Improving biological knowledge of albacore tuna, *Thunnus alalunga*, in the Indian Ocean: a scoping study

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Summary

This report presents the preliminary results of a scoping study for improving biological knowledge of albacore tuna (*Thunnus alalunga*) in the Indian Ocean Tuna Commission (IOTC) Area of Competence. The key objectives of the scoping study are to:

1. Undertake sensitivity analyses to indicate the sensitivity of the stock assessment to:
    1.1 the range of plausible values that might be estimated for each parameter; and
    1.2 potential structural changes to the assessment that might be informed by biological sampling.
2. Undertake power analyses on key biological parameters to determine sampling needs.
3. Using the outcomes of 1 and 2 above, and an understanding of the fisheries, outline the sampling considerations and develop a sampling design required to provide estimates of length- and age-based population parameters to improve stock assessments of albacore tuna in the Indian Ocean (IO).

The sensitivity of the stock assessment results to altered key biological parameters was investigated within the framework of the preliminary 2019 IO stock assessment model ('base model'). A range of alternative model options were configured to evaluate the influence of changes to the key biological parameters on the stock assessment and status of albacore tuna in the IO, including alternative values for the length-weight relationship, maturity-at-length ogive, variation in length-at-age, growth functions, and female natural mortality rates. The sensitivity of the model to spatial variation in growth rates was also considered by partitioning the model into two regions (east and west) that was also configured for fish in the eastern region having a higher growth rate than fish in the western region. The estimates of key stock status metrics were compared to the base model to assess the sensitivity of the results to the range of biological parameters evaluated. Simulation modelling was undertaken to evaluate the utility of the collection of length composition and age composition data from one of the main longline fisheries (LL 3 southwestern IO). Simulations were also conducted that incorporated a 2% per annum increase in the CPUE indices from 2001 to 2017 to assess the influence of bias in the CPUE indices.

The alternative growth function resulted in a deterioration in the fit to both the CPUE indices and the length composition data sets (from all longline fisheries). The increased variation in length-at-age improved the fit to the length composition data from the southern longline fisheries (LL3 and LL4), yet resulted in a deterioration in the fit to the LL3 CPUE indices. Partitioning the western and eastern regions of the IO improved the fit to the LL3 CPUE indices relative to the base model, and, to a lesser extent, the length composition data from each of the longline fisheries. Applying the different growth functions to the eastern region of the model improved the fit to the eastern CPUE indices (LL4) but eroded the fit to the eastern length composition data (LL2 and LL4).

The estimates of stock status were most strongly influenced by the changes related to the assumptions related to growth. The growth function and variation in length-at-age sensitivities both yielded considerably more pessimistic estimates of current stock status. Changes in the maturity ogive and female natural mortality influenced the magnitude of the reference biomass levels, although resulting stock status ratios were not appreciably different from the base model. The spatial partitioning of the model into two regions yielded a considerably more optimistic estimate of current stock status and higher overall yields compared to the base model. Changing the growth functions for the eastern

partition resulted in a marginal increase in maximum sustainable yield but did not appreciably change the estimates of current stock status.

Biomass trajectories from the models that included simulated length or simulated age data were similar to the base model, although including the age data resulted in a positive bias in estimates of absolute biomass and current stock status. Including length or age data resulted in a small improvement in the precision of the estimates of the recent level of biomass (from about 2000 onwards). The introduction of the biased CPUE indices yielded a more optimistic biomass trajectory during the recent period relative to the base model. The inclusion of the simulated length data did not change the trajectory of the CPUE biased model, while the inclusion of the age data resulted in a positive bias in the magnitude of the biomass that was most pronounced during the “data rich” period. There was only a small deterioration in the fit to the age data between the models with and without bias included in the CPUE indices, suggesting that an examination of the fit to the age composition data would not provide evidence of a bias in the index.

The second objective of this study is to assess sample size requirements to inform the sampling protocol. Preliminary simulation modelling was carried out by bootstrap resampling of the south Pacific Ocean albacore tuna dataset. Specifically, we fitted nine growth models to each resampled dataset and identified best fitting model (the model with the lowest AIC). This ‘best’ model was then used to predict size for fish aged 4 and 10 located at longitude 200°E. The ability of the models to characterize the relationship between growth parameters and longitude improved with increasing sample size, but evidence for such a relationship was reliably identified even in the lower range of sample sizes. As expected, coefficients of variation for predicted lengths at ages 4 and 10 decreased with increasing sample size. At 10% of the actual sample size the CV was 3.3% and 3.4% for females, and 2.4% and 2.5% for males. These decreased with increasing sample sizes to reach 1.1% and 1.0% for females and 0.6% and 0.6% for males at 100% of the actual sample sizes. Additional analyses are planned to explore sample size requirements for reproductive parameters, including female gonad index, spawning frequency and batch fecundity.

The third objective of this study is to outline the sampling considerations and develop a sampling design to improve understanding of albacore tuna biology in the IO. Given spatial and temporal patterns in biological parameters observed elsewhere (e.g. South Pacific Ocean), we recommend that sampling cover the full geographic range of the stock in the IO, with good representation across months/seasons, over at least a full year. Sampling should be maintained in a second year, and ideally longer (i.e. three or more years), to determine if there is variation in parameters such as growth, maturity, and sex ratios over time. Sampling of the Japanese and Taiwanese, and potentially Chinese and Korean, longline fleets, via observers, will be critical to ensuring a regular and broad geographical spread of samples, and ensuring that catch information (location, date, time and state of fish when landed) is available. Sampling several local longline fleets, including Mauritius, Réunion and South Africa, and potentially Australia, Indonesia, Sri Lanka and Tanzania, will be will be important for increasing sample sizes in specific geographical areas, as well as for increasing the likelihood of sampling small fish. Opportunistic sampling of the recreational fishery in South Africa, such as through sports fishing competitions, may further increase the likelihood of obtaining small fish. We recommend sampling a small number of fish from every longline set, given that such an approach is more practical to implement, and generally preferred by industry, than more complex protocols in which a variable number of fish are sampled. Training and standardised sets of sampling equipment should be provided to observers and port samples to ensure consistent, best-practice approaches are employed. Laboratory analyses, sample storage and data management should similarly follow current best-practice approaches.

1 Introduction

Albacore tuna (*Thunnus alalunga*) are found in tropical, sub-tropical and temperate waters worldwide from approximately 50°N to 45°S. The species supports valuable commercial fisheries and important artisanal and subsistence fisheries across its range, representing an estimated 5% of the global commercial tuna catch in 2017 (SPC-OFP 2018). In the Indian Ocean (IO), the commercial catch of albacore tuna has grown substantially since commercial fishing commenced in the 1950s. Recent catches have fluctuated between ~30,000 to ~40,000 tonnes per year since a peak catch of ~43,000 tonnes in 2010 (IOTC 2016). The vast majority of landings are taken by longline (Figure 1), with the bulk of catches in recent years occurring in the waters north-east and south-east of Madagascar and south-west of Western Australia (Figure 2), primarily by Japanese and Taiwanese flagged vessels (Figure 3). Comparatively smaller catches are made by purse-seine, pole-and-line and gillnetting (Figure 1; Figure 4). Catches by purse-seine in 2016 and 2017 were made primarily by European Union (EU) fleets (Figure 5). Relatively large catches were obtained via driftnets in the 1980s and early 1990s (Figure 1) (IOTC 2019a,b).

Albacore tuna in the Indian Ocean is considered a single stock for assessment purposes. Knowledge of the stock structure, however, is uncertain. Larvae of albacore tuna are distributed in two separate and distinct zones, one in the eastern IO and the other in the western IO (Ueyanagi 1969), suggesting the existence of two distinct stocks. Based on morphometrics and DNA sequence analyses, Yeh et al. (1996) similarly proposed the existence of eastern and western IO stocks, separated at around 90°E. Other genetic studies have been largely uninformative in defining structure within the IO, with most global studies including only a single sampling location in the IO (e.g. Chow and Ushiama 1995; Montes et al. 2012). Examination of microsatellite DNA markers failed to differentiate between samples from the western IO and Atlantic Ocean (Montes et al. 2012), possibly due to some degree of mixing in the waters of South Africa. Lack of knowledge of the stock structure has long been considered, and remains, a key uncertainty in assessments of albacore tuna in the IO (Anon 1995; Langley and Hoyle 2016). Elsewhere, distinct northern hemisphere and southern hemisphere stocks are considered to occur in both the Atlantic and Pacific Oceans (Nikolic et al. 2017).

Although the migratory patterns of albacore tuna in the IO are poorly understood, the species is considered to be one of only four tuna species that are truly migratory and undertake seasonal migrations to specific feeding and spawning areas (Nikolic et al. 2017). Spawning of albacore tuna in the IO is thought to occur between 10°S and 30°S during summer, potentially in distinct areas in the eastern and western IO, and juveniles quickly move south of 30°S (Ueyanagi 1969; Dhurmeea et al. 2016; Nikolic et al. 2017). It has been suggested that juveniles and subadults do not return to the subtropics and tropics until they mature (Chen et al. 2005; Nikolic et al. 2017).

The most recent stock assessment for Indian Ocean albacore tuna estimated that the stock was unlikely to be overfished and that it was unlikely that overfishing was occurring (Langley and Hoyle 2016). This assessment, however, used many biological parameters that were either uncertain or assumed. For example, in the absence of any published studies estimating growth using direct ageing methods in the IO, the most recent assessment used the growth curve of Chen et al. (2012) developed for the North Pacific Ocean, as the parameterisation was considered to be closer to the Indian Ocean (Langley and Hoyle 2016). Similarly, in the absence of maturity data, the maturity at age estimate of Farley et al. (2013a, 2014), calculated for South Pacific Ocean albacore tuna, was used (Langley and Hoyle 2016).

1.1 Biology of albacore tuna, with reference to the Indian Ocean

The biology of albacore tuna in the Atlantic and Pacific Oceans has been the focus of a number of studies and is generally well understood. In the Atlantic Ocean, sex-specific growth has been observed, with the average maximum length of males larger than females (Bard 1981). The sex ratio is approximately 1:1 in all length classes preceding sexual maturity, after which sex ratios become increasingly male biased with length (Bard 1981). Sexual maturity for populations in the northeast Atlantic is reached between 90 and 94 cm fork length (FL), at around 5 years of age, with no differences noted between sexes (Bard 1981).

Sex-specific and spatial variation in growth have been observed for albacore tuna in the both the South Pacific Ocean and North Pacific Ocean (Chen et al. 2012; Williams et al. 2012). In the South Pacific Ocean, males obtain greater lengths than females for a given age from around four years of age, and individuals of both sexes obtain greater length-at-age at more easterly longitudes than at westerly longitudes (Williams et al. 2012). Longitudinal variation in length at age may also occur in the North Pacific Ocean stock (Xu et al. 2014).

In contrast to populations in the Atlantic and Pacific Oceans, there have been very few and limited studies on the biology of albacore tuna in the IO. For example, prior to 2019, there were no direct age estimates of growth available for albacore tuna anywhere in the IO. Accordingly, the IOTC Working Party on Temperate Tunas (WPTmT) recently identified the need to improve the understanding of life-history parameters for albacore tuna in the IO, and to improve understanding of the uncertainty in key demographic parameters on stock assessment results. In particular, it was noted that collaborative research across facilities on albacore tuna biology, including age and growth, length and age at maturity, and fecundity at age/length, was required, and recommended such collaborative research be undertaken as a high priority in recent WPTmT Programs of Work (IOTC 2014, 2016, 2019c).

Dhurmeea et al. (2016) provide an account of the reproductive biology of albacore tuna in the western Indian Ocean, based on 1,790 fish (923 females and 867 males), obtained from pole-and-line, purse-seine and longline vessels. Consistent with South Pacific stocks, spawning in albacore tuna in the IO was found to occur between 10°S and 30°S, from October to January (Dhurmeea et al. 2016). Larger females were found to have a longer spawning period than smaller individuals. The mean length at 50% maturity was estimated at 85.3 cm FL. As with elsewhere, albacore tuna in the IO where found to be batch spawners, spawning on average every 2.2 days within the spawning region and spawning months. Their results, however, were considered likely biased due to a lack of small (< 65 cm FL) fish (IOTC 2019d), and were limited to only a small portion of the IO.

In 2017, the IOTC Secretariat developed and funded a research project to estimate the age and growth of albacore tuna in the IO. Preliminary findings of this research were provided in Farley et al. (2019). Whilst providing a preliminary examination of the growth of albacore tuna in the IO using direct ageing techniques, and of female maturity at age based on samples from Dhurmeea et al. (2016), results were limited in both time and space, being based on 600 fish collected across two years across a small geographical area (between latitudes 0–40°S and 15–65°E), and limited by a lack of small fish. Accordingly, Farley et al. (2019) make several recommendations to further this work, including that otoliths from small fish (particularly < 75 cm FL) be collected and analysed to improve growth estimations; that ovaries and otoliths from small fish (particularly < 90 cm FL) be collected and analysed to improve maturity estimations; and that otolith and ovary sampling be expanded across the IO to examine spatial patterns in growth and maturity. Farley et al. (2019) also recommended that if otoliths from fish aged < 1 year are collected, that daily ageing be undertaken on (i) the longitudinal section to estimate length-at-age of very small fish and (ii) the transverse sections to confirm the location of the first opaque growth zone; that further work be undertaken to examine the timing of increment formation and refine the age algorithm; and that direct validation of the age estimation methods is undertaken in the IO.

1.2 This study

In 2019 the Food and Agriculture Organization of the United Nations, through the IOTC Secretariat, commissioned a scoping study to provide recommendations for improving the range of biological information for albacore tuna across the broader IO. The key objectives of the scoping study were to:

1. Undertake sensitivity analyses to indicate the sensitivity of the stock assessment to:
    1.1 the range of plausible values that might be estimated for each parameter; and
    1.2 potential structural changes to the assessment that might be informed by biological sampling.
2. Undertake power analyses on key biological parameters to determine sampling needs.
3. Using the outcomes of 1 and 2 above, and an understanding of the fisheries, outline the sampling considerations and develop a sampling design required to provide estimates of length- and age-based population parameters to improve stock assessments of albacore tuna in the IO.

This paper describes the preliminary results of this scoping study.

2 Assessing the impact of altered biological parameters on stock assessments of albacore tuna in the Indian Ocean

2.1 Approach

For the WPTmT07, a stock assessment has been developed for IO albacore tuna using a statistical age structured population model (Langley 2019). The assessment has been implemented in Stock Synthesis and includes catch, length composition data and longline CPUE indices to 2017. The primary assessment model is structured as a sex-specific (two sex), spatially aggregated model (single region) including four main longline fisheries. The longline CPUE indices from the south-western area (LL3) of the model are included as the primary abundance index from 1979–2017. Longline CPUE indices from the earlier period are not considered to represent a reliable index of stock abundance.

The longline fisheries from the southern areas are estimated to have a lower selectivity of the larger fish in the population, reflecting the lower proportion of large fish in the length composition compared to the longline fisheries in the equatorial areas. Recruitment deviates are estimated for the time period for which CPUE indices are available. There is concern regarding the reliability of the length composition data from the longline fisheries (e.g. Geehan and Hoyle 2013) and, correspondingly, these data have been assigned a low weighting in the assessment model. More details of the assessment model structure and assumptions are available in the relevant WPTmT07 document (Langley 2019).

For this study, a range of alternative model options were configured to evaluate the influence of changes to the key biological parameters on the stock assessment and status of albacore tuna in the IO (Table 1). The estimates of key stock status metrics were compared to the base model to assess the sensitivity of the results to the range of biological parameters evaluated. The current study focussed on those parameters that could be refined through further biological sampling, rather than providing a full range of model sensitivities. The final stock assessment includes additional sensitivities related to the stock-recruitment relationship and natural mortality.

The range of model sensitivities included alternative published values for the length-weight relationship for Indian Ocean albacore tuna (*LengthWeight*) (Figure 6, Table 1) and maturity-at-length from western Indian Ocean albacore tuna (*MaturityOgive*). There is uncertainty in the growth estimates for the younger age classes and an alternative growth function was configured to emphasise growth differences in the younger age classes (*GrowthYoung*) (Figure 7). There is also limited information available for the accurate determination of the variation of length-at-age. The *LengthAtAge* sensitivity incorporated a higher degree variation in length-at-age than assumed in the base model (Figure 8).

Larger length classes of albacore tuna tend to be dominated by male fish. This may be simply a function of differential growth of older male and female fish (*cf* Williams et al. 2012; Farley et al. 2019), although it has also been postulated that the larger female fish may have a higher mortality rate following the onset of sexual maturity. Correspondingly, the *NatMortAge* sensitivity increased the natural mortality of female fish from 0.30 to 0.35 for the age classes 4 years and older (Table 1).

Differential growth of albacore tuna has been observed for the South Pacific with growth rates increasing eastward. To investigate the sensitivity of the model to spatial variation in growth rates it was necessary to partition the model into two regions. Thus, the *EastWest* model was configured with two model regions (delineated at 75°E) with discrete populations (i.e. no movement between regions). The LL3 and LL4 CPUE indices represented the primary abundance indices in the western and eastern regions, respectively. The model estimated the overall distribution of recruitment between the two regions with the distribution of recruitment amongst the two regions was also allowed to vary annually. The two-region model was then configured to include two region-specific “growth morphs” with fish in the eastern region having a higher growth rate than fish in the western region (*EastWestGrowth*) (Figure 9).

A further set of models were used to evaluate the utility of the collection of length composition and age composition data from one of the main longline fisheries (LL 3 southwestern Indian Ocean). The approach used the base assessment model to simulate length and age composition data from the recent period (1995–2016). No sampling error (or bias) was associated with the simulated data sets, which is an unrealistic assumption. However, the analysis is considered exploratory and simply provides an indication of the potential scale of the influence of these two sets of data. A more thorough study should incorporate an appropriate (but unknown) magnitude of sampling variation in the derivation of the two sets of data.

The simulated data sets were then incorporated within separate iterations of the assessment model to compare the influence of the length sampling and age sampling data. For each scenario, the simulated data sets were assigned a high associated weighting, reflecting the precision of the simulated data (ESS age comp 50, ESS length comp 20).

2.2 Results

The alternative growth function incorporated in the *GrowthYoung* model resulted in a considerable deterioration in the fit to both the CPUE indices and the length composition data sets (from all longline fisheries) (Table 2 and Table 3). The increased variation in length-at-age (*LengthAtAge*) improved the fit to the length composition data from the southern longline fisheries (LL3 and LL4), although there was a considerable deterioration in the fit to the LL3 CPUE indices.

