Selectivity changes and spatial size patterns of bigeye and yellowfin tuna in the early years of the Japanese longline fishery.

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Executive Summary

Integrated stock assessments are very dependent on understanding the fisheries that provide the data, and the biology and ecology of the species assessed. Two of the primary datasets in tropical tuna assessments are the catch and effort data used to generate indices of abundance, and the associated size frequency data. The Indian Ocean Tuna Commission's 7th Working Party on Methods (IOTC-2016-WPM07-R) noted that declines in CPUE in the early stages of fisheries may be associated with juvenilization of the population (i.e. the older and larger mature individuals were more vulnerable to capture in the early time periods of the fishery). The WPM agreed that this factor should be investigated in parallel with the CPUE standardization process, and noted that analysis of the size data would improve the understanding of the fishery.

We standardized the size data to reveal patterns that can otherwise be hidden by changes in the distribution of effort through time. Spatial size variation was significant, as were changes in mean sizes captured. There was a substantial decline in the mean sizes captured during the 1950s, which is consistent with the juvenilization hypothesis. The rate of decline appears too rapid to represent change in the size structure of the population, given the size of the catches, which is reflected in the inability of the yellowfin stock assessment to fit the early size data. We recommend further analyses that include bigeye size data starting in 1952. It would also be useful to compare early size changes across oceans and fleets, and for other species such as billfish; and investigating size changes after the resumption of fishing in the piracy area near Somalia.

Spatial size variation has not previously been reported for Indian Ocean bigeye and yellowfin tuna. However it is common in tunas, due to either ontogenetic changes or growth variation. The significant spatial variation in both yellowfin and bigeye tunas in the Japanese size data was consistent across datasets collected in different ways. The Japanese spatial patterns contrast with the Taiwanese length frequency data, which show relatively little spatial size variation. Taiwanese mean sizes change substantially through time, but these changes are believed to be due more to sampling problems than to population change. It would be useful to review the spatial location information associated with the Taiwanese size data.

Introduction

Integrated stock assessments are very dependent on understanding the fisheries that provide the data, and the biology and ecology of the species assessed. Two of the primary datasets in tropical tuna assessments are the catch and effort data used to generate indices of abundance, and the

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associated size frequency data. The Indian Ocean Tuna Commission's 7th Working Party on Methods (IOTC-2016-WPM07-R) noted that declines in CPUE in the early stages of fisheries may be associated with juvenilization of the population (i.e. the older and larger mature individuals were more vulnerable to capture in the early time periods of the fishery). The WPM agreed that this factor should be investigated in parallel with the CPUE standardization process, and noted that analysis of the size data would improve the understanding of the fishery.

When standardizing lengths to estimate temporal changes, spatial patterns must also be estimated. This provided an opportunity to explore the spatial size patterns in the Indian Ocean.

Spatial size variation has not previously been reported for Indian Ocean bigeye and yellowfin tuna. However it is common in tunas, due to either ontogenetic changes or growth variation. Albacore provide examples of both, with small immature fish caught at higher latitudes than mature fish (Farley *et al.* 2014), and faster growth rates and larger average sizes further east in the south Pacific (Williams *et al.* 2012).

Data description and analysis methods

The data (Table 1) were imported into R (R Core Team 2016), and prepared by allocating to location and time strata. The data were used as provided, with no additional range checking or cleaning. Due to changes in rounding practices through time (Hoyle *et al.* 2017), we generated adjusted bins that represented the midpoint of each bin, which depended on the binning interval and the rounding direction by year.

Data were provided for multiple species but here we focus on bigeye and yellowfin tuna. For 1952-1964 only yellowfin data were provided, and were measured in very large numbers. Other species were measured during this period but are held in a different database which was not provided. Samples were obtained from commercial vessels and from training and research vessels.

Measurements included both lengths and weights. Weight samples were all recorded in 1 kg bins, while length samples were recorded in 1, 2, and 5 cm bins (Figure 1). Albacore length measurements were all at 1 cm resolution, and weight samples were only a small proportion. Bigeye and yellowfin initially included mostly 2 cm and 1 kg bins, but 1 cm bins increased and comprised most of the dataset by 2016. Samples at 2 cm resolution were available for every year from 1952-1988, with smaller numbers from 1999-2001, and a few more in 2005 and 2006. All three species included a few samples at 5 cm resolution, mostly in the early 2000s.

Measured fish were allocated to location strata with resolutions (degrees latitude by longitude) 10 x 20, 5 x 10, and 1 x 1, with a few allocated to 5 x 5 (Figure 2). All samples were recorded at 5 x 10 resolution until 1965, when 10 x 20 resolution was introduced. This was followed by 1 x 1 resolution in 1967, which quickly became dominant. Since 1995 all samples have been reported at 1x1 spatial resolution.

Sample locations by period and spatial resolution are shown in figures 3 to 8. Before 1955, almost all sampling was from the north-eastern areas, but by the end of the decade had spread to cover the whole Indian Ocean (Figure 3). By the 1970's most bigeye and yellowfin samples were obtained from tropical areas, particularly east of 75 °E, with relatively few samples from further south.

We standardized the size data by fitting generalized linear model by species, spatial resolution, and data type (lengths and weights), with normally distributed errors. The model took the following form: $size \sim yq + grid + \epsilon$, where *size* was the adjusted bin value, *yq* was a combined year-quarter effect, and *grid* was the spatial cell given the resolution of the data. Both variables were fitted as categorical variables. For mapping, mean sizes were predicted across the grid, with the year-quarter variable fixed at the level of the year-quarter with the most records.

Yellowfin and bigeye size data were standardized separately for each measurement unit, with year-quarter means plotted and spatial grid means mapped (Figures 13 to 17). For yellowfin, the 1 x 1 length data covered the period from 1967-2016, the 1 x 1 weight data covered 1986-1996, the 5 x 10 length data covered 1952-1968, and the 5 x 10 weight data covered 1953 and 1956-1991. The bigeye data coverage was similar to yellowfin but started in 1965. The 5 x 10 bigeye length dataset is therefore only 3 years long, and was not analysed. Length data at 1 x 1 resolution are also reported.

Results

In the yellowfin 5 x 10 length data, there was a strong and well-defined decline in size indices from about 130 cm in 1952 to about 110 cm by 1960 (Figure 9). The 5 x 10 weight indices also declined from a mean of about 40 kg in 1956 to stabilise in the early 1960s at around 30 kg (Figure 10).

For bigeye tuna, size indices from the 5 x 10 weight dataset were relatively stable with possibly a slight decline to average of about 40 kg by 1970 (Figure 11). They were subsequently very variable with the low sample sizes until the early 1980s, when the mean weight became more stable and again averaged about 40 kg, possibly declining slightly over the decade. In the 1 x 1 length data, temporal indices were relatively stable until 1980 but then declined until about 1990, increased until the mid-1990s, declined until 2000 and then became very variable and uncertain as sample sizes declined (Figure 12).

Spatial patterns for yellowfin were clearly indicated in the 5 x 10 length and weight datasets (Figures 13 and 14), with smaller fish in equatorial areas, particularly in the northwest and far east. Larger fish occurred south of 10 S, particularly in the Mozambique channel and to the west of 80 E. Longline-caught fish also appear larger on average in the Bay of Bengal than further west. Minor differences between the size and weight dataset patterns were likely due to low sample sizes. The 1 x 1 length data had much smaller spatial coverage but the patterns were generally consistent, with a suggestion of larger fish in the south-eastern Indian Ocean near Australia (Figure 15).

Spatial patterns for bigeye were less well-defined but were also consistent between the two available datasets (Figures 16 and 17). In both datasets, larger fish were caught north of the equator, both to the west of 70 E and near Sri Lanka, than were caught in southern areas, particularly to the east of 80 E.

Discussion

Yellowfin tuna mean sizes declined rapidly during the early years of the fishery, stabilising by about 1960. The rate of decline appears to be too rapid to represent change in the size structure of the population, given the size of the catches. This is reflected in the inability of the yellowfin stock assessment to fit the early size data (Figure 21, Langley 2015).

This decline occurs in standardized size data, which indicates that the size reduction is not due to sampling in areas with smaller fish, but to reduction in the average size of fish across all locations. However, effort expanded progressively across the Indian Ocean, so further analysis by area is recommended, to better understand the rates at which sizes changed within each fished area.

Size changes were not clearly observed in the bigeye tuna size data, probably because the dataset does not start early enough. We recommend further analyses that include bigeye size data starting in 1952. It would also be useful to compare early size changes across oceans and fleets, and for other species such as billfish.

