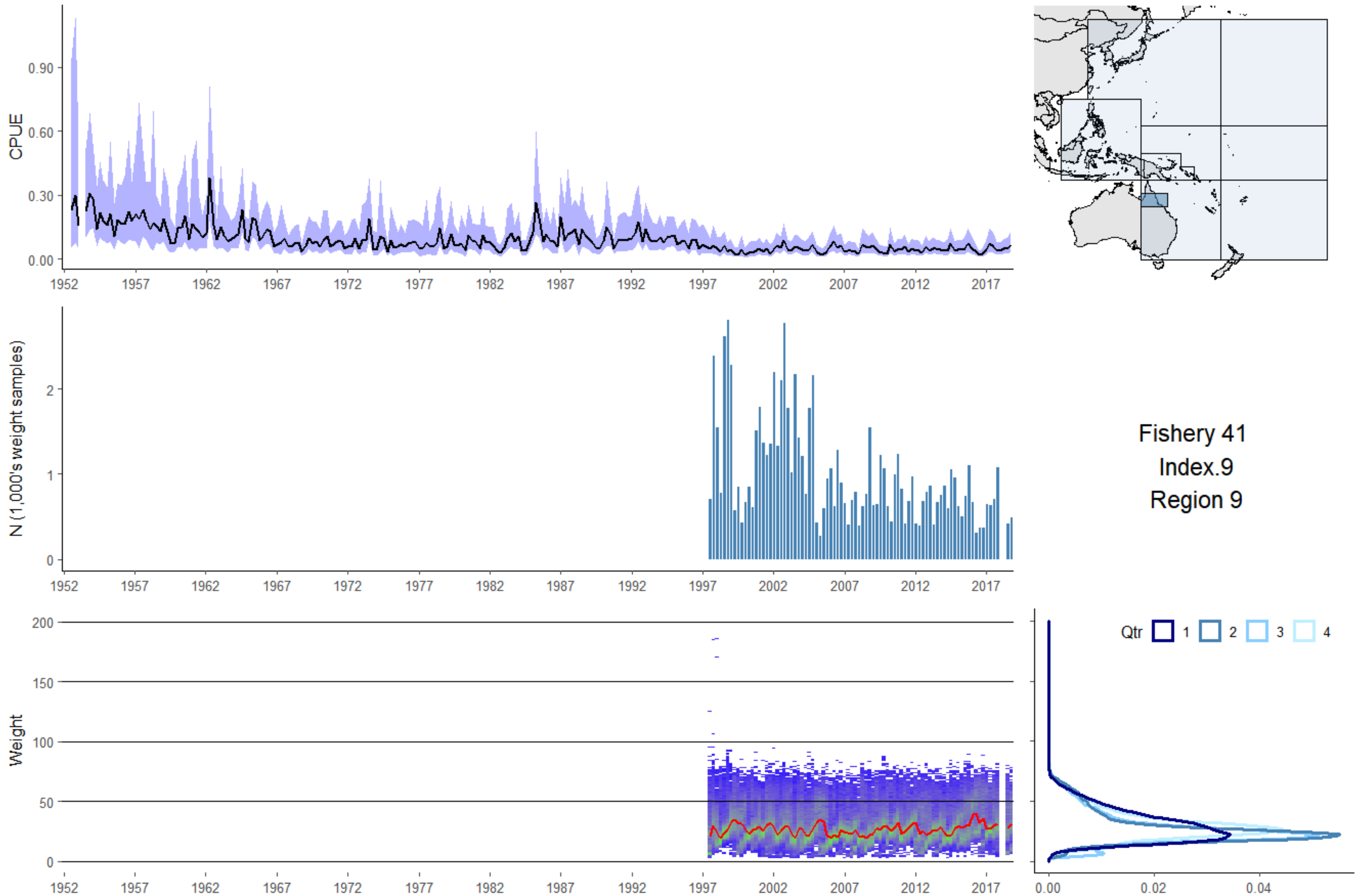

Figure 101: Summary plot of CPUE of yellowfin tuna (black line is mean, shaded area is the mean +/- 2sd based on the penalties applied in the model), the number of size samples available, and the size distribution of fish measured or weighed, for index fishery 41.