Partitioning the western and eastern regions of the Indian Ocean (*EastWest*) resulted in an improvement in the fit to the LL3 CPUE indices, relative to the base model. There was also a small improvement in the fit to the length composition data from each of the longline fisheries (Table 2 and Table 3). Applying the different growth functions to the eastern region of the model (*EastWestGrowth*) improved the fit to the eastern CPUE indices (LL4) but eroded the fit to the eastern length composition data (LL2 and LL4).

Of the range of model options, the estimates of stock status were most strongly influenced by the changes related to the growth parameterisation; the *GrowthYoung* and *LengthAtAge* sensitivities both yielded considerably more pessimistic estimates of current stock status (Table 4). Changes in the maturity ogive (*MaturityOgive*) and female natural mortality (*NatMortAge*) influenced the magnitude of the reference biomass levels, although the stock status ratios were not appreciably different from the base model (Table 4). Nonetheless, the *MaturityOgive* and *NatMortAge* sensitivities estimated similar yields (*MSY*) compared to the base model.

The spatial partitioning of the model into two regions (*EastWest*) yielded a considerably more optimistic estimate of current stock status and higher overall yields compared to the base model. Changing the growth functions for the eastern partition of the stock (*EastWestGrowth*) resulted in a marginal increase in *MSY* yield relative to the *EastWest* model but did not appreciably change the estimates of current stock status (Table 4).

The biomass trajectories from the models that included the simulated length or simulated age data were very similar to the base model, although the inclusion of the age data did result in a positive bias in the level of absolute biomass (15% for the terminal year) and the estimate of current stock status (10%) (Figure 10). This was associated with a higher estimate of the overall level of recruitment from the model. The inclusion of the length or age data resulted in a small improvement in the precision of the estimates of the recent level of biomass corresponding to the “data rich” period (from about 2000 onwards) (Figure 11).

A further set of simulations were conducted that incorporated a bias in the CPUE indices for the recent period; incorporating a 2% per annum increase in the CPUE indices from 2001 to 2017. The biased model was then rerun with the simulated length and age data sets (derived from the unbiased model). The introduction of the biased CPUE indices yielded a more optimistic biomass trajectory during the recent period, relative to the base model (Figure 12). The inclusion of the simulated length data did not change the trajectory of the CPUE biased model. However, the inclusion of the age data resulted in a positive bias in the magnitude of the biomass that was most pronounced during the “data rich” period. This was evident in the change in the estimated level of recruitment with the inclusion of the age data (Figure 13). There was only a small deterioration in the fit to the age data between the models without (age likelihood 1.86) and with (age likelihood 2.129) bias included in the CPUE indices, suggesting that an examination of the fit to the age composition data would not provide evidence of a bias in the index.

This preliminary study indicates that the age (and length) composition data are uninformative about stock size (and fishing mortality) in the context of the current stock assessment framework. Instead, these data interact strongly with the available abundance information in the parameterisation of recruitment. Clearly, considerable emphasis is required to ensure that the abundance information is sufficiently reliable to maximise the utility of the sampling data collected from the fishery.

3 Determining sampling needs

The aim of this component was to determine the sample sizes required to provide representative estimates of key biological parameters for albacore tuna in the IO. This is necessary from both a population dynamics viewpoint (understanding the biology, and how this varies spatially or temporally) and to provide inputs for the stock assessment.

3.1 Approach

Simulation modelling using the dataset for albacore tuna in the South Pacific Ocean (see Williams et al. 2012; Farley et al. 2013a,b, 2014) was undertaken to determine the sampling regime required to a) achieve target levels of precision for key biological parameters, and b) identify and estimate relationships with covariates via model selection. The original dataset included 399 sets, of which 254 sets included 970 females and 335 included 928 males.

The parameters investigated included:

- Growth:
    - Length at ages 4 and 10, and location 200°E
    - Model selection

Simulation was carried out by bootstrap resampling of the South Pacific albacore tuna dataset. We resampled the dataset with replacement, with proportions (*prop*) of the available data (with *nset* rows) equal to 10%, 20%, 30%, 40%, 60%, 80%, 100%, and 120%. Thus, we randomly selected *ns* sets = *prop* x *nset*, with replacement. Then within each selected set we enumerated the number of fish in the original sample (*nf*) and randomly resampled *nf* fish from the set with replacement.

Within the resampled dataset, each resampled set was allocated a new set id, so that original sets that had been sampled more than once were treated as separate sets in analyses that used set id as a random effect.

Resampling was carried out 1000 times for each value of *prop*, with each realisation of the resampled data taken to represent a new random dataset.

For the growth simulations we fitted nine models to each resampled dataset and identified the model with the lowest AIC. This 'best' model was then used to predict size for fish aged 4 and 10 located at longitude 200°E.

The nine models included all possible combinations of linear and quadratic relationships between longitude and the parameters K and L∞ in the logistic model.

1. mod_1: $len \sim linf * \left(1 + e^{-K.(age-t0)}\right)^{-1}$
2. mod_l1: $len \sim (linf + linf2.lon) * \left(1 + e^{-K.(age-t0)}\right)^{-1}$
3. mod_l2: $len \sim (linf + linf2.lon + linf3.lon^2) * \left(1 + e^{-K.(age-t0)}\right)^{-1}$
4. mod_k1: $len \sim linf * \left(1 + e^{-(K+K2.lon).(age-t0)}\right)^{-1}$
5. mod_k2: $len \sim linf * \left(1 + e^{-(K+K2.lon+K3.lon^2).(age-t0)}\right)^{-1}$

6. mod_lk1: $len \sim (linf + linf2.lon) * \left(1 + e^{-(K+K2.lon).(age-t0)}\right)^{-1}$
7. mod_lk2: $len \sim (linf + linf2.lon + linf3.lon^2) * \left(1 + e^{-(K+K2.lon).(age-t0)}\right)^{-1}$
8. mod_lk3: $len \sim (linf + linf2.lon) * \left(1 + e^{-(K+K2.lon+K3.lon^2).(age-t0)}\right)^{-1}$
9. mod_lk4: $len \sim (linf + linf2.lon + linf3.lon^2) * \left(1 + e^{-(K+K2.lon+K3.lon^2).(age-t0)}\right)^{-1}$

3.2 Results

In the growth analyses there were differences between males and females in the rates at which the various models were selected (Figure 14). For females, the best fitting model was the most commonly selected at true sample sizes or higher. However simpler models with less spatial variation in L∞ were also relatively common, including mod_lk3, mod_k2, and mod_lk2. With less than 80% of the true sample sizes, model mod_k2 was the most common. For males, mod_lk4 was the most commonly selected even at 10% of the true sample sizes. However, the probability of selecting this model became steadily lower with smaller sample sizes and was less than 50% when simulated sample sizes were lower than 50% of the actual sample size.

Coefficients of variation for predicted lengths at ages 4 and 10 decreased with increasing sample size (Figure 15). At 10% of the actual sample size the CV was 3.3% and 3.4% for females, and 2.4% and 2.5% for males. These decreased with increasing sample sizes to reach 1.1% and 1.0% for females and 0.6% and 0.6% for males at 100% of the actual sample sizes.

Additional analyses will be conducted on:

- Female gonad index (GI)
    - GI at 100 cm FL
    - Model selection
- Spawning frequency
    - Spawning frequency at 100 cm FL
    - Model selection
- Batch fecundity
    - Fecundity at length 100 cm FL
    - Model selection.

4 Design of a biological sampling program for albacore tuna in the Indian Ocean

Our analyses in Section 2, as well as previous and current stock assessments for albacore tuna in the IO, suggest stock assessments and resulting status determinations are sensitive to uncertainties around growth, reproduction and spatial structure (Hoyle et al. 2014; Langley and Hoyle 2016, Langley 2019).

4.1 Sampling considerations

4.1.1 Growth

Several factors need to be considered in attempting to obtain unbiased estimates of growth parameters for each sex/year/area strata, including:

- **Sex-specific patterns of growth**, including spatial variation in sex ratios, observed for albacore tuna within the IO (Farley et al. 2019) and elsewhere (e.g. South Pacific Ocean, Williams et al. 2012).

- **Latitudinal variation in distribution**. As discussed above, the size composition of albacore tuna in the IO varies with latitude, consistent with stocks in the Atlantic and Pacific Oceans. Generally, larger, mature albacore tuna are concentrated in equatorial areas, while smaller, immature albacore tuna are distributed at higher latitudes, with a boundary at about 30°S that roughly corresponds to the occurrence of the Circumpolar Current (Chen et al. 2005; Geehan and Hoyle 2013).

- **The potential for longitudinal differences in growth**, such as observed in South Pacific albacore tuna (Williams et al. 2012). Such variation may result from spatial variation in growth, selectivity, or size-dependent movement (Williams et al. 2012).

- **Ensuring sampling includes small fish** (i.e., < 75 cm FL). Obtaining small fish represents a significant challenge, and one that will require considerable collaborative effort and coordination to resolve. In the South Pacific study (Williams et al. 2012; Farley et al. 2013a,b, 2014), small fish were sourced from the troll fishery in New Zealand, and from recreational fishers along Australia’s east coast, and in particular Tasmania, i.e., between approximately 40-45°S. Comparable options are generally not available in the IO. Catches by South African-flagged vessels are largely made by the pole-and-line fleet, which target juvenile and sub-adult albacore tuna between 2 and 3 years old (average of 86 cm FL), primarily in the Atlantic Ocean, with only occasional forays into the Indian Ocean (Parker et al. 2018). In South African waters, smaller catches are made by longline vessels operating with the IOTC Area of Competence, typically between 26°S and 36°S, and thus are largely comprised of adult fish (Parker et al. 2018). According to IOTC records, less than 1% of fish from which fork length measurements exist in the IOTC database (over 4.6. million fish) are recorded as having a length of 50 cm or less, with the majority of these small individuals reported by fresh and deep-freezing Taiwanese longliners in the years between 2012 and 2017 (for FLL) and early 2000s (for LL) (IOTC 2019d).

- **The collection of variatic otoliths or otherwise unreadable otoliths, and the potential for damage to otoliths upon collection**. It is likely that a small percentage of collected otoliths will be variatic or otherwise unreadable, or broken upon collection making sectioning unsuitable. Therefore, larger number of otoliths will need to be collected than processed.

4.1.2 Reproductive parameters

Maturity

Robust, IO-wide estimates of maturity depend on both immature and mature individuals being sampled in an unbiased way. Estimating the maturity schedule is difficult for species such as albacore tuna where the mature fish migrate to discrete areas to spawn, or where there is any bias towards mature/immature fish in the sampling program. Although the migratory patterns of albacore tuna in the IO are poorly understood, the species is considered to be one of only four tuna species that are truly migratory and undertake seasonal migrations to specific feeding and spawning areas (Nikolic et al. 2017). Spawning of albacore tuna in the IO is thought to occur between 10°S and 30°S during summer, potentially in distinct areas in the eastern and western IO, and juveniles quickly move south of 30°S (Ueyanagi 1969; Dhurmeea et al. 2016; Nikolic et al. 2017). It has been suggested that juveniles and subadults do not return to the subtropics and tropics until they mature (Chen et al. 2005; Nikolic et al. 2017). Particular considerations include:

- **Ensuring small/immature fish are adequately represented**. Farley et al. (2019) estimated the length and age at 50% maturity for female albacore tuna in the western IO to be around 84.9 cm FL and 3.2 years, although these estimates were derived in the general absence of small fish. Thus, for maturity estimates, it is recommended that sampling should cover the entire length range of the harvested component of albacore tuna in the IO. Accordingly, sampling should cover the full latitudinal range of albacore tuna in the IO, and not just areas where catches are greatest.

- **Seasonal and latitudinal effects on length and age at maturity.** In the South Pacific Ocean, Farley et al. (2014) observed that the proportion of mature females at length varied significantly with latitude and time of year. Specifically, females at northern latitudes (~10–20°S) were mature at significantly smaller lengths and ages than females at southern latitudes (~20–40°S), particularly during the spawning season, a result Farley et al. (2019) attributed to different geographic distributions of mature and immature fish during the year. Such patterns have a significant effect on maturity ogives and subsequent calculations of reproductive output, making it critical to account for such spatial and temporal variability in designing a sampling program (Farley et al. 2019).

- **Longitudinal effects on length and age at maturity**. Given the potential for longitudinal variation in growth, longitudinal differences in maturity also need to be considered. Sampling should thus cover the full longitudinal range of albacore tuna in the IO, whilst simultaneously covering the full latitudinal range.

- **Sampling time**. In the South Pacific Ocean, Farley et al. (2014) reported that mature but regenerating female albacore tuna can be distinguished from immature females during the non-spawning season, and that the proportion of mature females at length varied significantly with time of year and latitude. Accordingly, year-round sampling covering all latitudes is required for estimating maturity in albacore tuna.

Spawning season

- **Sampling time, and potential for area differences**. Dhurmeea et al. (2016) observed a clear pattern of spawning of albacore tuna, with spawning concentrated between October and January and peak spawning occurring in November and December. However, their sampling was limited to the western IO (between 10°E and 70°E), and little is known of the timing and location of spawning in the central or eastern IO. Latitudinal effects also need to be considered, with Dhurmeea et al. (2016) observing spawning capable females occurring between 10°S and 30°S only during the spawning season and occurring south of 30°S outside of the spawning season (i.e., in the austral winter). Differences in spawning frequency may also be apparent: while Farley et al. (2013a) found no significant regional variation in female spawning frequency, Dhurmeea et al. (2016) observed that individuals caught from waters east of Madagascar spawned more frequently (mean spawning interval = 2.2. days) than those across the entire western IO (mean spawning interval = 3.4 days). It is recommended that monthly samples, taken from across the geographic range of albacore tuna in IO, be collected to confirm the time and location of spawning, and spawning frequency.

- **Size of fish**. Farley et al. (2013a) observed that the proportion of active females and the spawning fraction increased with length and age, and that larger, older fish were more active at either end of the spawning season than small, young fish; a feature that has significant implications for reproductive output. A similar pattern was observed by Dhurmeea et al. (2016) for albacore tuna in the western IO, with a higher proportion of smaller-sized females in regressing and regenerating phases observed compared to large females, which were mostly in the spawning capable phase during the same period. To confirm such a pattern exists over the broader IO, it is recommended that a range of lengths be sampled, with samples collected over a monthly basis.

Fecundity and reproductive output

- **Potential for area differences**. Farley et al. (2013a) observed that for South Pacific albacore tuna, the average gonad index varied with longitude, with fish caught in easterly longitudes having heavier gonads for their size than fish in westerly longitudes.

4.1.3 Stratified vs. random sampling

Deciding whether to randomly sub-sample fish from each trip/set or conduct length stratified sampling is topical issue in biological sampling programs. On the one hand, random sampling often leaves older individuals poorly represented in biological studies. Because these fish also tend to be larger, there is an incentive to disproportionally sample large fish. On the other, stratifying sample collection by size (length) can bias estimates of length-at-age, fitted VB parameters, and derivative estimates of natural mortality (Goodyear 2019). Moreover, mixed designs, such as supplemented sampling of large fish, have been demonstrated to sometimes be worse with respect to biases than fully size-stratified designs (Goodyear 2019). Such biases may be corrected using age-lengths keys (ALKs), drawn from a random sample of the population (Goodyear 2019), however given uncertainties raised regarding the representativeness of length composition data for albacore tuna in the IO (Geehan and Hoyle 2013), the use of an ALK for this purpose is not recommended. Accordingly, it is recommended that random sampling of fish within sets be undertaken.

4.1.4 What tissue to sample

To address the considerations outlined above, the following biological material and data are required:

- Sagittal otoliths (for direct age estimation);
- Gonads (for estimations of maturity, batch fecundity, spawning frequency/fraction, and overall reproductive output);
- First dorsal fin spine (to compare/verify age against that from otoliths; particularly for small fish i.e., < 70 cm FL);
- Weight, to the nearest 0.1 kg (whole and dressed for conversion factors);
- Capture date, location and time (if possible);
- Whether the fish was alive or dead when landed (this being particularly important for mature fish during the spawning season to assess the time it takes to resorb postovulatory follicles for spawning frequency calculations); and
- Fishing method.

Additionally, the following material should be collected if opportunities exist (these materials are not requisite for addressing the considerations outlined above, but provide significant value-adding to a biological sampling program by facilitating examinations of population structure and genetic connectivity, short-term residency patterns, diets and food web positioning, and methylmercury and other organometallic toxin concentrations):

- Liver (a piece approximately 4–5 cm long);
- Stomach (cut as close to the gills as possible); and
- Muscle tissue (approximately 4-5 cm sample cut from the back of the fish or from near the anus).

4.1.5 What fleets/fisheries to sample

A number of nations have fished for albacore tuna in the IOTC Area of Competence in recent years. Below we provide a synthesis of the main fishing nations, focusing on recent catch statistics, how fish are processed, and current observer and port sampling programs.

Australia: The number of active Australian-flagged longline vessels and levels of fishing effort in the IO have remained low in recent years, largely due to reduced profitability. In 2017, three vessels from the Western Tuna and Billfish Fishery (WTBF) and seven vessels from the Eastern Tuna and Billfish Fishery (ETBF) fished in the IOTC Area of Competence (Hobsbawn et al. 2018). All vessels combined, the total catch of albacore tuna by Australian flagged longline vessels in the IOTC Area of Competence was 18.6 t (Hobsbawn et al. 2018), equating to around 890 individuals. Most fish are landed fresh (on ice or brine chilled) (K. Williams, WW Fisheries, pers. comm.). A further 0.2 t was caught by Commonwealth multi-purpose vessels (trolling, pole-and-line, dropline and handline). No albacore tuna were reported in Western Australian state fisheries catches in 2016 or 2017. Estimates of the recreational catch for tuna, including albacore tuna, within the IOTC Area of Competence in Australian waters is uncertain (Hobsbawn et al. 2018).

In 2007, an observer program was implemented in the WTBF. Since 1 July 2015, all observer coverage on Australian-flagged vessels in the WTBF has been via electronic monitoring (Hobsbawn et al. 2018). A port sampling program for the WTBF has been in place since 1999, with weight data for individual fish collected by operators (K. Williams, pers. comm.). In 2017, 854 individual albacore tuna were measured within the IOTC Area of Competence by this program (Hobsbawn et al. 2018). However, , the lack of 'on-the-ground' staff may mean sampling personnel have to travel to this location on a regular basis, making monthly sampling difficult and/or costly (unless operators were willing to undertake sampling).

China: The Chinese fleet operating in the IOTC Area of Competence consisted of 71 deep-frozen longliners and 10 fresh longliners in 2017 (Zhu et al. 2018). Combined, these vessels caught 3,646 mt of albacore tuna in 2017, with 1,320 mt taken by deep-frozen longliners and 2,326 mt taken by fresh longliners. In 2017 catches from both fleets predominantly came from the southern IO (Zhu et al. 2018; Figure 16).