Comparison with data from other fishing methods, such as purse seining and pole and line methods, may also be informative. Capture by longline or pole and line involves a decision to strike a hook by an individual fish, so behavioural differences among individuals may affect catchability. Purse seining involves less individual choice by the fish, and may be less likely to involve juvenilization.

We also recommend examining size patterns in the piracy area near Somalia when fishing resumed. If juvenilization is due to higher catchability of some larger fish, we would expect to see more large fish in the catch when fishing is reintroduced after a period without fishing.

The observed spatial size variation patterns are consistent between datasets collected in different ways. This suggests that the features are real, and not artefacts of the sampling processes. The most likely cause of the size patterns is spatial variation in the average size of fish. However other factors that must be ruled out include spatial variation in either fishing practices or fish availability at size. We note that similar patterns are observed in the bigeye 5 x 10 dataset which comes mostly from the 1960s and the 1 x 1 dataset collected since the 1970s (Figure 2). However it may be more useful to explore this issue using data from other oceans such as the Pacific, where longline data were collected more consistently and for a much longer period.

The model used assumes no interaction between time and location, which implies that any trends in size occurred uniformly in all areas. However, this is unlikely to be true if sizes changed in response to fishing, particularly in the early years as fishing spread across the Indian Ocean. Sampling locations are reasonably representative of fishing, and show that the north-eastern Indian Ocean was fished first, and fishing rapidly spread further south (Figure 3). We recommend further analysis that considers time-area interactions, initially by running the models for shorter time periods. To facilitate this process it may be useful to combine datasets by aggregating to the higher spatial resolution, and converting weights to lengths.

Evidence of spatial size variation may help to improve the bigeye and yellowfin stock assessments, in which fish size is an important element (Langley 2015; Langley 2016). These assessment use Stock Synthesis (Methot & Wetzel 2013) and assume that fisheries have constant selectivity in space and time. Size frequency data are fitted relatively poorly in these assessments (e.g. Sharma *et al.* 2014). We suggest comparing the spatial size patterns reported here with the fisheries defined in the stock assessments, and potentially redefining them so that each fishery covers an area within which sizes are not too variable. In general, asymptotic selectivity should be reserved for the longline fisheries in which the largest fish are caught. This analysis provides new information based on analysis of a long-term dataset.

The patterns observed in the Japanese data modelled here are different from those seen in the Taiwanese size data, which showed much less spatial differentiation (Geehan & Hoyle 2013). Taiwanese mean sizes change substantially through time, but these changes are believed to be due more to sampling problems than to population change, which may also be true of the lack of spatial variation. It would be useful to review the spatial location information associated with the Taiwanese size data. As discussed above, the Taiwanese data come from a much more recent period than the Japanese data, so spatial size distributions may be different. Experience with data from the Pacific suggests that such spatial size variation is maintained through time, but further analysis, preferably across multiple ocean datasets, is required to verify this point.

Further work includes:

- Add bigeye samples from the 1952-1964 period to the models, which would provide much better information about bigeye spatial patterns, and early period juvenilization.
- Explore possible causes of size variation by a) using the stock assessments to explore spatial growth patterns by fitting to subsets of the size data, as done by Nicol *et al.* (2011); and b) modelling age-length data from otoliths while accounting for sample location.
- Extend analyses beyond mean size to model size distributions and proportions.
- Parallel studies of size variation in other oceans, other species in the Indian Ocean, and other gear types such as purse seine data.

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Tables

Table 1: Fields available in the size dataset, variable descriptions, and the meaning of each code.

Variable	Description	Codes	Meaning
Species		1 2 3 4 5 6 7 8 9 10 11 12	bluefin tuna southern bluefin tuna albacore bigeye yellowfin swordfish striped marlin blue marlin black marlin sailfish shortbill spearfish skipjack
level	Spatial resolution in degrees of latitude x longitude	1 2 3 4	10 x 20 5 x 10 5 x 5 1 x 1
latitudec	Latitude type	1 2	N S
longitudec	Longitude type	1 2	E W
fleet	Set type	1 2	Longline Longline (night setting)
vesselc	Type of vessel	1 >2	Commercial vessel Training and research vessel
M_unit	Measurement unit	1 2 3 4 5 6 7 8	kg 1 cm 1 kg 2 kg 5 kg 1 cm 2 cm 5 cm
place	Sampling location	1 2 3 4 5 6 7 8 9 10 11 12 13	On board by fishermen Port sampling Kagoshima Port sampling Katsuura Port sampling Yaizu Port sampling Shimizu Port sampling Tokyo Port sampling Shiogama Port sampling Kesennuma SBT monitor ship Port sampling Sakai-minato Port sampling Kamaishi Port sampling Misakai On board observer
sex		0 1 2	unknown female male

Figures

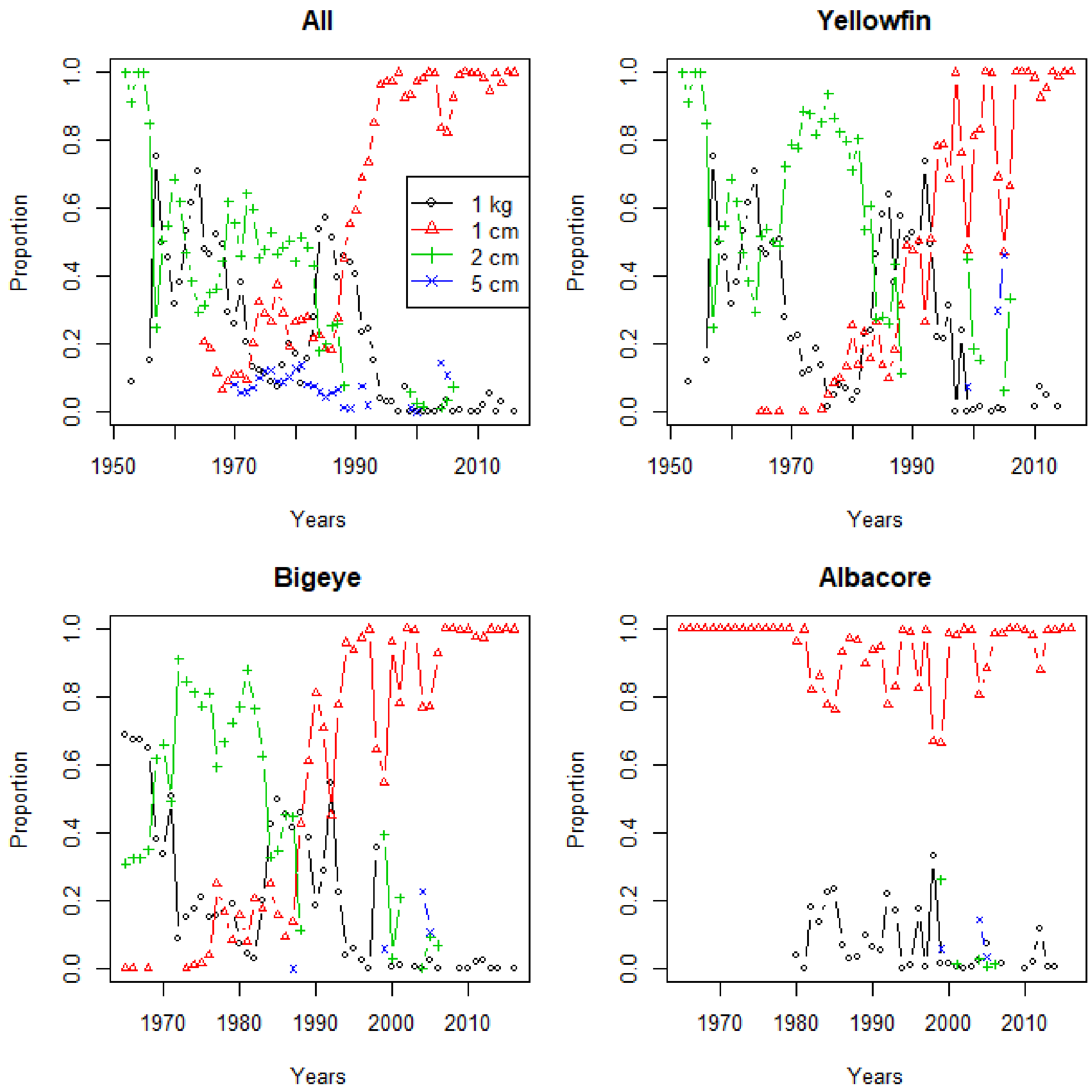

Figure 1: Proportions of measurements by measurement unit and year, for all species combined and separately for bigeye, yellowfin, and albacore.