China has operated an observer program in the IOTC Area of Competence since 2002. Four observers were deployed in 2017, all on deep-frozen longliners, with observer trips occurring in the north-west IO, immediately east and south-east of Madagascar, and the southern IO between approximately 50°E and 80°E at around 33°S (Jiangfeng Zhu, Shanghai Ocean University, pers. comm., Zhu et al. 2018). The total number of albacore tuna measured through this program is low (e.g. 52 individual fish in 2012, 26 in 2013; Zou et al. 2014), although observer coverage has increased in recent years. China has also implemented a port sampling program since 2012. In 2017, 300 albacore tuna were measured in this sampling program, though a key challenge of this sampling is the lack of detailed capture information, particularly around catch date and location (Zhu et al. 2018).

Comoros: The Comoros fleet operating in the IOTC Area of Competence is exclusively artisanal, with vessels ranging up to approximately 25 miles from the coast, with durations of up to a week. Fisheries use a variety of gears, in particular handline, trolling and vertical longline / dropstone, and land fish fresh. The fleet caught an estimated 37 t of albacore tuna in 2017. The artisanal nature of the fleet and vast number of geographically disparate landing sites makes sampling at this location difficult.

EU-France: Excluding the overseas departments of Réunion and Mayotte (discussed below), the French fishing fleet operating in the IOTC Area of Competence in 2017 consisted of 12 purse-seine vessels (Bach et al. 2018). Landings are mainly in Victoria (Seychelles), Port Louis (Mauritius) and Diego Suarez (Madagascar). Combined, these vessels caught 66,945 t of tuna in 2017, with albacore tuna constituting less than 0.5% of the total catch (149 mt) (Bach et al. 2018).

EU-France-Mayotte**:** The Mahoran longline fleet consisted of three active vessels in 2017, all of which targeted swordfish in surface waters (Bach et al. 2018). Catches of albacore tuna by this fleet are unknown but likely to be negligible, with a total of 30.6 t of tuna (all species) caught in 2017, with the bulk of this being yellowfin tuna and bigeye tuna (Bach et al. 2018).

An extensive small-scale fleet operates in coastal and nearshore waters of Mayotte, consisting of 141 registered 'professional' vessels in 2017, along with around 300 un-registered 'non-professional' vessels that use similar gears, and around 700 canoes. In 2017, the registered portion of this fleet caught 646 t of pelagic and demersal fish (Bach et al. 2018). Catches of albacore tuna by this fleet are unknown but considered low.

EU-France-Reunion**:** There were 40 longline vessels operating out of Réunion in 2018, 19 of which were 'semi-industrial' (12–24m in length) vessels that operated in offshore waters and 21 of which were smaller vessels that primarily operated in coastal waters (S. Bonhommeau, IFREMER, pers. comm.). In addition, a number (131 in 2018) of small-scale fishing boats that use handline and small longlines occasionally catch albacore tuna in the nearshore waters around Réunion. The offshore longline fleet caught 195 t of albacore tuna in 2018 and approximately 149 mt of albacore tuna in 2017, which constituted around 13% of the total catch of this fleet (S. Bonhommeau, pers. comm., IOTC 2019a). The coastal longline fleet caught approximately 65 mt of albacore tuna in 2018 (equating to approximately 16% of the total catch and 37% of the tuna catch of this fleet), while the small-scale fleet caught approximately 18.7 t in 2018 (equating to approximately 2% of the total catch of this fleet and 6% of the fleet's tuna catch) (S. Bonhommeau, pers. comm.). All catches are landed in Réunion, with the majority of catches landed fresh.

An observer program for the offshore longline fleet has been operation since 2010; the observer program covers approximately 10% of trips (S. Bonhommeau, pers. comm.).

Réunion has a port sampling program in place for its industrial longline fleet. In 2018, 590 albacore tuna were measured through this sampling program, including 510 from the semi-industrial fleet and 80 from the small coastal longline fleet (S. Bonhommeau, pers. comm.). In addition, there is an established, ongoing biological sampling program in Reunion, with approximately 150 albacore tuna sampled for otoliths, gonads and muscle each year since 2018 (ranging from around 90–110 cm FL) (S. Bonhommeau, pers. comm.). Fish are generally gutted upon landed at Réunion, but fishers are compensated to keep the viscera for a limited number of fish. Most fish are sold whole (i.e. with head intact), but a small number are sold without the head, and can thus be sampled for otoliths (S. Bonhommeau, pers. comm.).

EU-Italy: The Italian fishing fleet operating in the IOTC Area of Competence in 2017 consisted of a single purse-seine vessel. This vessel caught a total of 2 mt of albacore tuna in 2017 (UE-Italy 2018).

EU-Portugal: The Portuguese fishing vessels operating in the IOTC Area of Competence consisted only of pelagic longliners targeting swordfish (Coelho 2018). Catches of albacore tuna by this fleet are negligible, with < 6 mt caught in 2017 (IOTC 2019a).

EU-Spain: There were 14 EU-Spanish-flagged industrial longline vessels operating in the IOTC Area of Competence in 2017, along with 14 purse-seine vessels. Spanish-flagged longline vessels do not target albacore tuna, and have not reported any albacore tuna catches in recent years.

The purse-seine fleet caught 100 t of albacore tuna in 2017 (0.07% of the fleets' total annual purse-seine catch for that year), largely as by-catch (IEO and SGP 2018).

EU-United Kingdom: The UK fishing fleet operating in the IOTC Area of Competence in 2017 consisted of two longline vessels. These vessels mainly target swordfish and sharks, and caught a total of 579.8 t in the IOTC Area of Competence in 2017, including 3.1 mt of albacore tuna (constituting approximately 0.5% of the total catch) (United Kingdom 2018).

***India*:** Little is known of albacore tuna catches by Indian-flagged vessels. Catches are likely to be negligible, with no reference to albacore tuna made in the most recent submitted national report to the IOTC Scientific Committee (Premchand et al. 2015), and no catches of albacore tuna reported in data submitted to the IOTC (IOTC 2019a).

***Indonesia*:** Indonesian-flagged vessels caught 6,994 t of albacore tuna in the IO in 2017, with the majority (6,399 t) landed by longline vessels (Ruchimat et al. 2018). Approximately 357 t of albacore tuna were landed at Benoa Port in 2017 (Ruchimat et al. 2018), where staff from the Research Institute for Tuna Fisheries undertake port sampling. However, most of the albacore tuna landed in Benoa are frozen without processing and sold whole, with vendors opposed to any sampling resulting in damage to the fish (Ririk Sulistyaningsih, Research Institute for Tuna Fisheries, pers. comm.), precluding the acquisition of biological samples such as otolith and gonads from these fish.

Fresh albacore tuna caught in the IOTC Area of Competence are landed at the ports of Sendang Biru and Pacitan on the island of Java In 2016, landings were around 500 mt and 213 mt, respectively (Ririk

Sulistyaningsih, pers. comm.). There is no existing sampling program for this fish, and sampling would require translocating a sampling team from Bali or Jakarta (and thus monthly sampling may prove difficult and/or costly).

Iran: Little is known of albacore tuna catches by Iranian vessels, with no reference to albacore tuna in the recent national report to the Scientific Committee of the IOTC (Anon 2018a). Catches are likely to be low, with no industrial longline vessels in operation (Anon 2018a). According to the IOTC, offshore gillnet vessels from I.R. Iran have extended their area of operation in recent years, and are now thought to operate on the high seas closer to the equator. However, the lack of catch-and-effort data from these fleets makes it difficult to assess whether they are operating in areas where catches of juvenile albacore tuna are likely to occur (IOTC 2019d).

Japan: Japan had 41 longliners operating in the IOTC Area of Competence in 2017, along with 3 purse-seiners. The longline fleet caught a total of 1,668 mt in 2017, a decline of 699 mt from the previous year (Anon 2018b). Since the 1960s, the species was largely caught as by-catch, although in recent years more Japanese longline vessels have been targeting albacore tuna, especially in the waters south-west of Australia and, to a lesser extent, around South Africa (Figure 17), largely due to decreased quota of southern bluefin tuna and enhanced market value of albacore tuna for sashimi products (Matsumoto 2016). No albacore tuna catch was reported from the purse-seine fleet in 2016 or 2017, consistent with the long-term trend of this fishery. The longline catch is unloaded abroad predominantly in a frozen state (Anon 2018b).

Japan has operated an observer program in the IOTC Area of Competence since 2010. During 2010–2016, observer numbers have ranged between 6 and 14 (average=10) per year, covering an average of 6.6% of hooks annually (Anon 2018b). In 2016, observers measured a total of 3,658 individual albacore tuna from a total of 9 vessels (Anon 2018b). In recent years, the bulk of observer coverage has been concentrated around the waters south-west of Australia (Figure 18), consistent with patterns in catch.

Kenya: Approximately 1,931 t of tuna (all species) were landed by artisanal fisheries in 2017 (Mueni et al. 2018). Due to the artisanal nature of the fleet it is not possible to identity the proportional of albacore tuna in the catch, though it is considered to be negligible. No port sampling of artisanal vessels is currently conducted (Mueni et al. 2018).

Madagascar: The Malagasy fleet operating in the IOTC Area of Competence in 2017 was comprised of seven longliners all less than 24 m in length. Since 2014, these longliners have operated exclusively in the waters east of Madagascar, generally been 14°S and 22°S. In 2017, the fleet caught approximately 39 t of albacore tuna within the IOTC Area of Competence, which was approximately half of the catch for 2016 (79 t). Port sampling is conducted in two ports on the east coast – Sainte Marie and Tamatave – where two and five longliners of the national fleet are based, respectively (MRHP et al. 2018).

Malaysia: Malaysia had 19 longline vessels operating in the IOTC Area of Competence in 2017, with 6 vessels operating in the southwest IO primarily targeting albacore tuna, and 13 operating in the east IO primarily targeting yellowfin and bigeye tunas (Samsudin et al. 2018). Combined, the vessels caught approximately 1,607 t of albacore tuna in 2017. The six vessels targeting albacore tuna unloaded their catch in a frozen state at Port Louis, Mauritius (Samsudin et al. 2018), precluding port sampling of this catch. At the time of writing, Malaysia did not have a national observer scheme, precluding any onboard sampling at present, although were looking to implement an observer program in mid-2019 (Samsudin et al. 2018).

Mauritius: Mauritius had 12 semi-industrial longliners operating in the IOTC Area of Competence in 2017, along with 2 purse-seiners (and one supply vessel). The longline vessels typically carry out short trips (9–11 days) and land most of their fish chilled. The total catch of albacore tuna by the semi-industrial longline fleet in 2017 was 36 mt, with the majority of this (34 mt) taken by longliners operating within the Mauritius EEZ, and the remainder taken off the coast of Mozambique (Sheik Mamode et al. 2018). Small amounts (around 1 mt) of albacore tuna were taken by the purse-seine fishery in 2017 (Sheik Mamode et al. 2018). The semi-industrial longline fleet is currently not covered by human observers. Observers are deployed on one of the purse-seine vessels (Sheik Mamode et al. 2018). Some port sampling of the semi-industrial longline catch is conducted at Port Louis, with 195 individual albacore tuna measured through this program to date (Sheik Mamode et al. 2018).

Mozambique: Mozambique had 2 industrial longliners licenced in 2017. The total catch of albacore tuna in 2017 by the national fleet was 0.84 t (Chacate and Mutombene 2018), equating to approximately 35 individuals. No albacore tuna were reported in artisanal catches in either 2016 or 2017 (Chacate and Mutombene 2018).

Oman: Little is known of albacore tuna catches by Omani-flagged vessels, with no reference to albacore tuna in the recent national report to the Scientific Committee of the IOTC (MAF 2018). Catches are likely to be low, with only one industrial longline vessel in operation (MAF 2018).

Pakistan: Little is known of albacore tuna catches by Pakistan vessels, with no reference to albacore tuna in the recent national report to the Scientific Committee of the IOTC (Khan 2018). Catches are likely to be low, with no industrial longline vessels in operation, and the majority of vessels using gillnets to catch yellowfin tuna, neritic tunas such as longtail tuna (*Thunnus tonggol*) and frigate tuna (*Auxis thazard*), and other nearshore pelagics (Khan 2018). According to the IOTC, offshore gillnet vessels from Pakistan have extended their area of operation in recent years, and are now thought to operate on the high seas closer to the equator. However, the lack of catch-and-effort data from these fleets makes it difficult to assess whether they are operating in areas where catches of juvenile albacore tuna are likely to occur (IOTC 2019d).

Philippines: The Philippines had only one active vessel operating in the IOTC Area of Competence in 2017, a purse-seiner. No albacore tuna were reported in catches from this vessel (Gongona et al. 2018).

Rep. of Korea: There were 13 Korean-flagged longline vessels operating in the IOTC Area of Competence in 2017, along with 3 purse-seine vessels. The longline fleet caught approximately 6,625 individual albacore tuna in 2017, down from 9,640 in 2016 and 16,656 in 2015 (Kim et al. 2018). This decline was largely related to a shift in fishing location, with a number of vessels shifting to target yellowfin tuna and bigeye tuna in the western tropical area between 5°N and 10°S and in the Mozambique Channel (Kim et al. 2018; Figure 19).

Korea has operated an observer program for distant water fisheries since 2010. In 2017, two observers were dispatched on Korean-flagged longline vessels within the IOTC Area of Competence, with both observers operating on trips within the Mozambique Channel (Kim et al. 2018).

Rep. of Maldives: There were 44 Maldivian-flagged longline vessels operating in the IOTC Area of Competence in 2017, including 7 vessels > 22.5 m, along with a number of pole-and-line and troll vessels. The total catch of the longline fleet was 139,000 t (Ahusan et al. 2018). Catches of albacore tuna however are likely to be negligible. Data supplied to the IOTC for the current stock assessment indicate that no albacore tuna were caught by the Maldivian-flagged industrial longline fleet in 2017 and < 5 t in 2016, with only small amounts caught by the coastal longline fleet (3.38 t in 2017) (IOTC 2019a).

Rep. of South Africa**:** The majority of catches of albacore tuna in South Africa are made in Atlantic Ocean waters, largely by the pole-and-line fleet operating out of Cape Town. There were 16 South African-flagged longline vessels and a single pole-and-line vessel operating in the IOTC Area of Competence in 2017, with the latter fishing in the Indian Ocean for a total of 12 hours (Parker et al. 2018). The total catch of albacore tuna by the South African large pelagic longline fleet in the IOTC Area of Competence was 26.5 t in 2017, slightly up from 19.9 t in 2016, but well below the annual catch of 2013 (177.5 t) (Parker et al. 2018). While the size structure of the catch was unknown at the time of writing, catches by the longline fleet in the IOTC Area of Competence typically occur between 26°S and 36°S (Parker et al. 2018), and thus likely to be comprised of adult fish.

One-hundred per-cent (100%) observer coverage is required on joint venture (foreign-flagged) longline vessels, with four observers actively observing on the three Japanese joint-venture vessels operating in the IOTC region in 2017, and a single trip from a local longline vessel observed. Length frequency data from the pelagic longline fleet are collected at sea by observers prior to the fish being dressed (Parker et al. 2018). Observers collect biological material when required (Parker et al. 2018). Approximately 655 individual albacore tuna were measured by observed on pelagic longline vessels in the IOTC Area of Competence in 2017 (Parker et al. 2018). There are no observers stationed on pole-and-line vessels (Parker et al. 2018).

South Africa had an active port sampling for albacore tuna (and other species), with length-frequency data collected through sampling of pole-and-line vessels by Department of Agriculture, Forestry and Fisheries (DAFF) staff from 2011–2018. The port sampling program is no longer operating due to staffing issues (D. Parker, Department of Agriculture, Forestry and Fisheries, pers. comm.). However, some port sampling is conducted on an ad-hoc basis when samples are required. Small fish (down to 60 cm FL) are occasionally available through this sampling (D. Parker, pers. comm.).

The boat-based recreational fishery also targets albacore tuna, along with other tunas and marlins. Opportunities exist to sample this fishery, such as has been previously conducted by DAFF staff in collaboration with the University of Cape Town, although this would be on an opportunistic basis (e.g. at fishing competitions). At the time of writing, the size structure of this fish sampled through these activities was unknown. It is likely some small fish are caught by recreational fishers, although arrangements would have to be made to retain these. Most of the recreational catch is taken from the International Commission for the Conservation of Atlantic Tunas (ICCAT) Area of Competence (D. Parker, pers. comm.), however evidence suggests these fish may form the same stock as found in South African waters in the IOTC Area of Competence (Montes et al. 2012).

Seychelles**:** There were 48 Seychellois-flagged industrial longline vessels operating in the IOTC Area of Competence in 2017, along with 13 purse-seine vessels and 31 small-scale semi-industrial longline vessels (Assan et al. 2018). Data supplied to the IOTC for the current stock assessment indicate that the industrial longline fleet caught approximately 656 mt of albacore tuna in 2017, or approximately 49,947 individuals, with the bulk of the catch occurring in the western IO between 12.5°N and 37.5°S (Figure 20), by frozen longline vessels (IOTC 2019a). The purse-seine fleet caught 56 mt of albacore tuna in 2017 (Assan et al. 2018). Albacore tuna are seldom if at all caught by the small-scale longline fleet (N. Bodin, Seychelles Fisheries Authority, pers. comm.). The industrial longline fleet is currently not covered by human observers, though electronic monitoring is being trialled on two vessels (Assan et al. 2018). The industrial longline fleet does not land in Port Victoria and there are no port sampling programmes for these vessels (Assan et al. 2018). Rather, a self-sampling programme is being implemented, whereby size frequency data are being recorded by the crew and transmitted to the Seychelles Fishing Authority (Assan et al. 2018). Port sampling is a routine activity for the purse-seine, small-scale longline and local artisanal fleets, although these activities are primarily focussed on yellowfin, skipjack and bigeye tunas (being the dominant species of these catches), with only one individual albacore tuna measured in 2017 (Assan et al. 2018).

Somalia: Catches of albacore tuna by Somali-flagged vessels are unknown, but likely to be negligible. There were no Somali-flagged vessels > 24 m operating in the IOTC Area of Competence in 2018, and albacore tuna is not a target species for artisanal fishers (Sheik Heile et al. 2018).

Sri Lanka**:** There were two Sri Lankan-flagged large (> 24 m) longline vessels in operation in the IOTC Area of Competence in 2017, along with a number of smaller longline, gillnet, and ring net vessels (Hewapathirana et al. 2018). The longline fleet landed an estimated 34.8 mt of albacore tuna, primarily in the northern IO, including the southern Arabian Sea and Bay of Bengal (Hewapathirana et al. 2018, IOTC 2019a). A further 33.5 mt was caught by offshore ring net, and 54.7 mt caught by offshore gillnet, in 2017.

The Department of Fisheries and National Aquatic Resources Research and Development Agency (NARA) undertake port sampling in 13 of the 15 coastal fisheries districts, focusing on offshore multiday boats and tuna-targeting coastal day boats (Hewapathirana et al. 2018). Only a small number of albacore tuna are encountered through this sampling (albacore tuna represented approximately 0.6% of all fish measured in port sampling in 2017) (Hewapathirana et al. 2018).

Taiwan,China**:** Taiwanese longliners have operated in the IOTC Area of Competence since the 1950s. In 2017, the Taiwanese fleet consisted of 138 large-scale vessels (> 100 GT) and 180 small-scale vessels (< 100 GT) (FA and OFDC 2018). In the recent decade, the catch of albacore tuna by Taiwanese longliners in the IOTC Area of Competence has fluctuated between 10,000 mt to 18,000 mt (Chang et al. 2016). In recent years longline operations have covered the geographic breadth of the IO, with the bulk of catches coming from the south western and south eastern regions (Wang 2019; Figure 3; Figure 22). The large-scale longline fleet caught approximately 5,199 mt of albacore tuna in 2017, predominantly from 30°S to 40°S, while the small-scale longline fleet caught approximately 17,283 mt, predominantly in the western IO (FA and OFDC 2018). Catches of the large-scale fleet are unloaded at Mauritius, although most vessels tranship their catch at sea (Ren-Fen Wu, Overseas Fisheries Development Council, pers. comm.), potentially limiting the catch information available. The small-scale fishery operates as two sub-fleets, with one sub-fleet targeting albacore tuna in the western IO and using Mauritius as a base (unloading at this location), and the other largely targeting tropical tuna in the eastern IO using Phuket (Thailand) and Sri Lanka as bases (unloading at these locations). Most of the small-scale longliners have freezers on board and thus store their catches frozen (Ren-Fen Wu, pers. comm.).

Taiwan maintains an active observer program in the IOTC Area of Competence. In 2017, there were 1,894 fishing days observed by 19 observers deployed on the large-scale tuna longline vessels. For the small-scale longline fishery, there were 756 fishing days observed by 12 observers. Observers collect fisheries data and size measurements of target species and record bycatch. At the time of writing, it was unknown whether vendors/markets would allow biological sampling of the catch.

Tanzania: No national report was available for review for Tanzania in 2017 or 2018. In 2015, Tanzania's national fleet in operation in the IOTC Area of Competence consisted of 3 commercial longliners and a number of small boats using small-scale gillnets, troll lines and longlines (Amir and Hamid 2016). The commercial longline fleet caught approximately 28 t of albacore tuna in 2015, with the bulk of catches made within the Tanzanian EEZ and in the waters north and northeast of Madagascar (Amir and Hamid 2016).

Thailand: Little is known of albacore tuna catches by Thai-flagged vessels in the IOTC Area of Competence, with no catch statistics for albacore tuna available in the recent national report to the Scientific Committee of the IOTC (Lirdwitayaprasit et al. 2018). Catches are likely to be low, with no industrial longline vessels and only a single purse-seine vessel in operation in 2016 and 2017 (Lirdwitayaprasit et al. 2018). Several foreign fleets unloaded in the Thai port of Phuket in 2017, including Bahamas, Malaysia, Panama, Taiwan,China, Republic of Korea, although these unloadings seldom have corresponding catch information available (Panjarat et al. 2016).

4.2 Sampling strategy

To sustain an effective biological sampling for albacore tuna in the IO, two important considerations are:

1) sample suitability, i.e., ensuring samples are adequate for addressing the research questions being asked, and
2) sampling efficiency i.e., ensuring value for effort.

Moreover, to undertake a complete study on the biology of albacore tuna in the IO, including, age, growth and reproduction, in light of the considerations described above, sampling should ideally cover the full geographic range of the stock in the IO, with good representation across months/seasons, over at least a full year. Sampling should be maintained in a second year, and ideally longer (i.e. three or more years), to determine if there is variation in parameters such as growth, maturity, and sex ratios over time.

Accordingly, to obtain the requisite number of samples and spatial coverage in a manner as efficient as possible, we recommend that sampling be conducted from the following fleets:

- Distant water fishing nations, in particular Japanese and Taiwanese-flagged longliners, and potentially Chinese and Korean longliners, via observers;
- Local fleets: South African longline fleet, Réunion longline fleet (including both offshore and coastal sectors), and Mauritius semi-industrial longline fleet; potentially Tanzanian, Sri Lankan, Indonesian and Australian WTBF longline fleets
- Opportunistic sampling of recreational fishers and game fishing clubs (e.g. during fishing tournaments) in South Africa to increase the potential for sampling small (< 75 cm FL) fish.

Sampling of the four major distant water fish nation (DWFN) longline fleets via observers will be critical to ensuring a regular and broad geographical spread of samples, and ensuring that catch information (location, date, time and state of fish when landed). Moreover, each of these fisheries holds its own intrinsic value for sampling. For example, sampling from the Japanese longline fleet will be crucial for obtaining fish from the south-eastern IO, while sampling from the Taiwanese longline fleets will be crucial to ensuring broad geographical coverage, particularly in the southern latitudes.

Sampling of local fleets may provide the opportunity for supplementing samples from DWFN fleets in specific geographic areas. Sampling from several of these fleets, in particular South Africa and potentially Australia, may also be beneficial for increasing the likelihood of sampling small fish.

Similarly, opportunistic sampling of the recreational fishery in South Africa, and particularly through sports fishing competitions, will further increase the likelihood of obtaining small fish.

Based on our experience conducting biological studies from vessel and port sampling, operators generally prefer to sample a fixed, smaller number of fish from every set or trip rather than a variable (e.g. over time and space), larger number of fish from a subset of trips. It is also practically easier to implement a sampling strategy in which a smaller, fixed number of individuals are sampled than it is to implement a more complex protocol that requires keeping track of which trips have been sampled, especially if this is to vary in time and space. A preliminary analysis based on Taiwanese longline data for 2017 provided by the IOTC (IOTC 2019a) indicates that a simple sampling strategy of sampling a five fish from 2% of sets in a year would result in approximately 1,629 individual albacore tuna being sampled (Table 5). It should be noted that these analyses are preliminary, based on assumed numbers of hooks per set (and the assumption that this is constant among regions), nominal (rather than regionally standardised) CPUE, assumed rates of zero catch set per region (adapted from Hoyle et al. 2015) and observer coverage rates that approximate those of the small-scale longline fishery (i.e., 2% FA and OFDC 2018). Further analyses of spatial and temporal trends in hook numbers per set, CPUE and observer coverage data of all major are warranted for adequately assessing the sampling effort necessary for obtaining required sample sizes.

4.2.1 Sampler training and equipment

Sampling over a broad spatial area, with temporal repetition, will accordingly require an intensive and coordinated effort, involving staff from many different Collaborating Contracting Parties and Non-Contracting Parties (CPCs), regional scientific authorities, and academic institutions. The collection of such a large dataset will also require participation by a range of experts in the analysis of samples and resulting data.

To minimise the possibility of introducing artificial variation between samples as a result of variability in sample collection, handling, management and storage methods between samplers (individuals, teams or organisations), consistent best-practice approaches should be employed. Training should be provided to all samplers prior to commencing sampling. This should include the development of appropriate training material, including theoretical modules and hands-on, practical training for collection and handling of samples as well as data collections for standardisation, similar to what is done in the Pacific Islands Regional Fisheries Observers (PIRFO) biological sampling training program. Protocols should be developed that clearly set out the objectives of the project, facilitate standardisation where possible, support the generation of useful metadata streams and provide team members with the tools they need for achieving a successful sampling programme. For sampling of albacore tuna, this should include protocols for obtaining fish, species identification, standardised approaches for collecting tissues, sample labelling, preserving and packaging, and metadata collection standards, as well as transport and logistical arrangements (including permitting). Special attention should be given to the sample storage methods and best practices should be developed to ensure that sample quality is maintained on the long-term.

Observer coordinating agencies within CPCs should be provided with biological sampling kits. Each observer tasked to undertake biological sampling should be provided with a kit, as well as spare equipment. A sampling kit (to sample 50 fish) should consist of:

- 1 knife (sharp);
- 1 saw;

- 1 pair fine tweezers to extract otoliths;
- 1 large plastic bag (to store samples onboard);
- 100 large clickseal / ziplock bags (50 bags for stomachs, 50 for gonads);
- 100 medium clickseal bags / ziplock bags (50 for muscle, 50 for livers);
- 50 cable tie labels;
- 50 small vials for otoliths;
- 1 pencil;
- Gel ice pack;
- Sampling instructions;
- Biological sampling pamphlet;
- Biological sampling forms; and
- Small kitchen scale for weighing gonads at sea (if subsampling of gonads at sea is required).

Each observer should also be equipped with a set of callipers for measuring whole fish.

4.2.2 Sample preservation and storage

Otsu and Uchida (1959) found no significant difference in the mean diameter of the most advanced group of oocytes (MAGO), or in oocyte size frequency distributions, between left and right ovaries or along the length of the ovary. However, they did find a significant difference in mean diameter of the MAGO between the periphery and centre of the ovary suggesting that oocyte development can vary across the ovary. Accordingly, should sub-sampling of the gonad be required (e.g. due to space considerations onboard fishing vessels), a core subsample (lumen to the periphery) should be taken from the mid-section of either ovary. In these instances the weight of the whole gonad should be obtained. Ideally, samples should be fixed fresh in 10% buffered formalin for histological sectioning. Should this not be possible (e.g. due to issues with obtaining formalin, or storage of formalin on fishing vessels), samples should be frozen immediately upon collection. A comparison of histological sections prepared from fresh and frozen-thawed material by Farley and Clear (2008) showed that frozen tissue, although not perfect due to the rupture of some cells, were nevertheless suitable for staging ovaries as the oocytes, postovulatory follicles and all stages of atresia could be identified and classified. It is recommended, however, that frozen gonad material be preserved as quickly as possible to reduce the possibility of tissue deterioration while frozen. It is also recommended that any subsamples be taken from the gonad while frozen, to reduce further deterioration during the thawing process. Regardless of the method of preservation, samples should be stored with an accompanying sample label facing outwards.

Collected material should be sent to a coordinating facility (laboratory) in each country for sub-sampling, coordination and packing to send to a processing laboratory. If received whole from gonad from observer or port sampling activities, gonads should be sub-sampled suing the approach outlined above (i.e. a core subsample (lumen to the periphery) should be taken from the mid-section of either ovary). Core subsamples should then be stored in histological cassettes in 10% buffered formalin ready for transport. Subsampling in this way will greatly reduce costs associated with sample transport, and allow the majority of the sample to remain within the collection nation. Otoliths and dorsal spines received from observer or port sampling activities should be cleaned, dried and placed into plastic vials and plastic bags, respectively, with an accompanying sample label, for transport and processing.

4.3 Laboratory processing, including workshops and capacity development

Ensuring standardisation and consistency in laboratory processing techniques for ageing and reproductive analyses is crucial to minimise the possibility of introducing artificial variation between samples as a result of variability in sample processing and storage methods between laboratories. Accordingly, it is recommended that all samples be sent to a single laboratory for independent laboratory processing. Ideally, samples should be processed in a consistent manner, and in accordance with those from the Western and Central Pacific Ocean (WCPO) to allow comparison between regions. Opportunities, in the form of workshops or training attachments, should be provided to staff from CPCs providing samples to learn current tissue processing (otolith ageing and gonad histology) and/or analytical techniques (subject to individual countries' discretion).

4.3.1 Ageing

In the laboratory, all otoliths and dorsal spines should be cleaned, dried and archived. Sectioning of otoliths and spines for annual ageing should follow protocols developed in Farley et al. (2013b; 2019). Briefly, four to five transverse sections, each approximately 300 µm thick, should be cut from each otolith, encompassing the primordium. Sections should be cleaned, dried, mounted onto glass microscope slides and covered with coverslips for reading. Each otolith section should be read independently by two readers, following the validated ageing protocol developed for South Pacific albacore tuna by Farley et al. (2013b). All readings should be conducted without knowledge of the size of fish, date of capture, or previous readings. Annotated images of each otolith section, marked with the counted opaque zones, should be captured using a Leica camera mounted to the microscope. Decimal ages should be calculated using an algorithm similar to that of Farley et al. (2013b), adapted for IO albacore tuna. Sectioning of otoliths for daily ageing should follow protocols of Williams et al. (2013).

4.3.2 Reproductive analyses

In the laboratory, if received whole, gonads should be weighed to the nearest 0.1 g and a core sub-sample should be taken and fixed in 10% buffered formalin. If gonads were frozen after collection, the sub-sample should be taken before the gonad is thawed. Tissue samples for histology should be embedded in paraffin and standard histological sections prepared (i.e. thin sections (approximately 8 µm) cut and stained with Harris' haematoxylin and eosin). Ovaries should be classified into the seven development classes used in Farley et al. (2019).

To estimate the variation in sizes of the most advanced group of oocytes, a sub-set of sections from ovaries with advanced yolked or migratory nucleus oocytes should be randomly sampled, and the diameters of a sub-sample of oocytes measured using a digital camera mounted on a stereo microscope.

Spawning frequency of females should be estimated using the postovulatory follicle method of Hunter and Macewicz (1985), recently applied to albacore tuna in the IO (Farley et al. 2014).

Batch fecundity should be estimated using the gravimetric method (Hunter et al. 1985) for females with late stage migratory nucleus or hydrated oocytes, following Farley et al. (2014). For each fish, a small sub-sample of tissue (e.g. 0.05–0.09 g; Farley et al. 2014) should be taken from the middle region of both ovary lobes, weighed (to the nearest 0.01 mg), and fixed in 10% buffered formalin. Each sub-sample should be teased apart under a stereo microscope and the number of migratory nucleus or hydrated oocytes counted. The number of oocytes per weight of the sub-sample should be raised to the weight of the ovary lobe to give an estimate of batch fecundity of the lobe, and estimates of two lobes summed to give an estimate of batch fecundity for the fish. Fecundity for the female population by length, age and month should be estimated as the product of batch fecundity at length and age, and spawning fraction at length and age in each month. Potential annual fecundity by length and age should be calculated by summing these across months.

4.3.3 Data management

Data management (including biological data and associated metadata) should be considered property of the relevant CPC responsible for their collection and should be stored within the CPC according to their own data storage policies. Biological data and associated metadata should be sent to the laboratory where it should be stored in existing, purpose-designed Oracle/ MS Access databases. Biological data resulting from any analysis (e.g. age estimations, reproductive data) should be sent back to the CPC of collection.

4.3.4 Sample management

Otoliths, dorsal spines, gonads and gonad subsamples should be archived. Any unused sample, the otolith and spine cross sections, and the ovary histology should remain in the archive and be available for future analysis. Access to the samples could then be evaluated by the relevant CPC in collaboration with the IOTC.

4.4 Budget

An indicative budget for this work is in development and will be supplied in the final version of this report. Indicative costs for tissue processing will be supplied at the 7th Working Party on Temperate Tuna (WPTmT07).

5 Recommendations

The WPTmT is invited to:

- NOTE that the scoping study will be finalised in mid-November 2019;
- NOTE the influence of biological parameters on albacore tuna stock assessments;
- RECOMMEND that biological sampling be carried out for albacore tuna in the Indian Ocean, noting the proposed sampling strategy;
- NOTE the information required to further develop the sampling strategy, in particular the relevant data (by assessment region) on the numbers of longline sets/hooks deployed per year, numbers of sets/hooks observed per year, and catch rates of albacore tuna per set/hook per year;

- RECOMMEND that fleets with significant fishing effort in the southern Indian Ocean commit sufficient resources, through their observer programs and national scientists, to ensure the program's success.

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Table 1. A description of the model sensitivities investigating the influence of key biological parameters included in the base Indian Ocean albacore tuna assessment model.

Model	**Description**	**Base model parameters**	**Alternative parameters**
LengthAtAge	Increase variation in length-at-age for males and females.	CVs for length-at-age CV_young 0.06 CV_old 0.025	CV_young 0.10 CV_old 0.10
LengthWeight	Use length-weight parameters from Kitakado et al. (2019)	*a* = 1.3718e-05 *b* = 3.0973	*a* = 6.9e-06 *b* = 3.2263
GrowthYoung	Investigate potential bias in growth for youngest age classes by constraining VB growth functions to pass through origin (Age 0, Length 0).	Female *k* = 0.38 Female *Length1*= 52.6 Female *Linf* = 103.8 Male *k* = 0.34 Male *Length1*= 52.0 Male *Linf* = 110.6	Female *k* = 0.478 Female *Length1*= 39.4 Female *Linf* = 103.8 Male *k* = 0.422 Male *Length1*= 38.05 Male *Linf* = 110.6
MaturityOgive	Use maturity at length from recent western Indian Ocean study (rather than South Pacific reproductive potential at length)	Length based Reproductive Potential from South Pacific albacore tuna.	Length based maturity ogive from Dhurmeea et al. (2016)
NatMortAge	Increase natural mortality of females aged 4+ yr from 0.30 to 0.35	*M* = 0.30 all ages	Females *M* = 0.30 Ages 1-3 *M* = 0.35 Ages >=4
EastWest	Two region model, recruitment variation in both east and west regions. No movement W<>E		
EastWestGrowth	Differences in growth between east and west IO. Higher (+40%) growth rate (*k*) in East relative to W (base values). No movement W<>E	Female *k* = 0.38 Male *k* = 0.34	FemaleW *k* = 0.38 MaleW *k* = 0.34 FemaleE *k* = 0.532 MaleE *k* = 0.476

Table 2. Change in the values of the likelihood components relative to the Base model. A deterioration (increase in LL) in the likelihood (of at least 1.0) is highlighted in red. An improvement in the likelihood (of at least 1.0) is highlighted in green. The two region models are compared separately.

Model	Total	CPUE	LF	Recruit	Priors
BASE	881.36	-139.79	1053.81	-32.76	0.00
Growth Young	-53.09	-4.52	-48.17	0.16	-0.55
LengthAtAge	1.07	-7.05	8.77	-0.73	0.00
LengthWeight	-0.33	-0.06	-0.29	0.02	0.00
Mature1	0.06	-0.13	0.24	-0.04	0.00
NatMortAge	1.73	-0.11	1.85	0.00	0.00
EastWest	758.07	-262.80	1049.04	-33.71	0.00
EastWestGrowth	-53.96	6.97	-59.67	0.43	-0.07

Table 3. Changes in individual likelihood components relative to the Base model. A deterioration in the likelihood (of at least 1.0) is highlighted in red. An improvement in the likelihood (of at least 1.0) is highlighted in green. The two region models are compared separately.