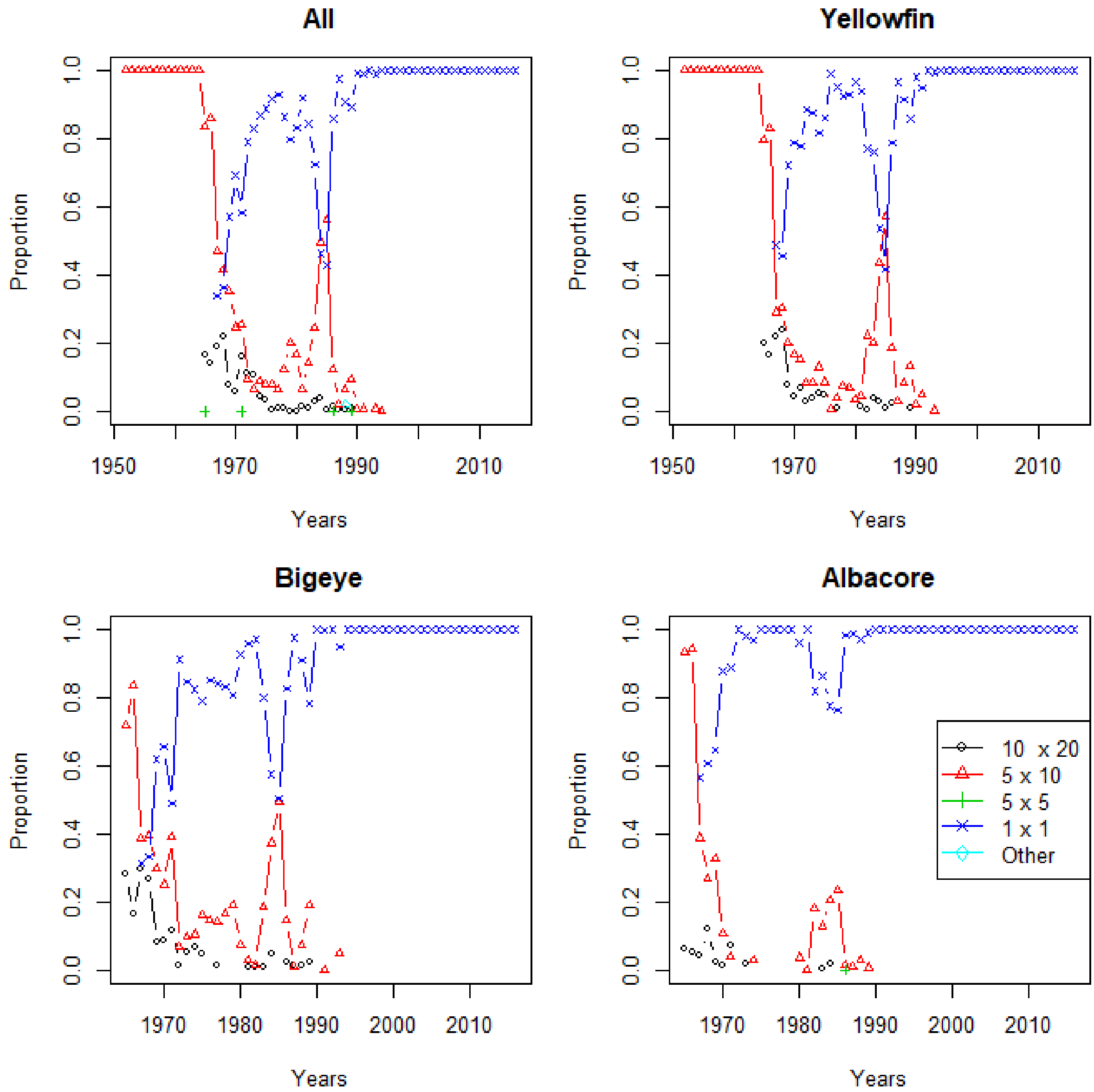

Figure 2: Proportions of measurements by spatial resolution and year, for all species combined and separately for bigeye, yellowfin, and albacore.

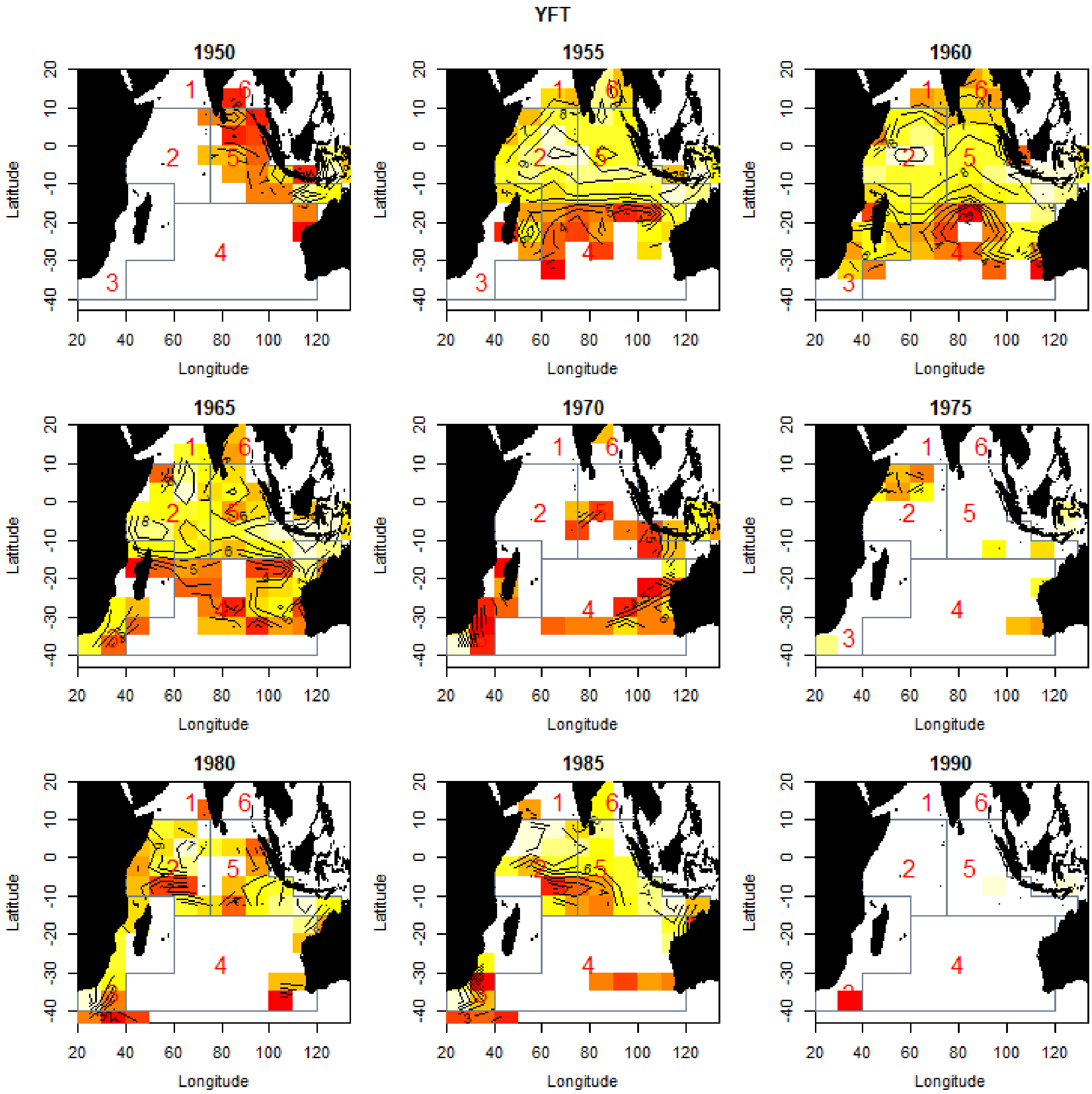

Figure 3: Yellowfin sampling locations and intensity for 5 x 10 data by 5-year period. Yellow indicates more samples than red, and white indicates no samples.