	CPUE		Length composition			
	LL3	LL4	LL1	LL2	LL3	LL4
BASE	-134.82	-	258.70	177.04	279.13	243.92
Growth Young	-4.88	-	-5.83	-5.15	-16.96	-2.40
LengthAtAge	-7.00	-	-2.37	1.39	21.30	21.49
LengthWeight	-0.05	-	-0.05	0.00	-0.01	0.00
MaturityOgive	-0.13	-	-0.03	0.02	-0.12	-0.05
NatMortAge	-0.12	-	0.83	0.57	0.25	0.08
EastWest	-136.99	-120.42	256.14	175.95	276.32	240.21
EastWestGrowth	-0.62	7.68	-1.09	-10.77	0.77	-33.68

Table 4. Comparison of stock status and yields and associated standard deviations (derived from covariance matrix) from the range of model options, in absolute value (upper) and percentage difference from the base model (lower) (>10% reduction highlighted in red, >10% increase highlighted in green).

Model	*SB0*		*SB2017*		*SB2017/SBMSY*		*F2017/FMSY*		*MSY*	
	Value	SD	Value	SD	Value	SD	Value	SD	Value	SD
BASE	103,612	6,265	26,567	6,290	1.246	0.226	1.227	0.202	33,302	1,854
Growth Young	110,327	4,590	23,419	5,079	0.994	0.179	1.469	0.222	31,333	1,079
LengthAtAge	91,320	2,941	15,816	3,194	0.827	0.146	1.676	0.226	30,132	745
LengthWeight	106,166	6,468	27,322	6,493	1.240	0.225	1.230	0.204	33,252	1,848
MaturityOgive	130,753	8,531	37,031	8,286	1.311	0.217	1.132	0.187	34,266	2,012
NatMortAge	84,689	5,278	22,673	5,331	1.283	0.230	1.200	0.198	33,748	1,928
EastWest	123,935	-	51,318	-	1.964	-	0.636	-	38,935	0
EastWestGrowth	129,299	-	54,739	-	1.967	-	0.667	-	39,679	0
Growth Young	6%	-27%	-12%	-19%	-20%	-21%	20%	10%	-6%	-42%
LengthAtAge	-12%	-53%	-40%	-49%	-34%	-35%	37%	12%	-10%	-60%
LengthWeight	2%	3%	3%	3%	0%	0%	0%	1%	0%	0%
MaturityOgive	26%	36%	39%	32%	5%	-4%	-8%	-8%	3%	9%
NatMortAge	-18%	-16%	-15%	-15%	3%	2%	-2%	-2%	1%	4%
EastWest	20%		93%		58%		-48%		17%	
EastWestGrowth	25%		106%		58%		-46%		19%	

Table 5. Estimated number of hooks and sets deployed, catches, nominal CPUE (for 2017) and potential sampling yield per assessment region for the Taiwanese longline fleet. The estimated number of fish available for sampling is based on a uniform observer coverage of 2% of sets per region and a sampling strategy whereby a maximum of five albacore tuna (i.e., the first five encountered) are sampled in each observed set.

Region	Total no. hooks deployed[1]	Estimated no. sets[2]	Catch (no.)[1]	% zero catches[3]	Number of fish available for sampling[4]
1	72,997,562	20,856	209,487	90	209
2	7,768,200	2,219	2,258	80	44
3	50,859,807	14,531	613,487	20	1,162
4	9,379,958	2,680	189,645	20	214

[1] Source: IOTC 2019a

[2] Assuming an average of 3,500 hooks per set (Hoyle et al. 2015)

[3] Approximated for albacore tuna assessment regions from Hoyle et al. (2015)

[4] Assuming 2% of sets are observed and 5 fish are sampled from each set

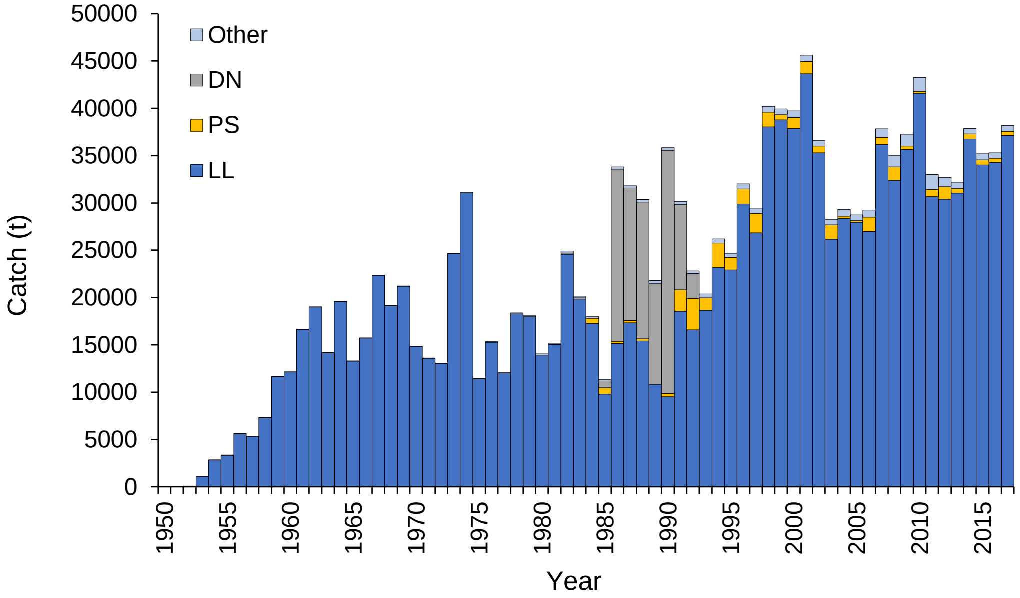

Figure 1. Total annual catch (mt) of albacore tuna by fishing method from 1950 to 2017. DN, driftnet; PS, purse-seine; LL, longline. Source: IOTC 2019b.

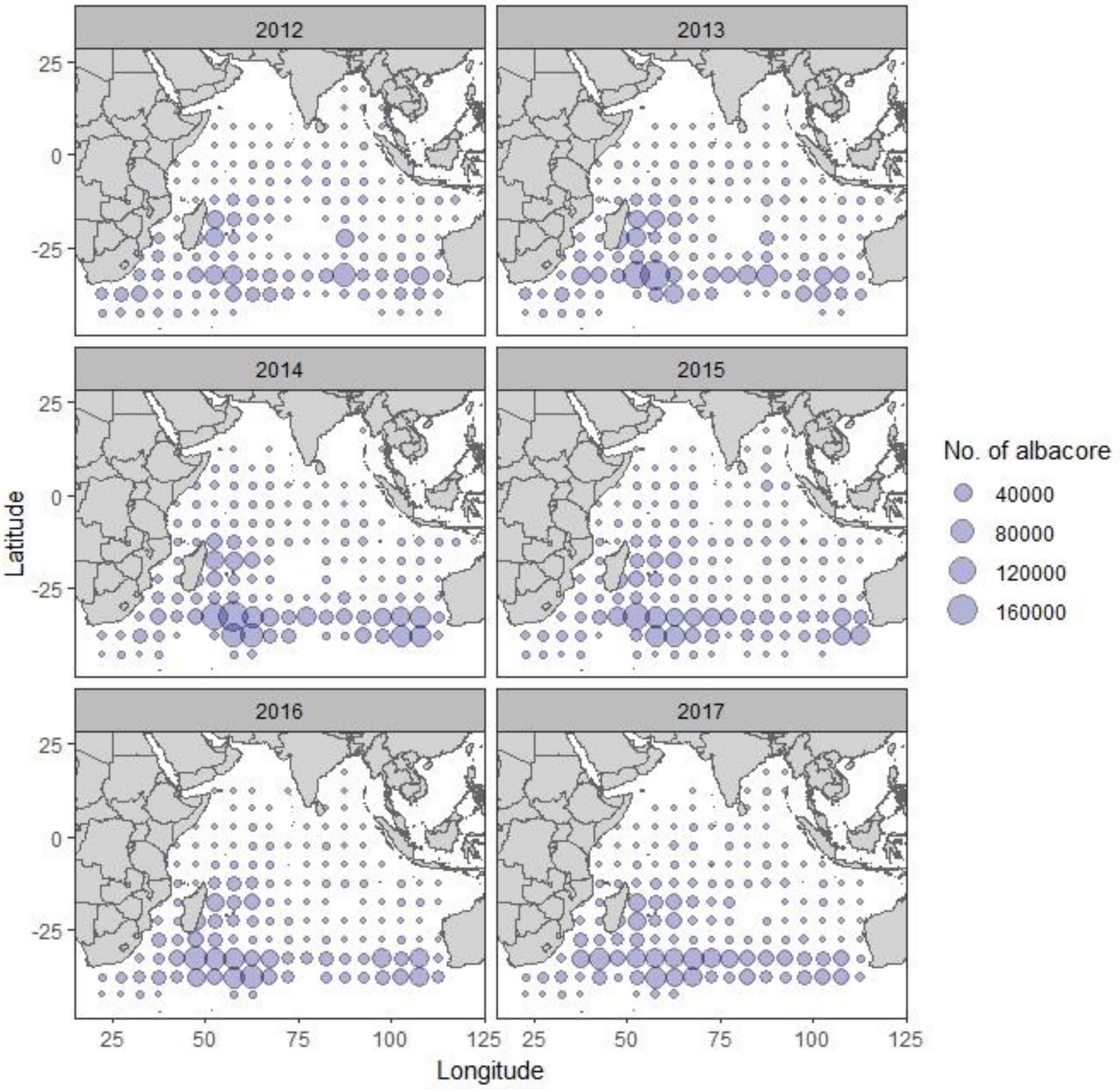

Figure 2. Total annual longline catches of albacore tuna, 2012–2017. The blue circles represent the aggregated longline catch (numbers of fish, by all fleets) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

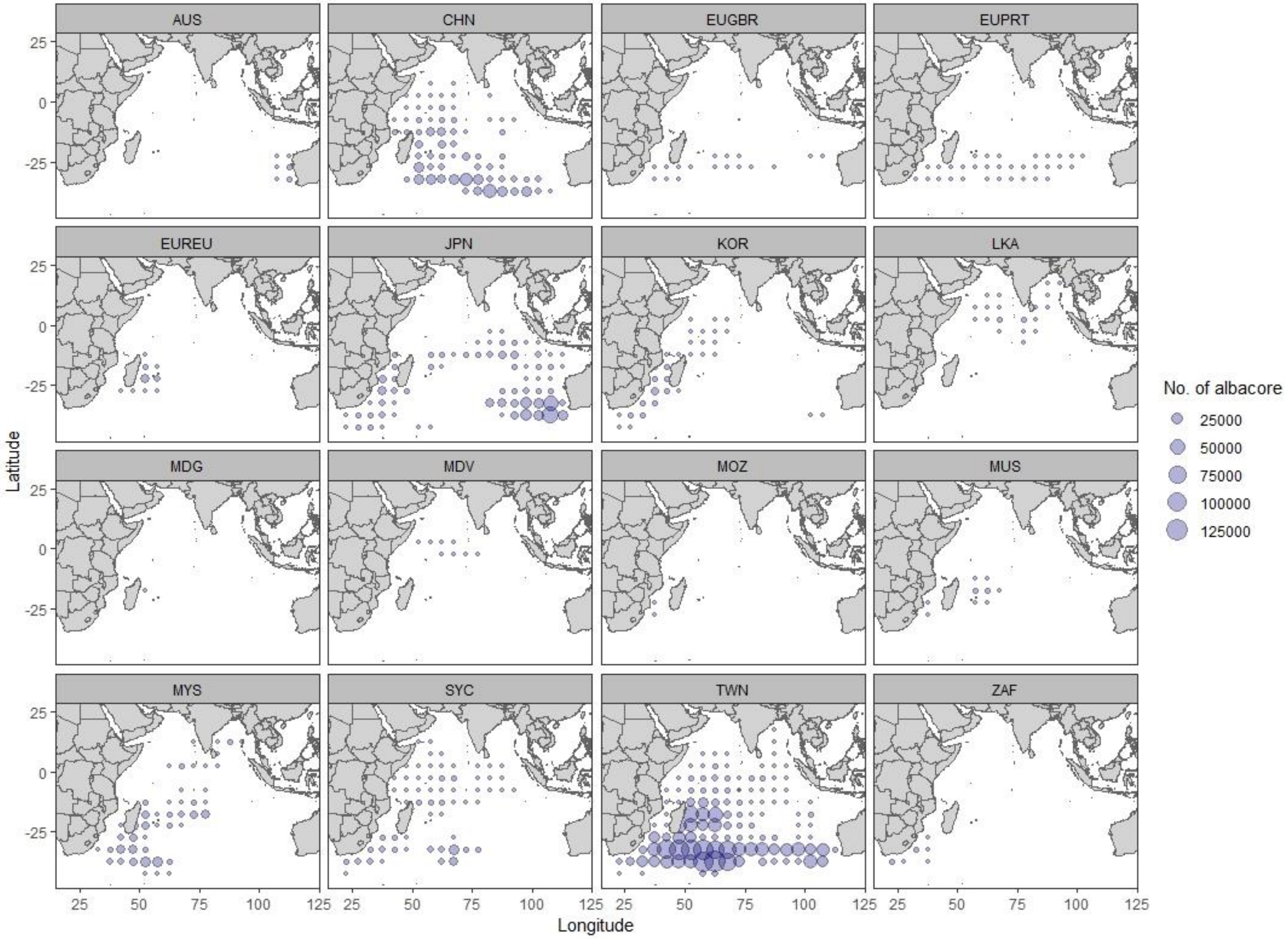

Figure 3. Total longline catch of albacore tuna by fleet, 2016–2017. The blue circles represent the aggregated longline catch (numbers of fish) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

AUS = Australia, CHN = China, EUGBR = United Kingdom, EUPRT = Portugal, EUREU = France-Reunion, JPN = Japan, KOR = Republic of Korea, LKA = Sri Lanka, MDG = Madagascar, MDV = Maldives, MOZ = Mozambique, MUS = Mauritius, MYS = Malaysia, SYC = Seychelles, TWN = Taiwan,China, ZAF = Republic of South Africa.

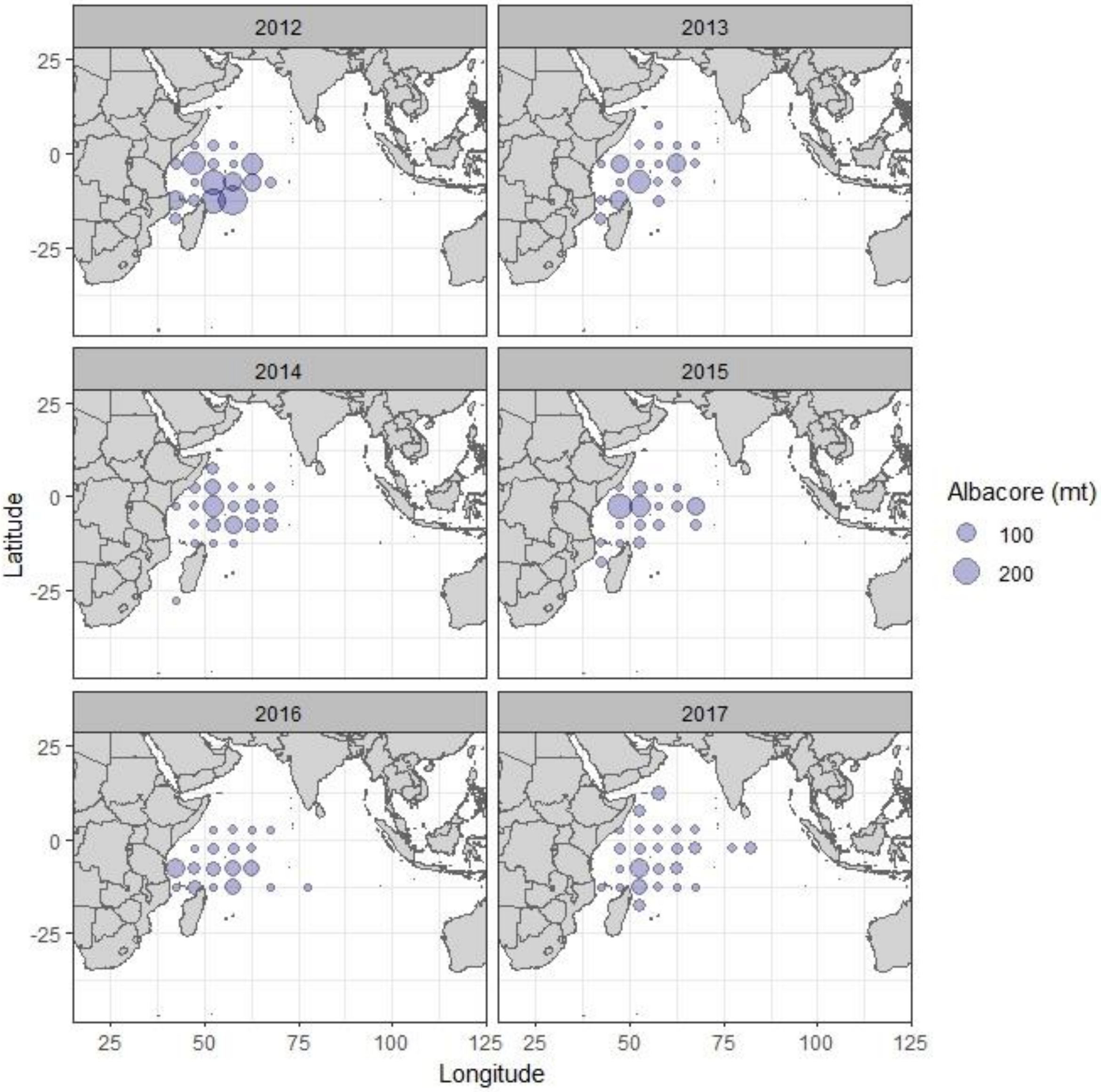

Figure 4. Total annual purse-seine catches of albacore tuna, 2012–2017. The blue circles represent the aggregated longline catch (weight of fish in mt, by all fleets) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

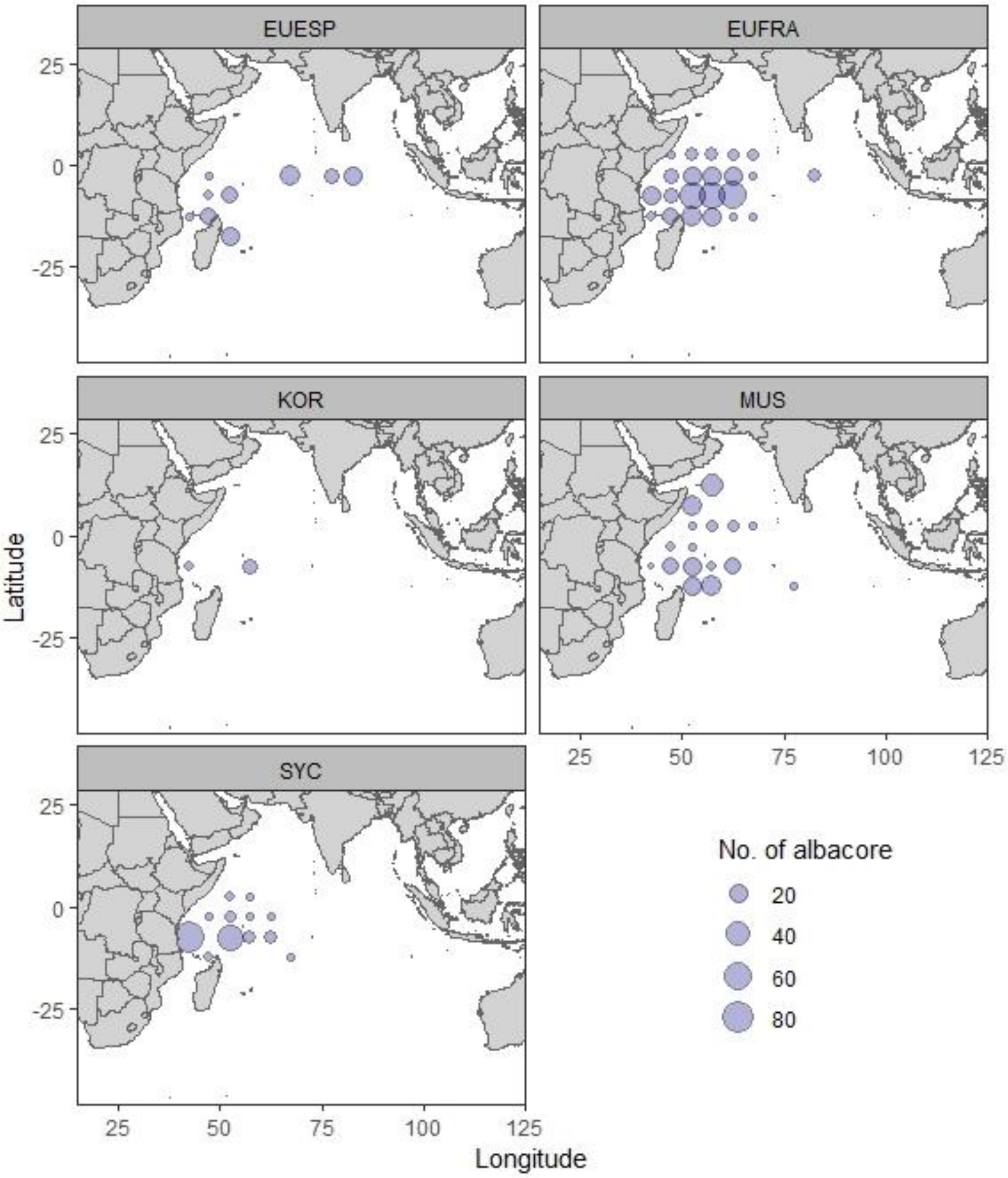

Figure 5. Total annual purse-seine catches of albacore tuna, 2012–2017. The blue circles represent the aggregated longline catch (weight of fish in mt, by all fleets) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

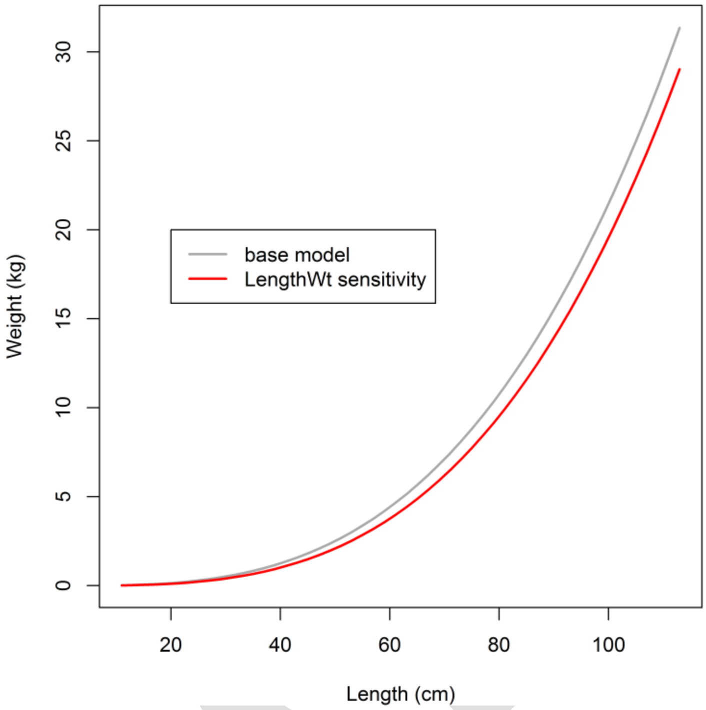

Figure 6. Comparison of the length-weight relationship used in the base model and the model sensitivity *LengthWeight*.

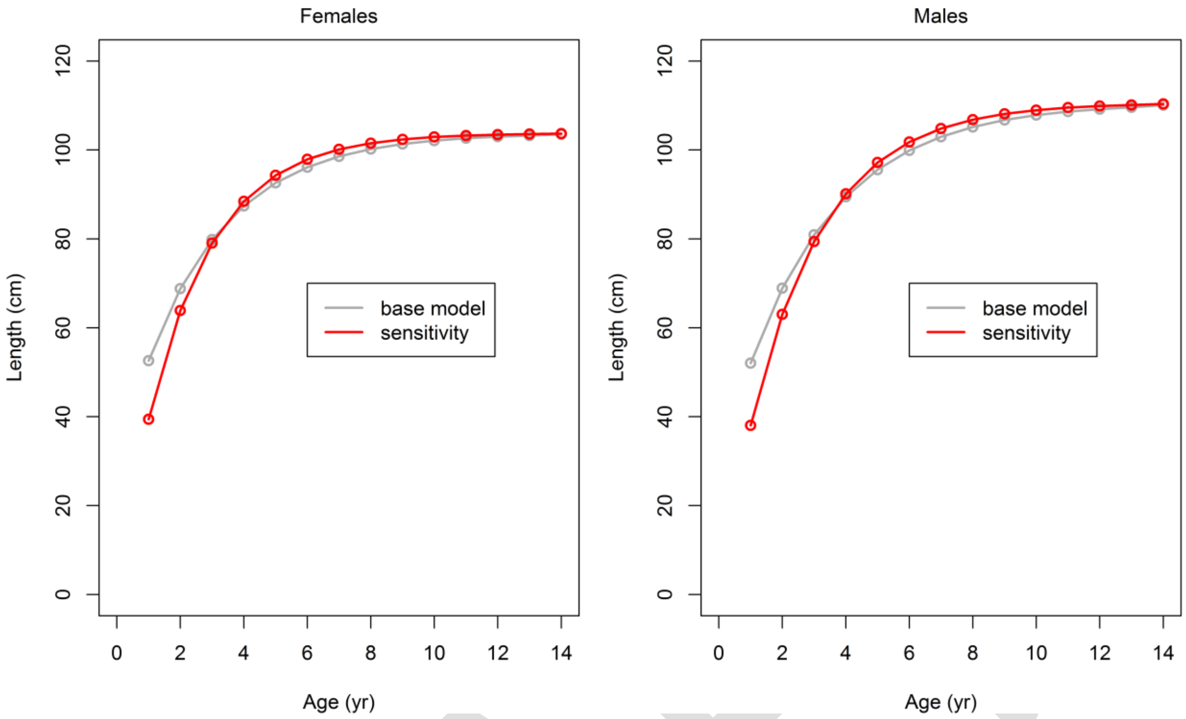

Figure 7. Comparison of the growth functions used in the base model and the model sensitivity *GrowthYoung.*

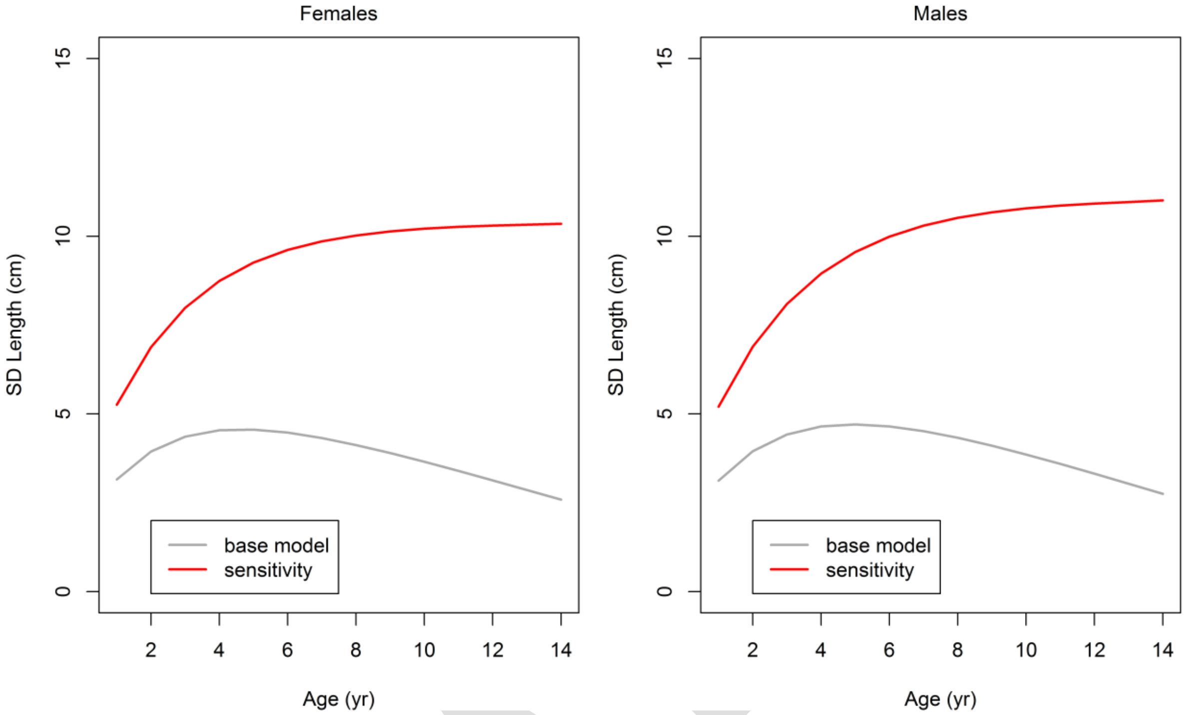

Figure 8. Parameterisation of the variation in length-at-age from the base model and the model sensitivity *LengthAtAge*.

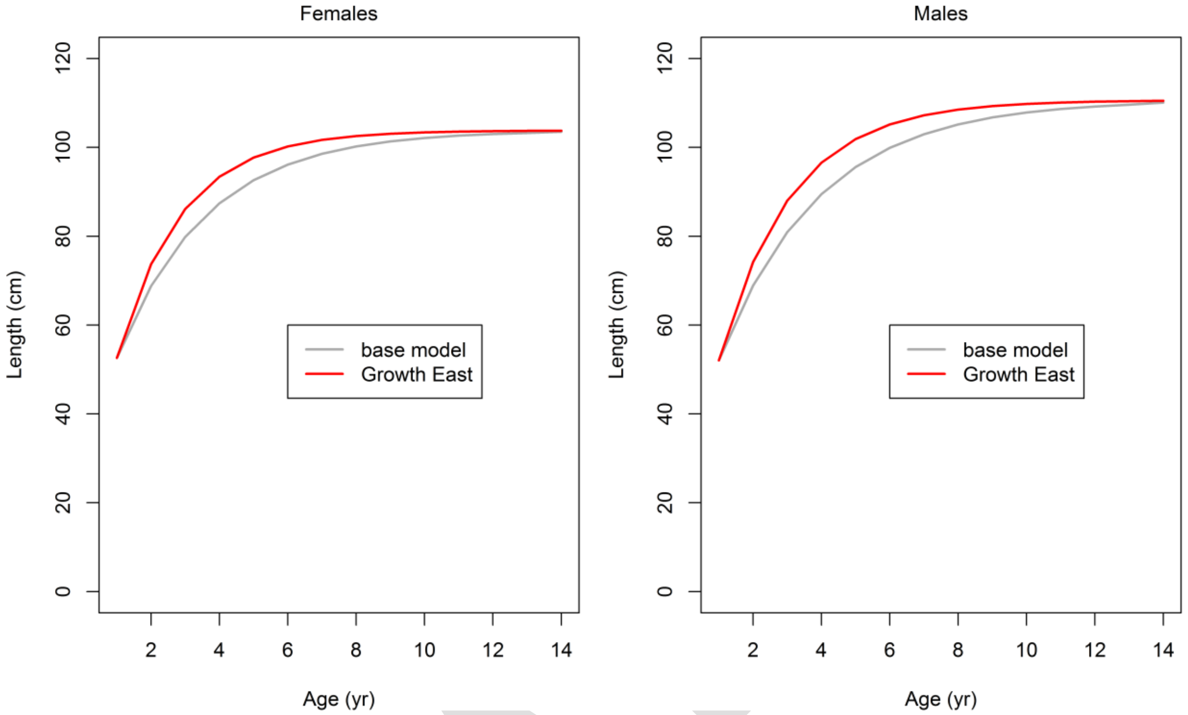

Figure 9. Comparison of the growth functions used in the base model and the growth assumed for the eastern Indian Ocean in the *EastWestGrowth* model sensitivity. Growth in the western Indian Ocean is assumed to be equivalent to the growth in the base model.

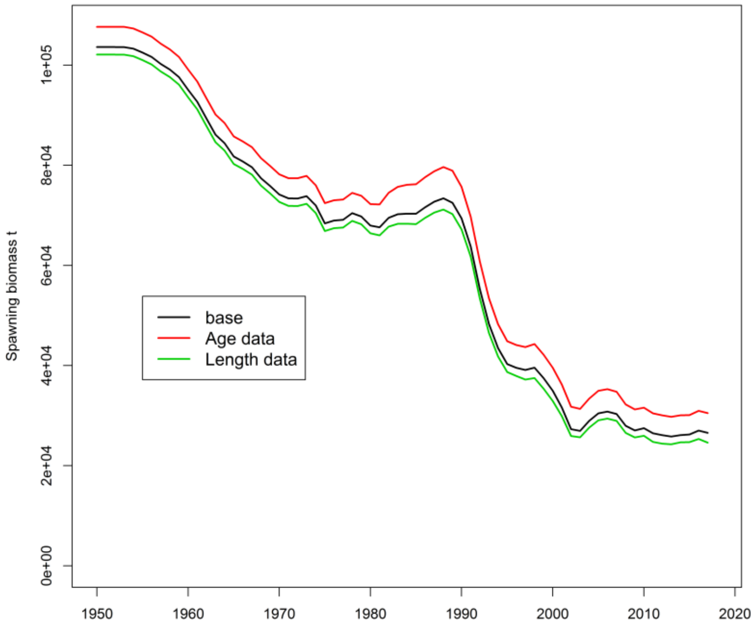

Figure 10. Spawning biomass trajectories for the base model and the base model with simulated length composition data or simulated age composition data included.

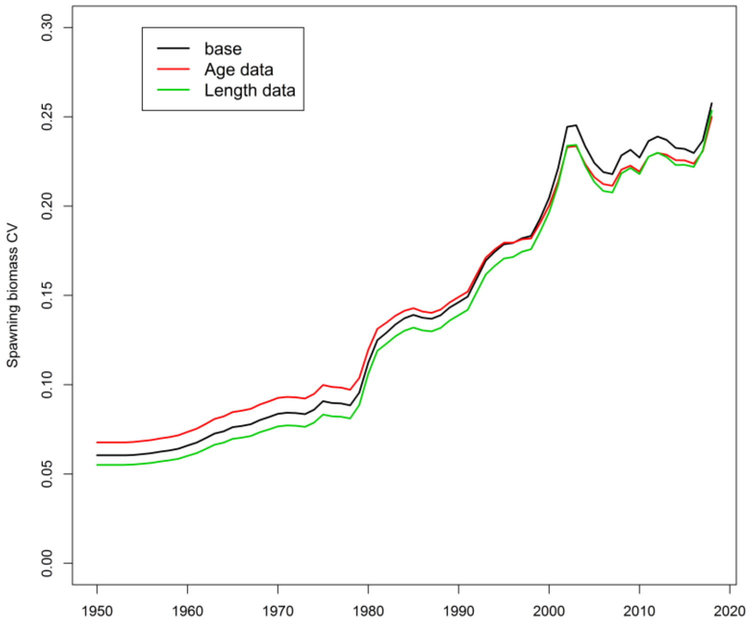

Figure 11. Annual coefficient of variation of the estimated spawning biomass for the base model and the base model with simulated length composition data or simulated age composition data included.