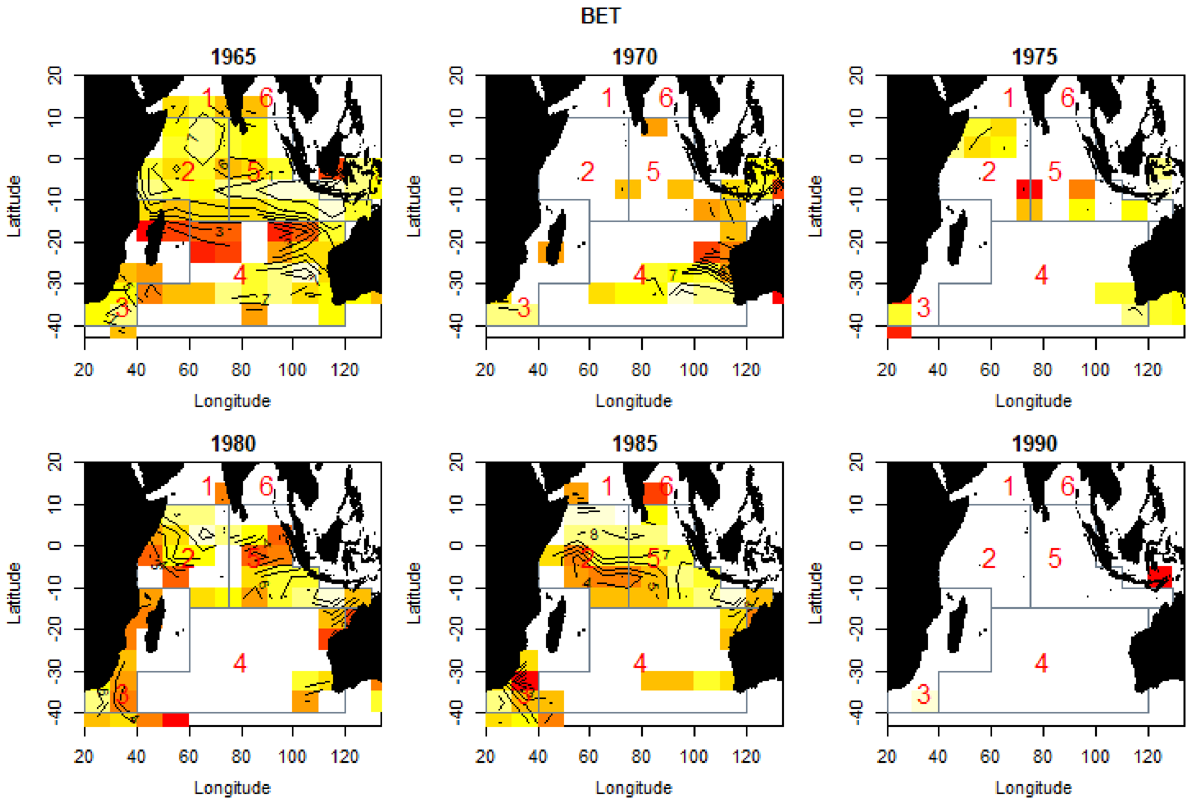

Figure 4: Bigeye sampling locations and intensity for 5 x 10 data by 5-year period. Yellow indicates more samples than red, and white indicates no samples.

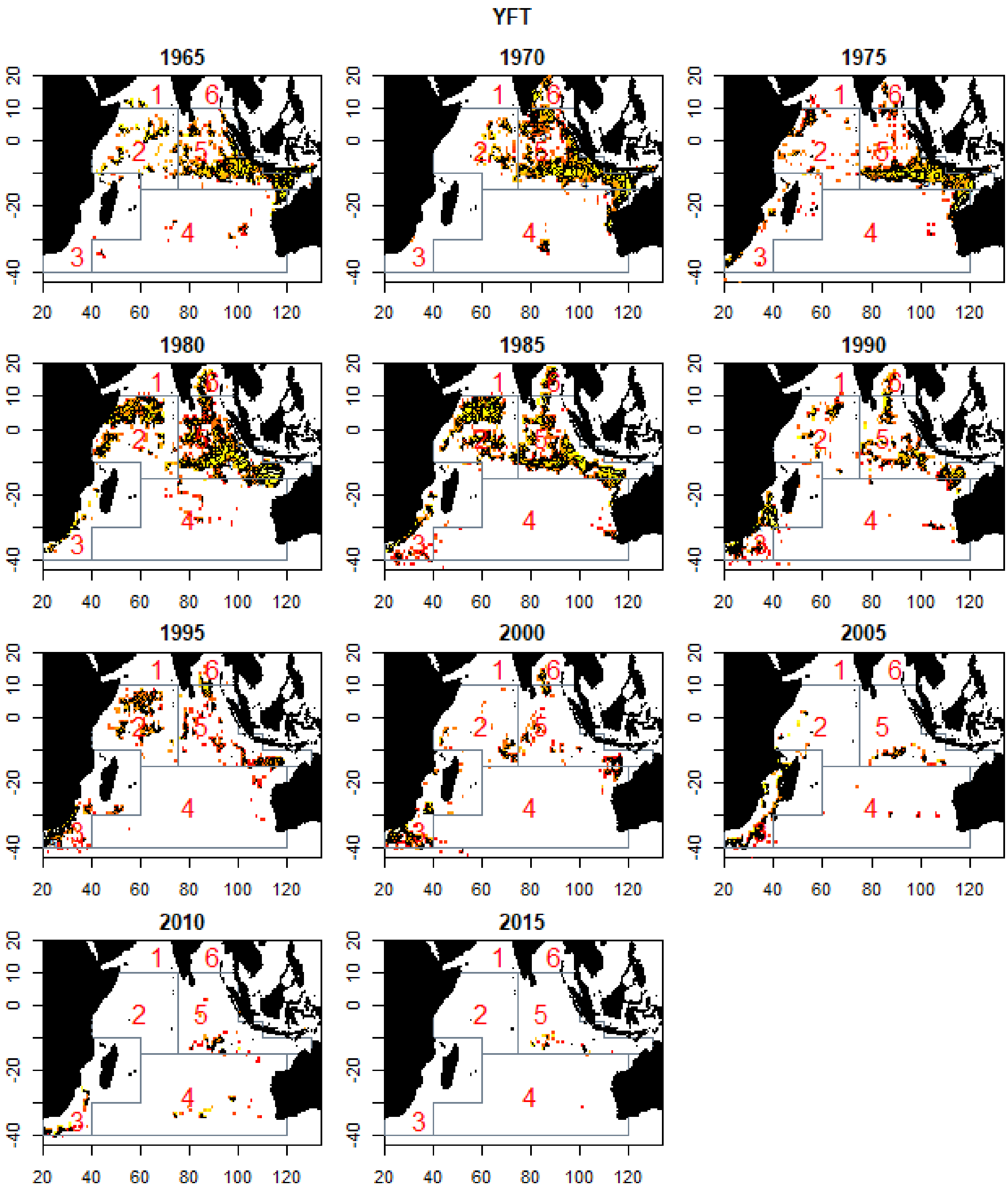

Figure 5: Yellowfin sampling locations and intensity for 1 x 1 data by 5-year period. Yellow indicates more samples than red, and white indicates no samples.

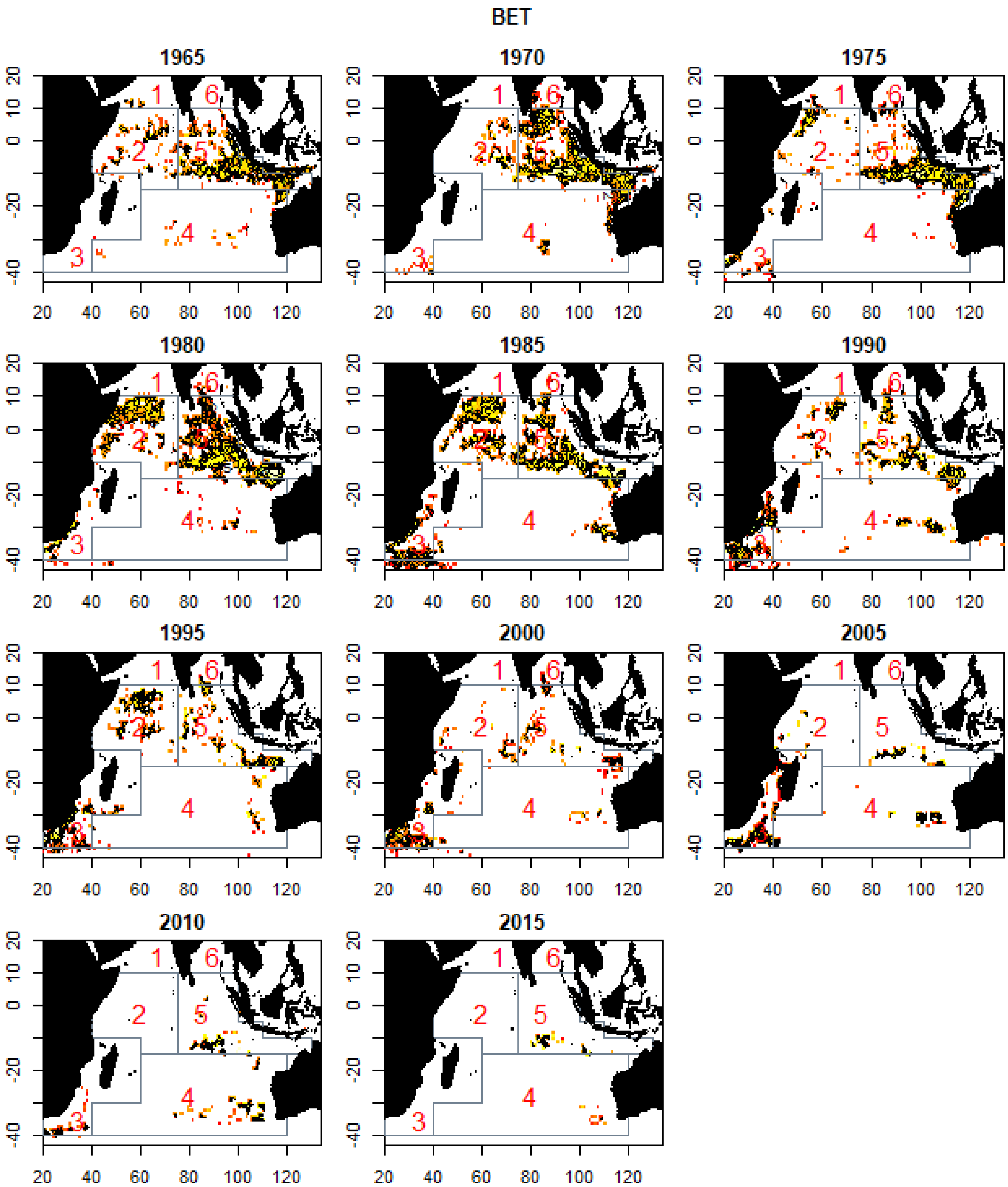

Figure 6: Bigeye sampling locations and intensity for 1 x 1 data by 5-year period. Yellow indicates more samples than red, and white indicates no samples.

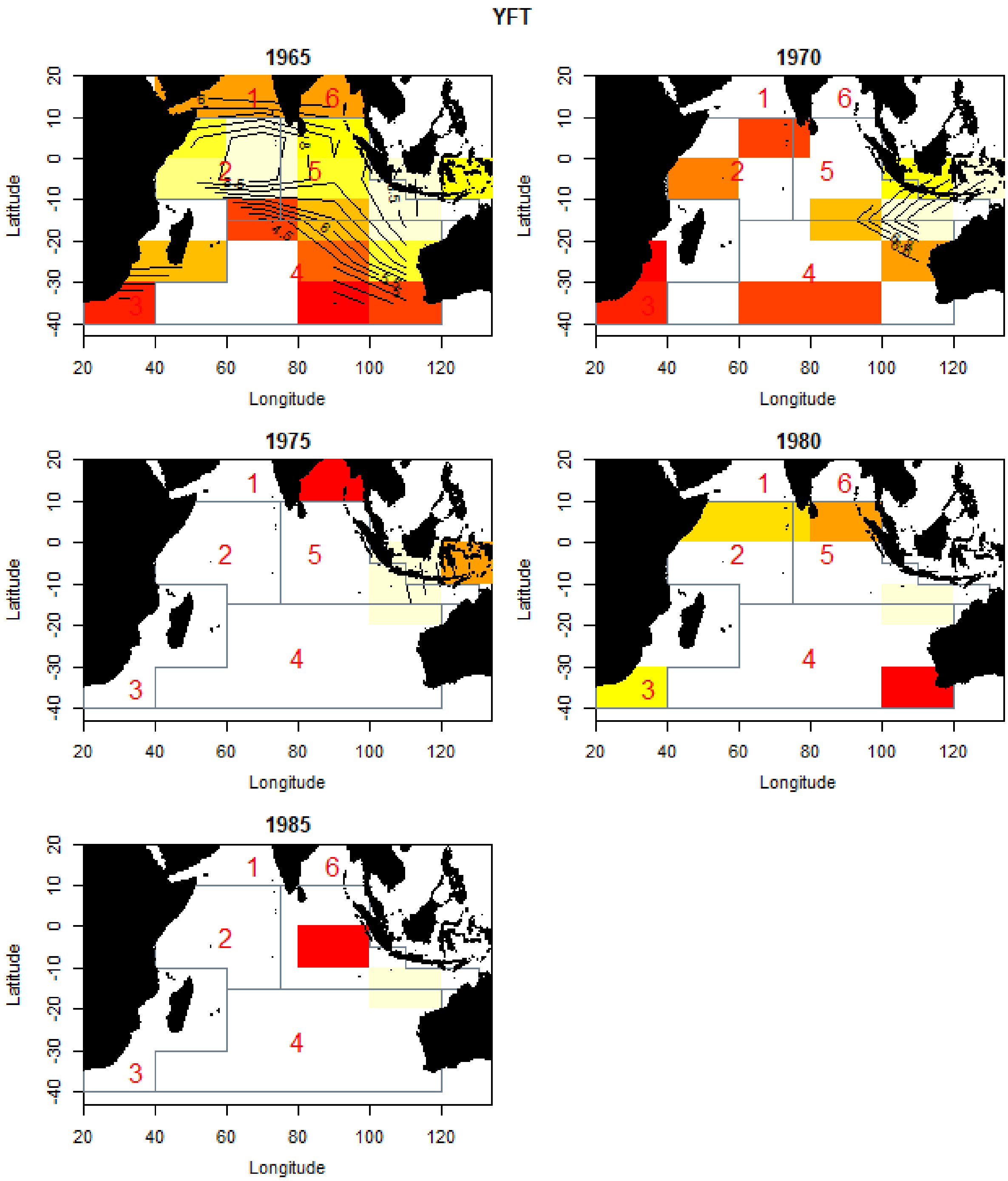

Figure 7: Yellowfin sampling locations and intensity for 10 x 20 data by 5-year period. Yellow indicates more samples than red, and white indicates no samples.