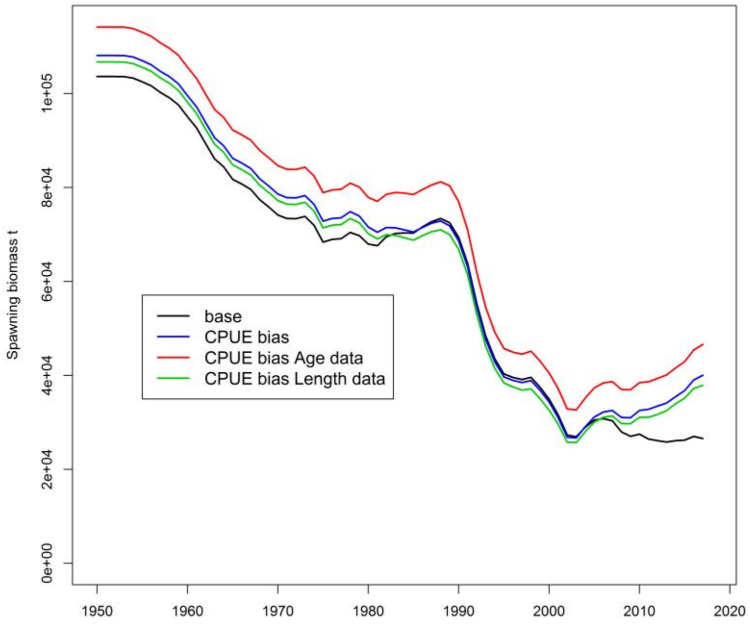

Figure 12. Spawning biomass trajectories for the base model, the biased CPUE model and the biased CPUE model with simulated length composition data or simulated age composition data included**.**

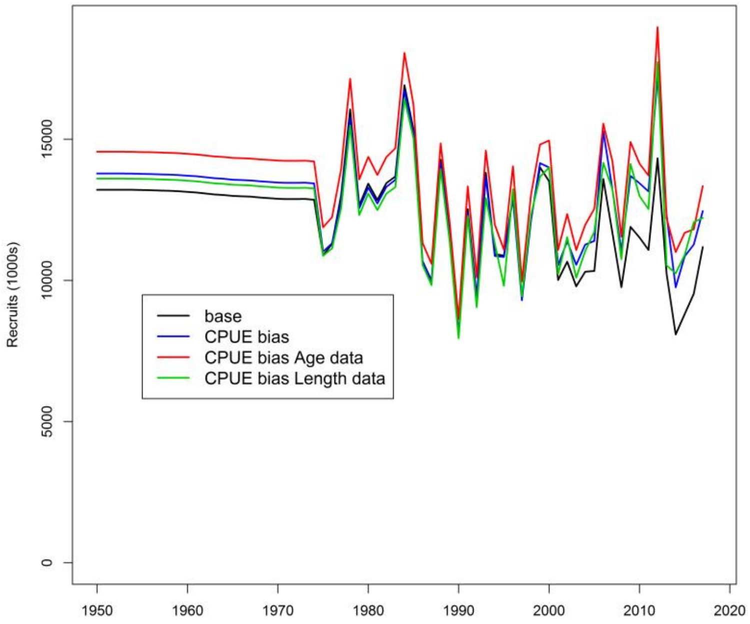

Figure 13. Annual recruitment for the base model, the biased CPUE model and the biased CPUE model and the base model with simulated length composition data or simulated age composition data included.

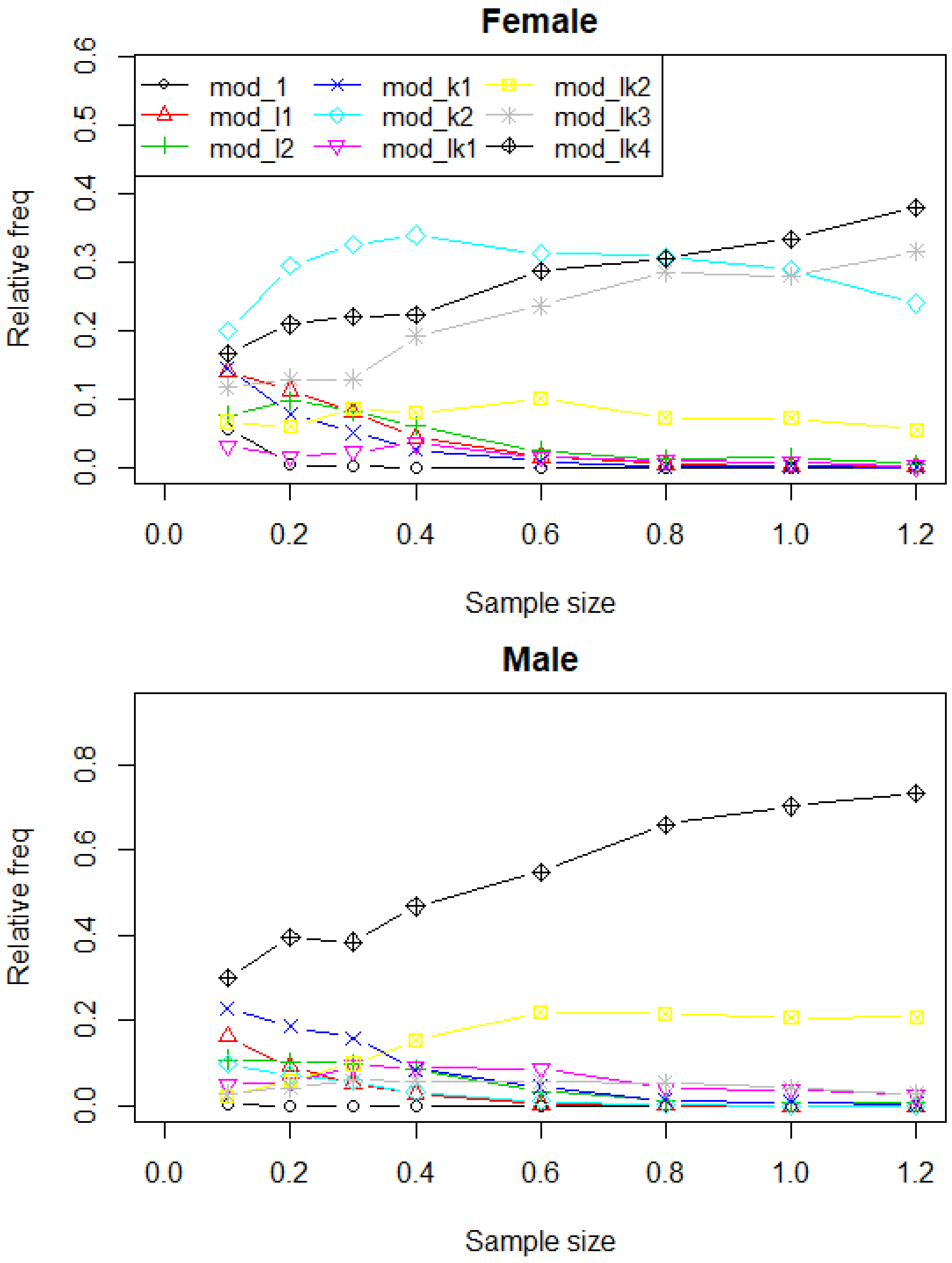

Figure 14. Frequency of growth model selection given differing sample sizes for female (above) and male (below) albacore tuna. Models are described in the text. Results are based on bootstrap resampling of Pacific length at age data at different proportions of the true sample sizes.

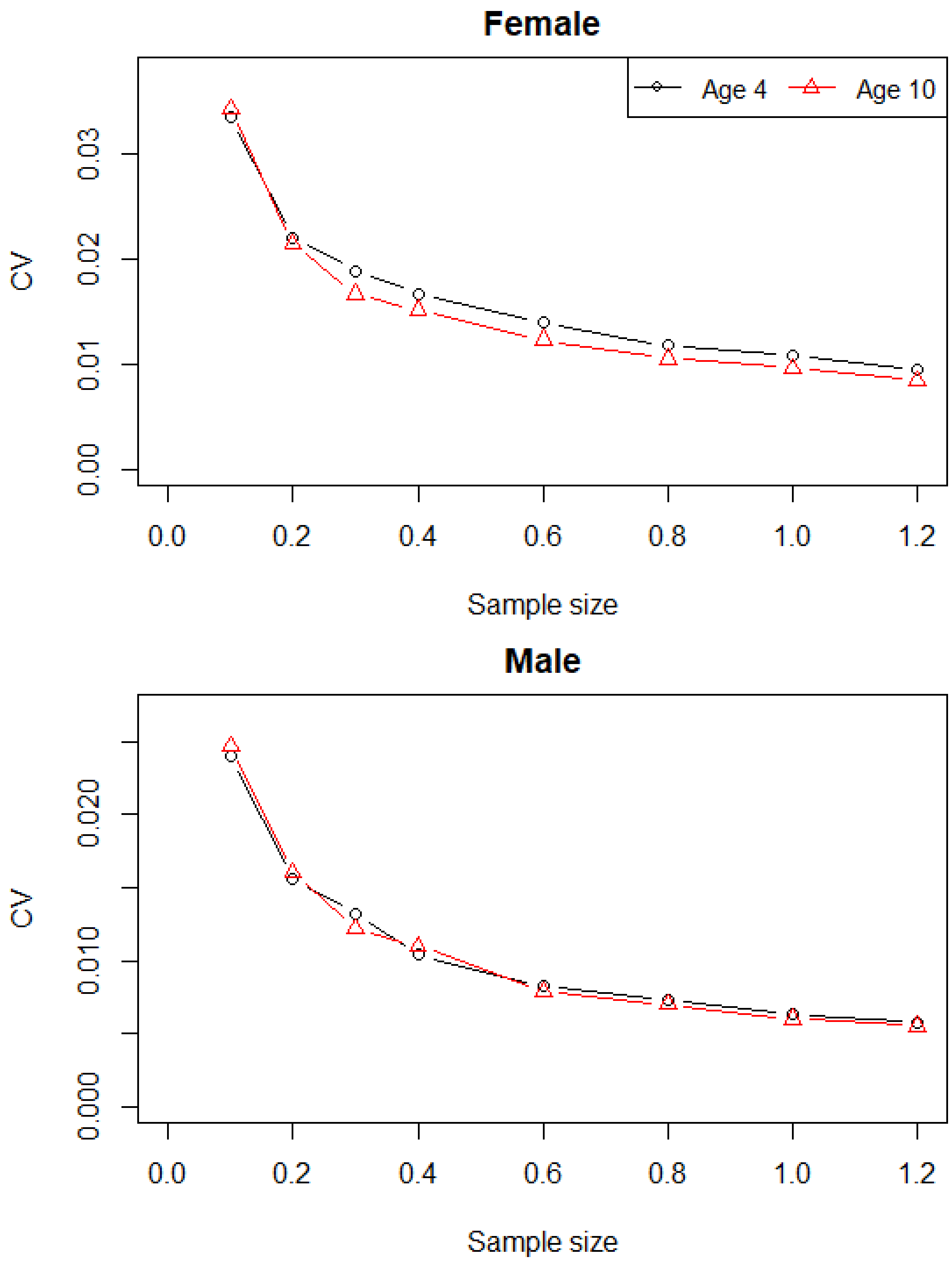

Figure 15. CV of predicted size at ages 4 and 10 for female (above) and male (below) albacore tuna, based on bootstrap resampling of Pacific length at age data at different proportions of the true sample sizes.

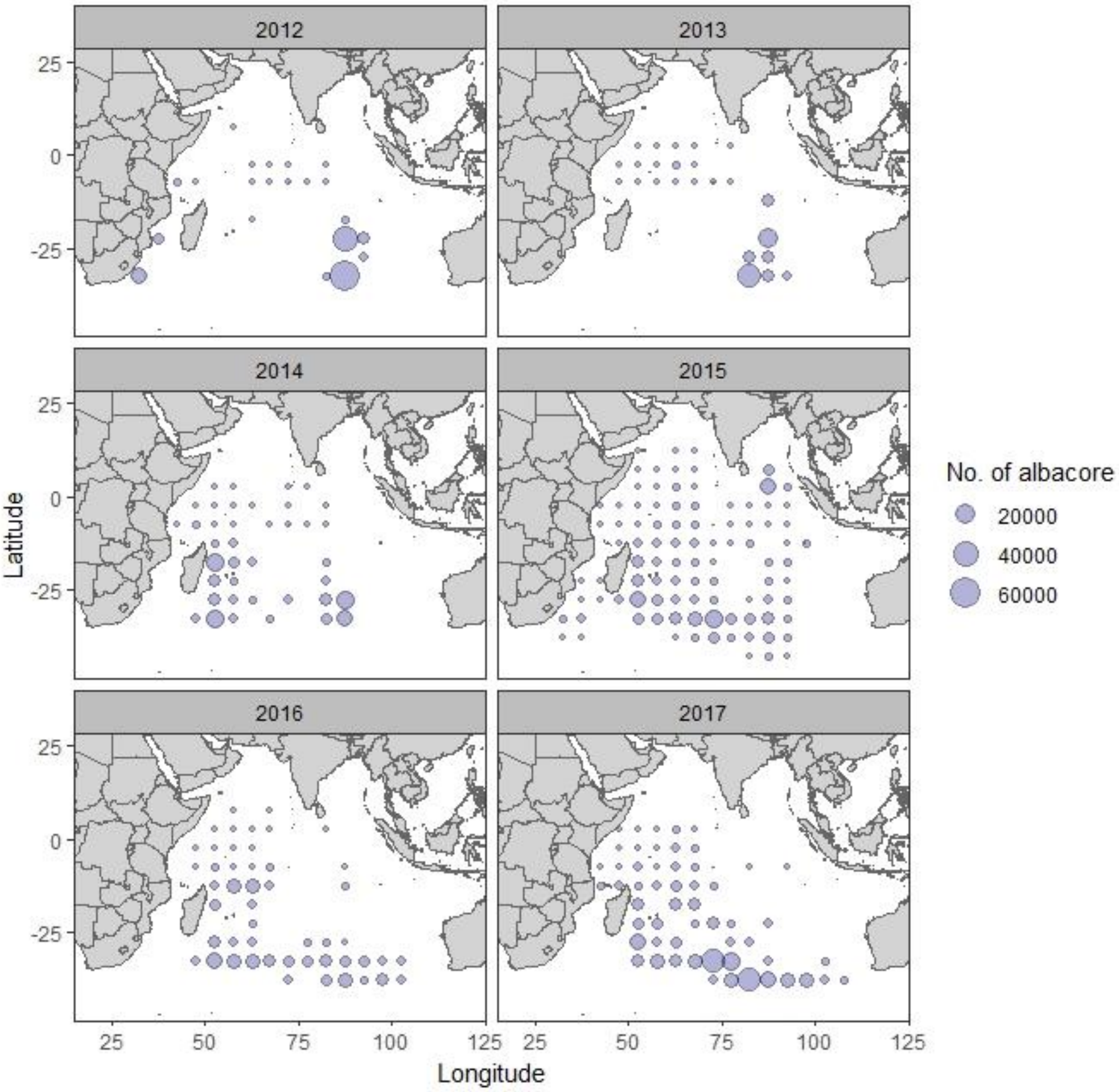

Figure 16. Total annual catch of albacore tuna by Chinese-flagged longline vessels, 2012–2017. The blue circles represent the aggregated longline catch (numbers of fish) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

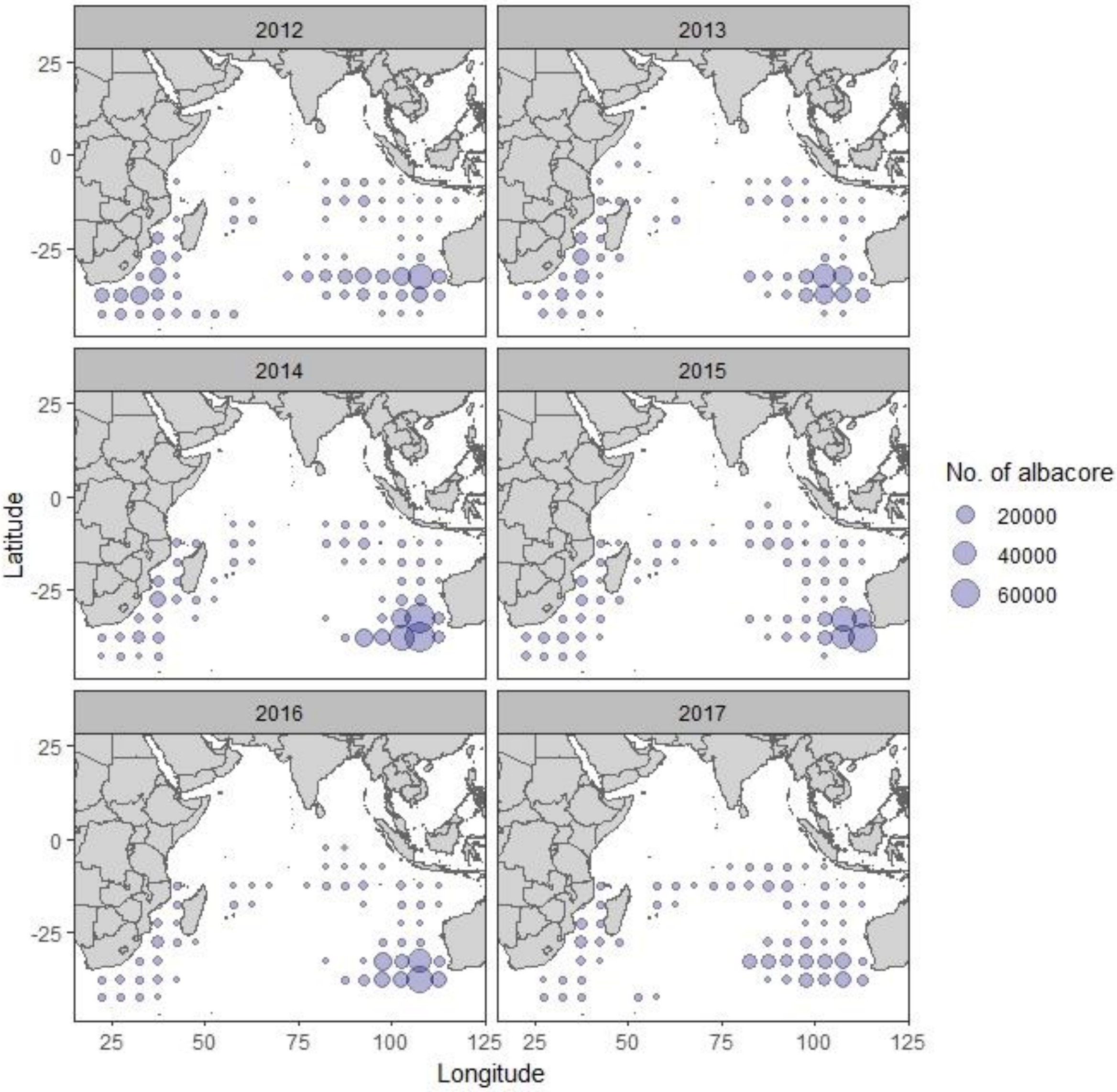

Figure 17. Total annual catch of albacore tuna by Japanese-flagged longline vessels, 2012–2017. The blue circles represent the aggregated longline catch (numbers of fish) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

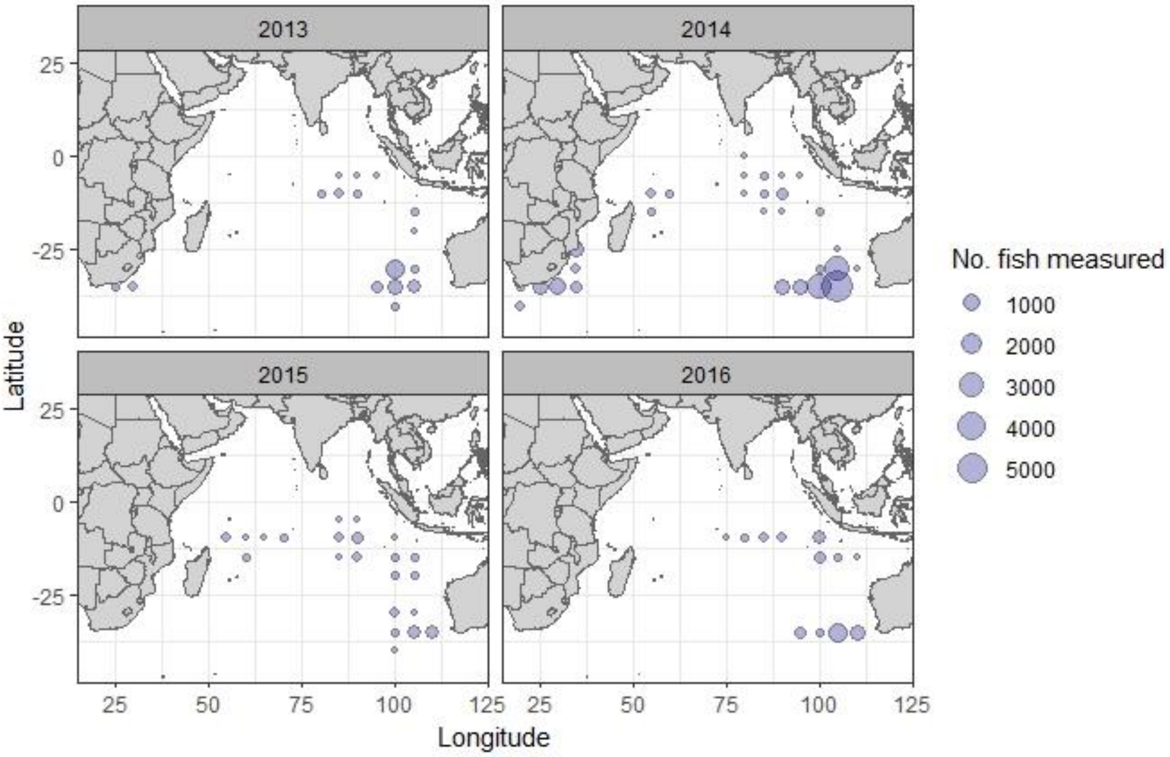

Figure 18. Numbers of albacore tuna measured by observers on Japanese longline vessels, 2013–2016. Source: IOTC 2019d. Note data for 2017 and 2018 were not available.