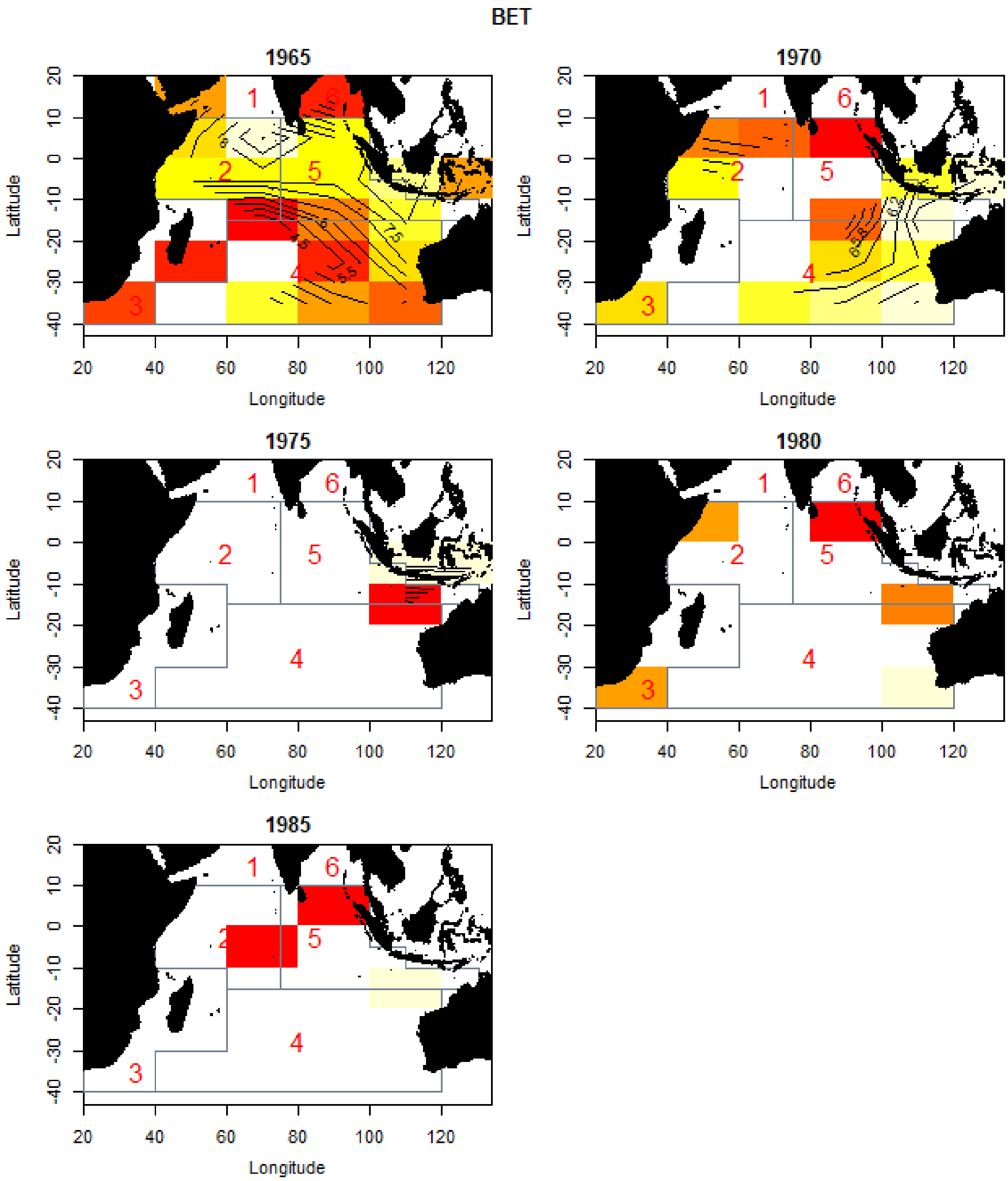

Figure 8: Bigeye sampling locations and intensity for 10 x 20 data by 5-year period. Yellow indicates more samples than red, and white indicates no samples.

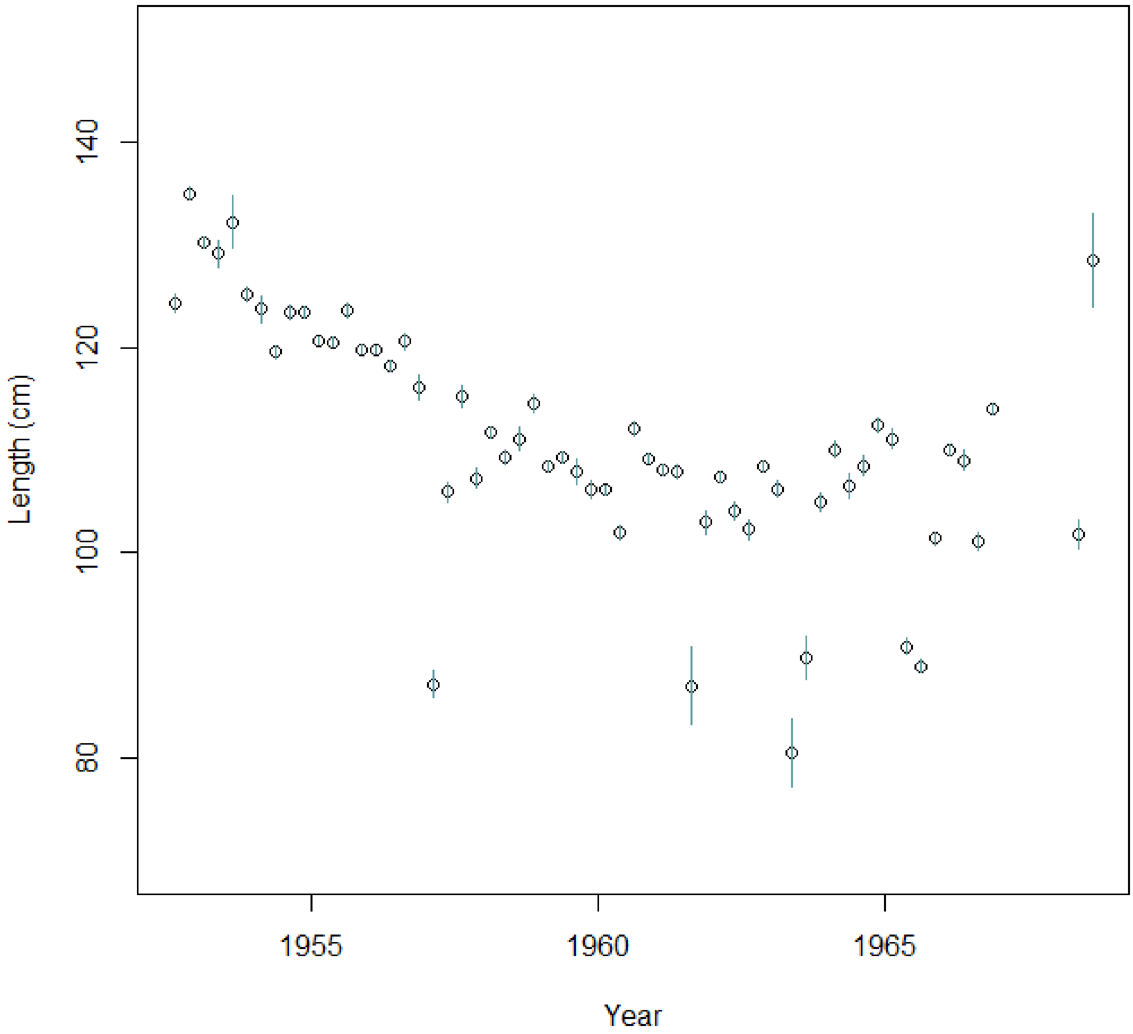

Figure 9: Yellowfin predicted quarterly mean lengths from a model fitted to 5 x 10 length data.

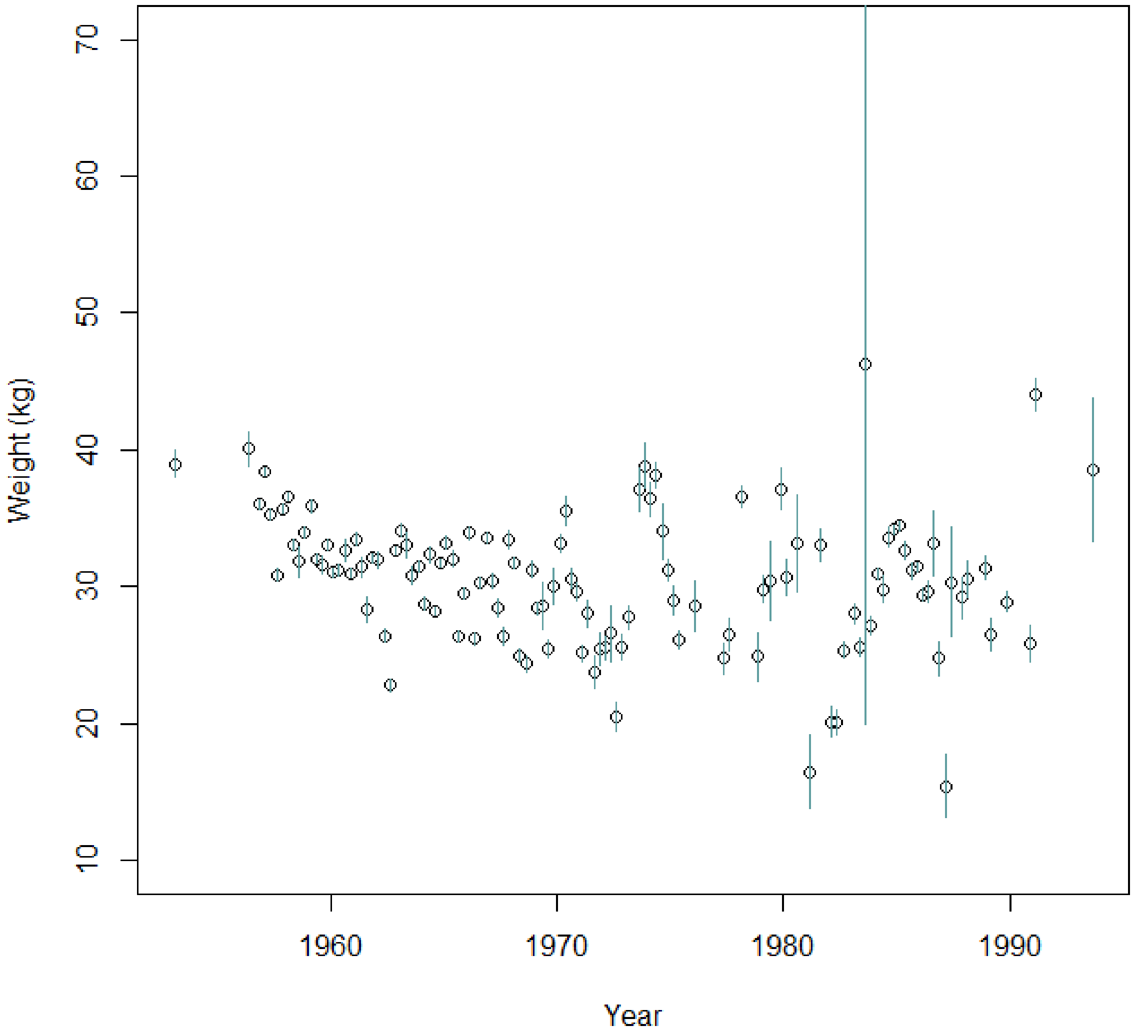

Figure 10: Yellowfin predicted quarterly mean weights from a model fitted to 5 x 10 weight data.

Figure 11: Bigeye predicted quarterly mean weights from a model fitted to 5 x 10 weight data.

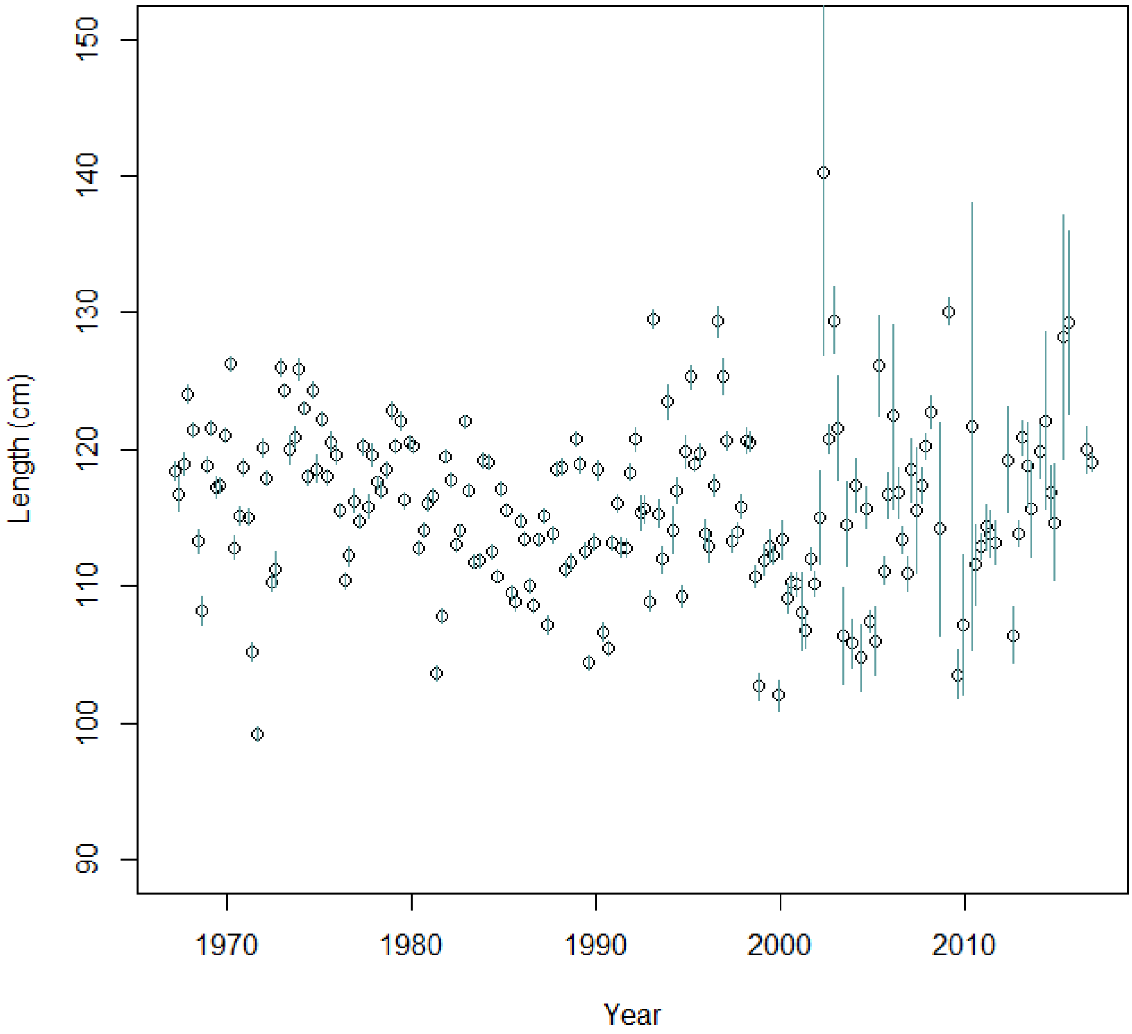

Figure 12: Bigeye predicted quarterly mean lengths from a model fitted to 1 x 1 length data.

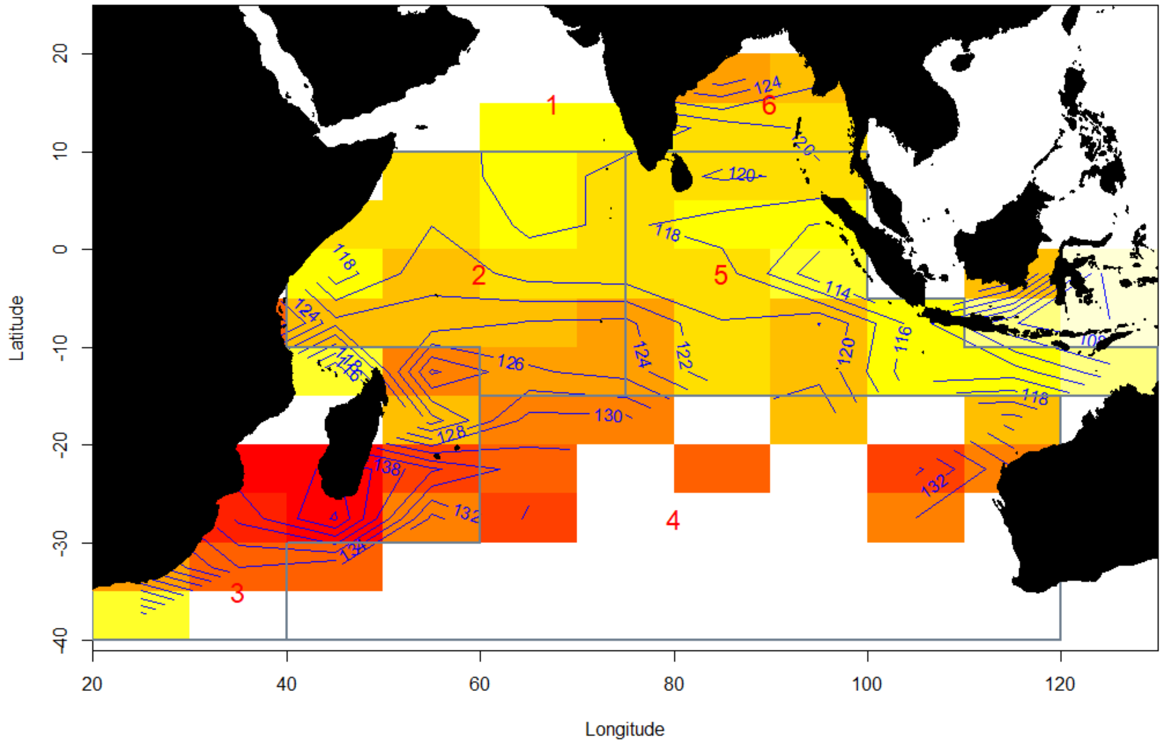

Figure 13: Yellowfin predicted mean lengths by stratum from a model fitted to 5 x 10 length data. Red indicates larger fish than yellow, and white indicates no samples.