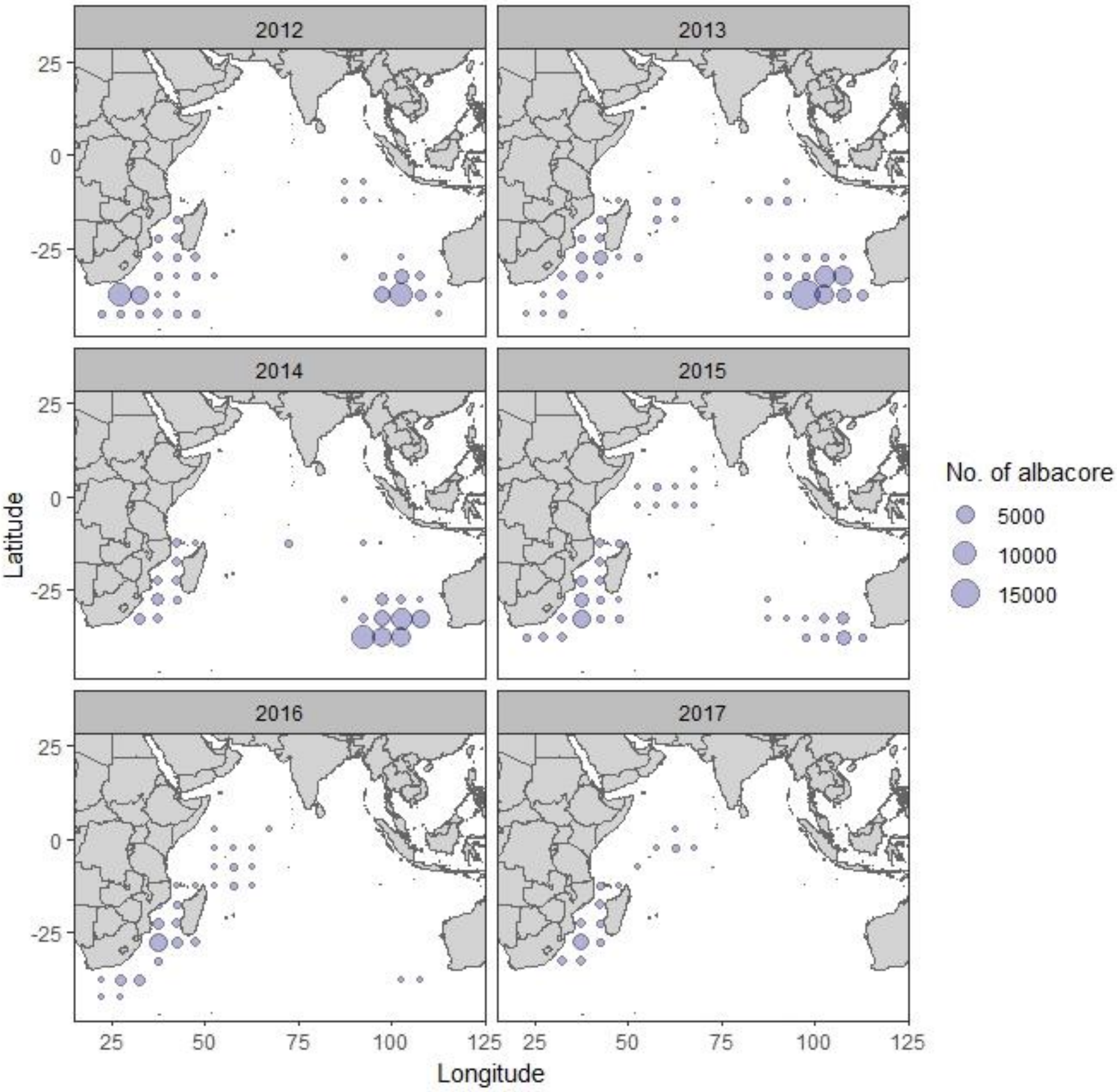

Figure 19. Total annual catch of albacore tuna by Korean-flagged longline vessels, 2012–2017. The blue circles represent the aggregated longline catch (numbers of fish) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

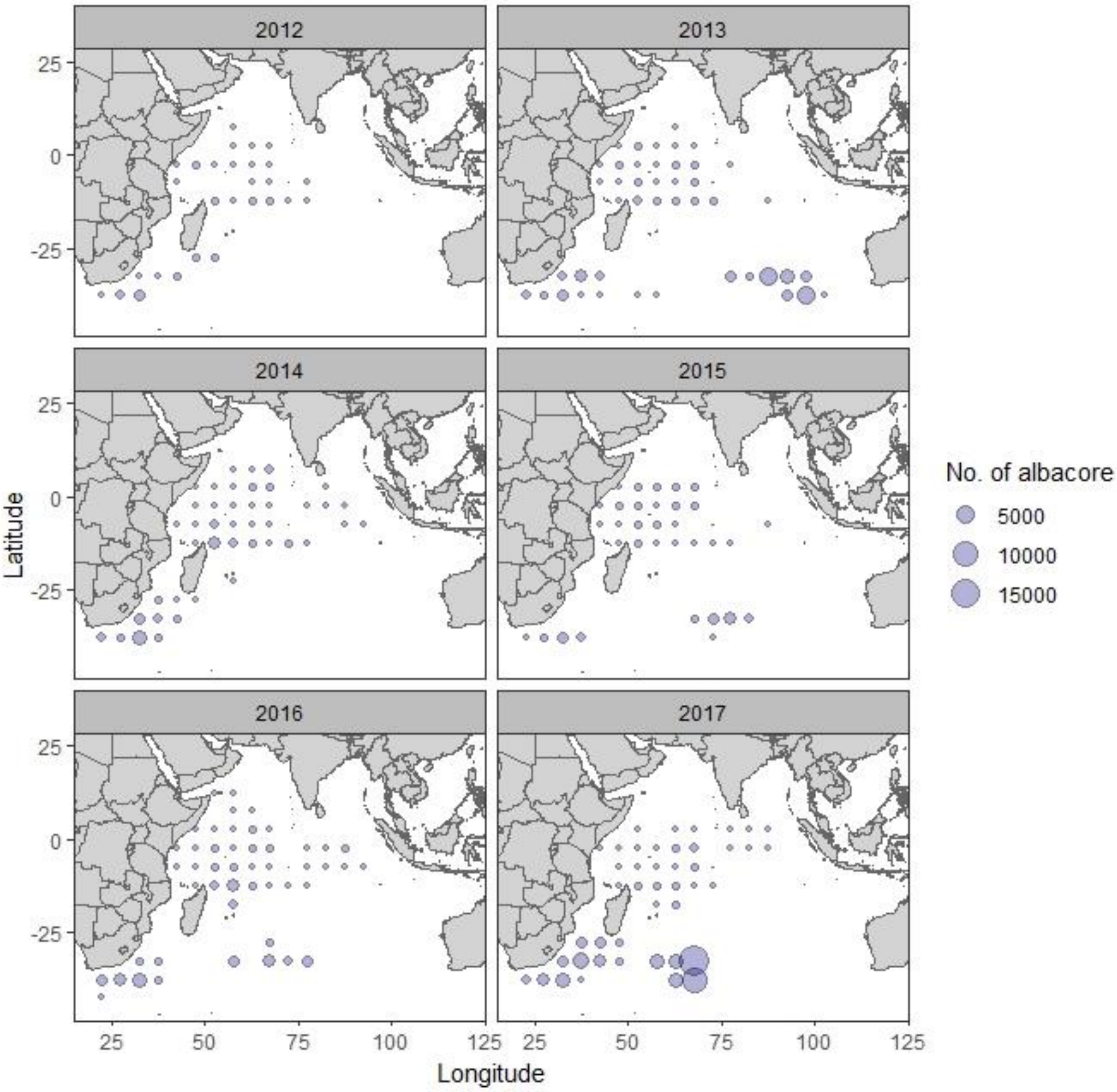

Figure 20. Total annual catch of albacore tuna by Seychelles-flagged longline vessels, 2012–2017. The blue circles represent the aggregated longline catch (numbers of fish) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.

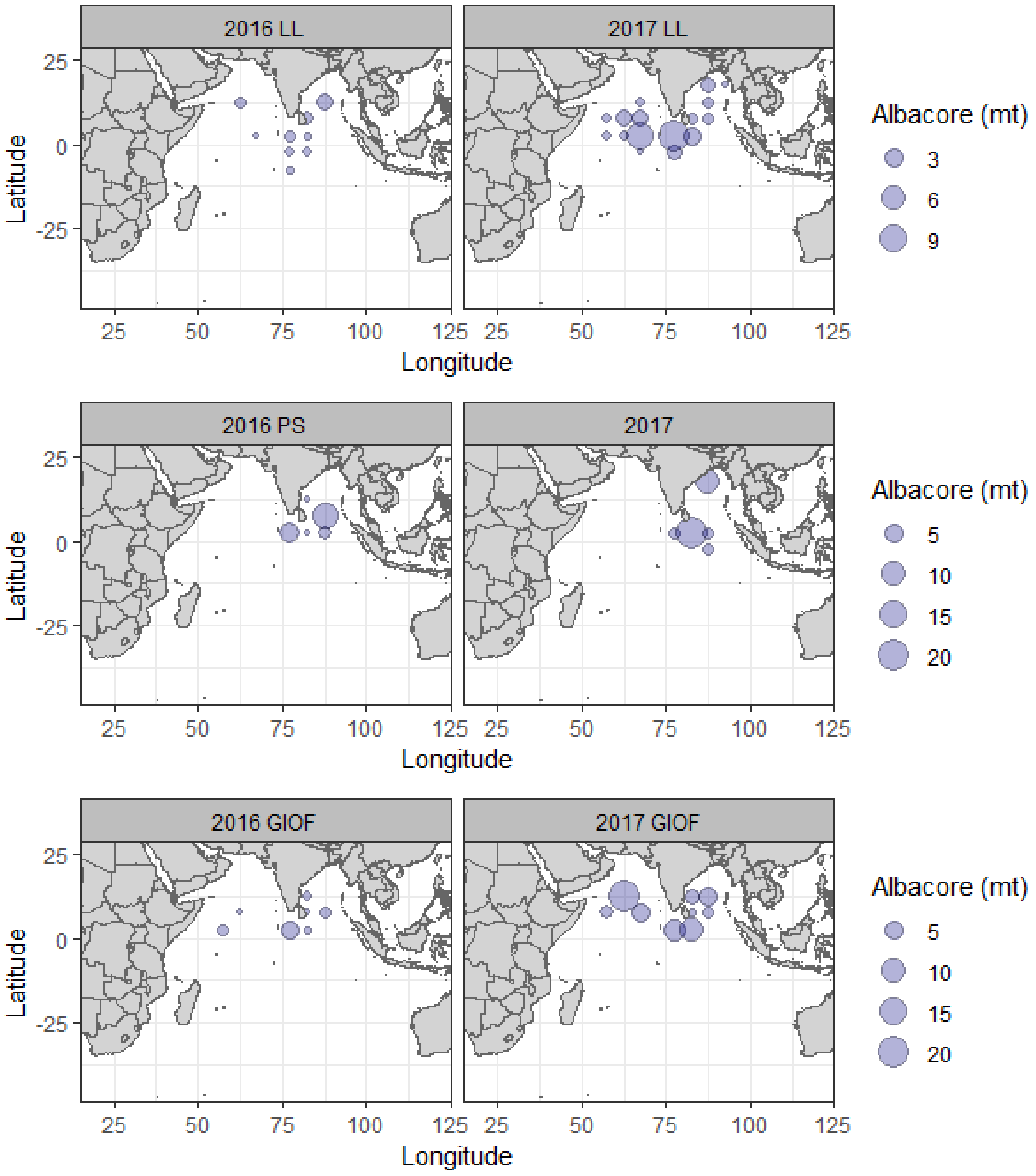

Figure 21. Total annual catch of albacore tuna by Sri Lankan-flagged vessels, 2016 and 2017. The blue circles represent the aggregated longline catch (numbers of fish) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch. LL = longline, PS = purse-seine, GIOF = gillnet (offshore).

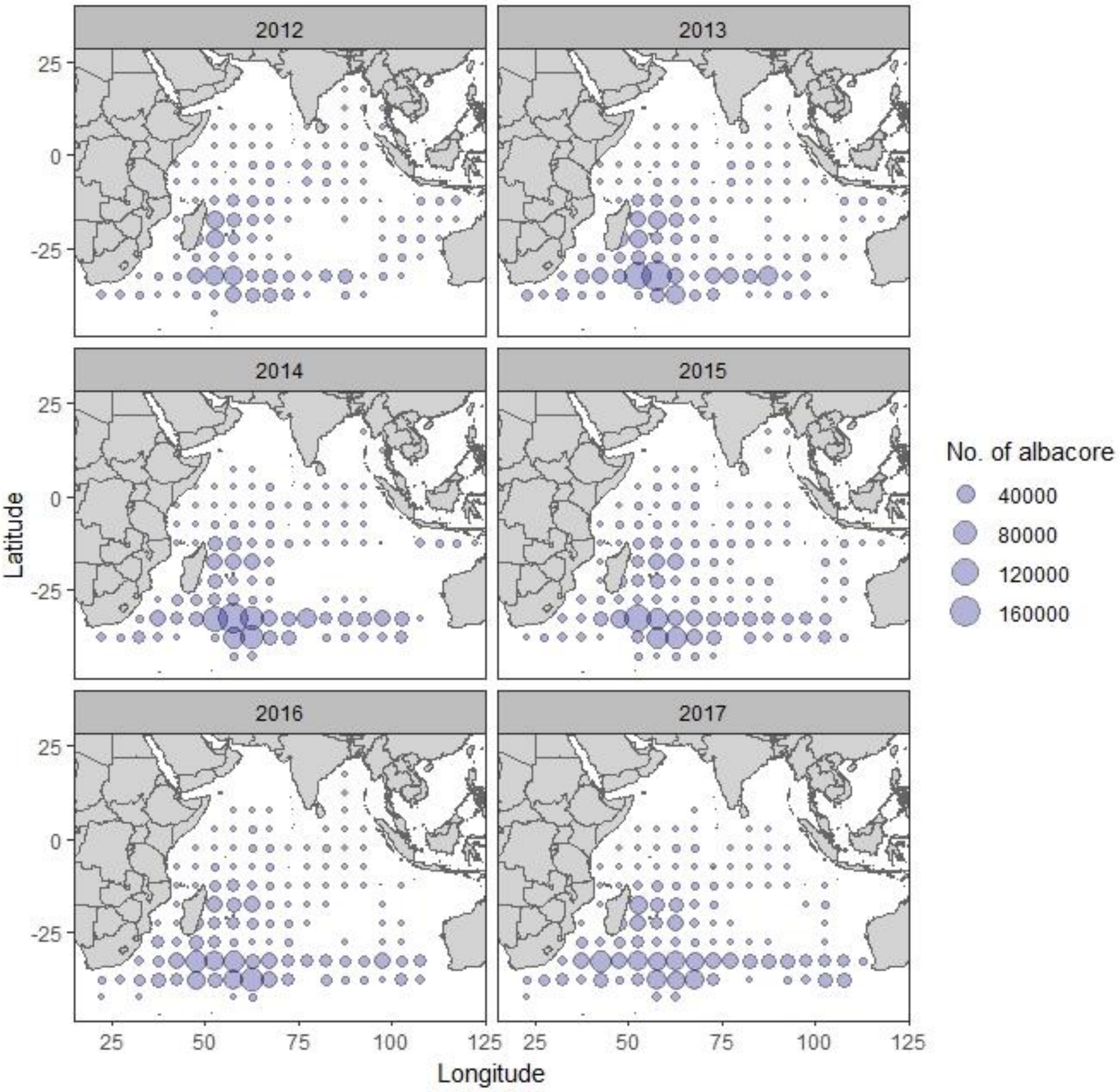

Figure 22. Total annual catch of albacore tuna by Taiwanese-flagged longline vessels, 2012–2017. The blue circles represent the aggregated longline catch (numbers of fish) by 5-degree cell. The area of the circles is proportional to the magnitude of the catch.