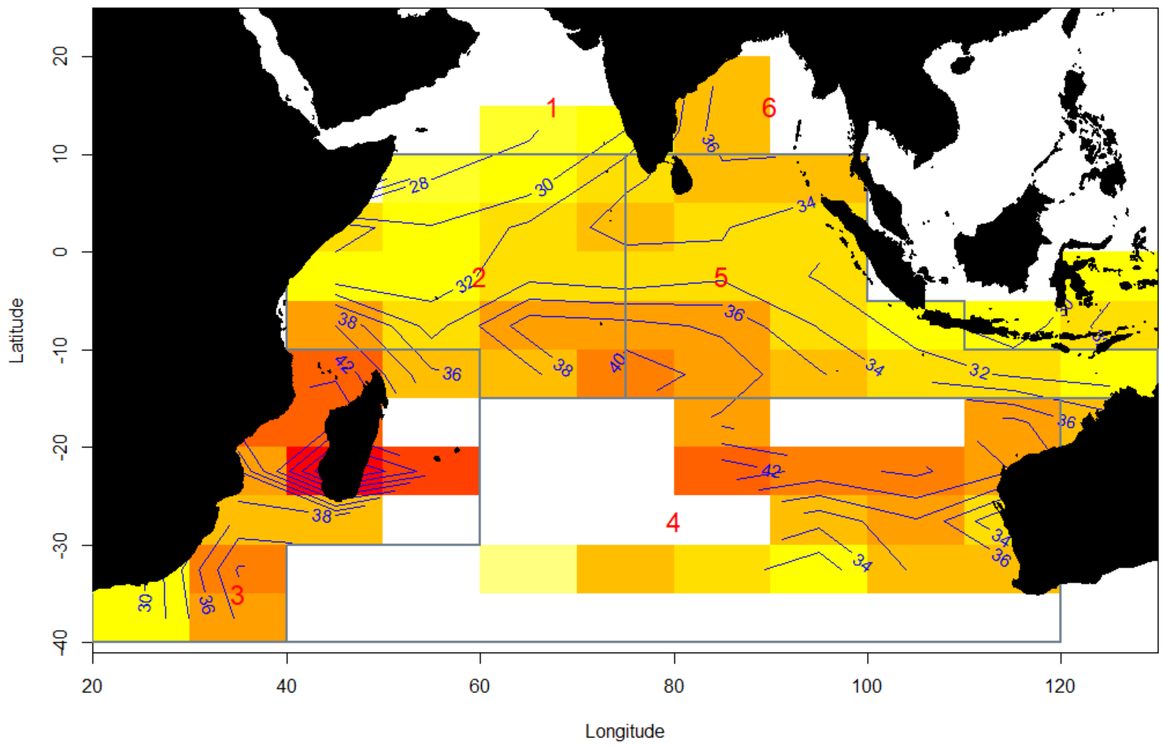

Figure 14: Yellowfin predicted mean weights per stratum from a model fitted to 5 x 10 weight data. Red indicates larger fish than yellow, and white indicates no samples. Red indicates larger fish than yellow, and white indicates no samples.

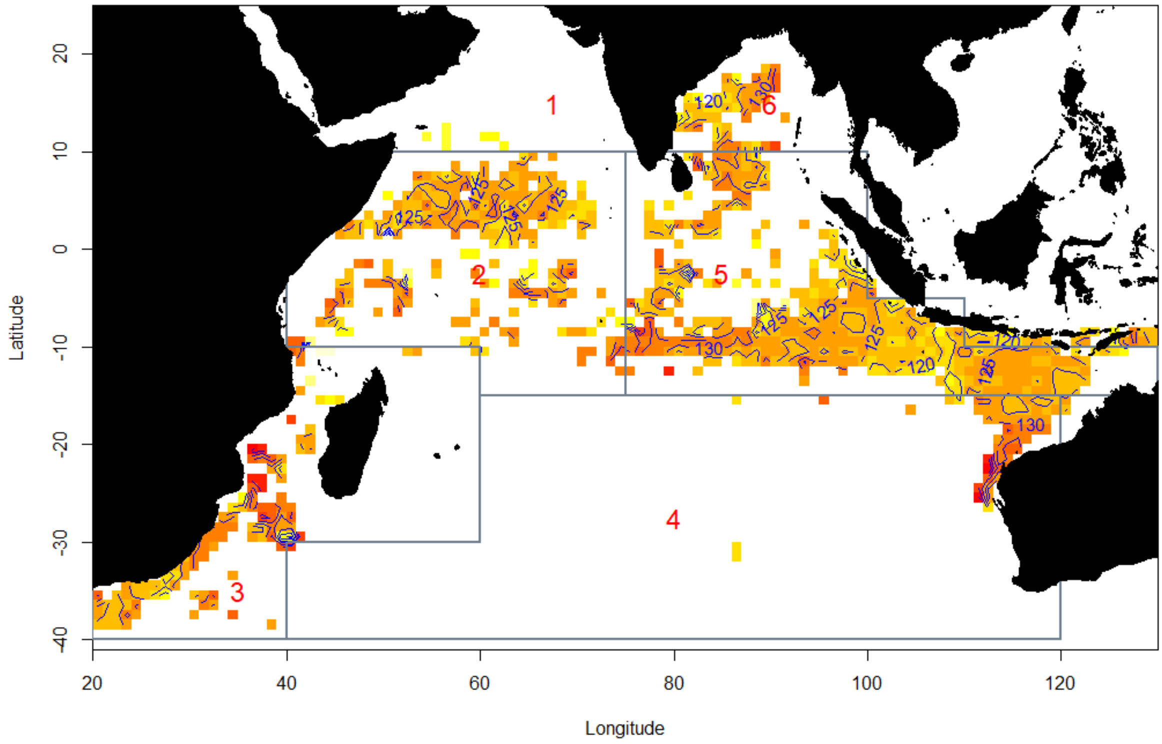

Figure 15: Yellowfin predicted mean lengths per stratum from a model fitted to 1 x 1 length data. Red indicates larger fish than yellow, and white indicates no samples.

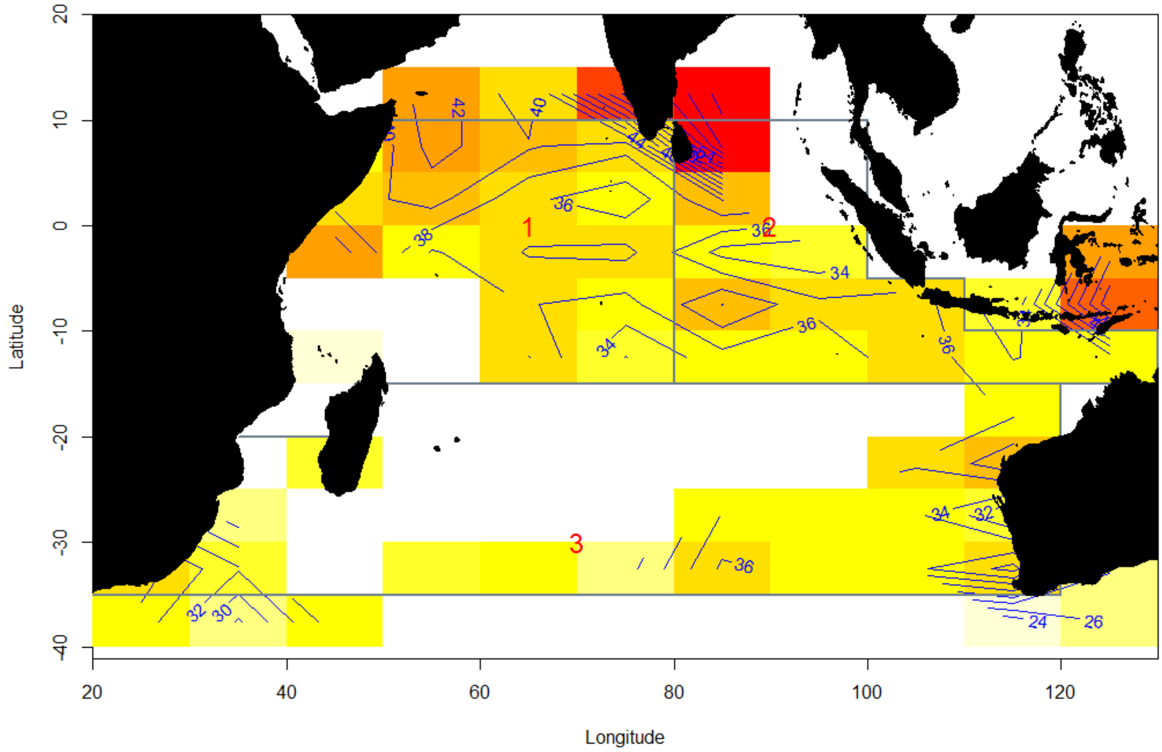

Figure 16: Bigeye predicted mean weights per stratum from a model fitted to 5 x 10 weight data. Red indicates larger fish than yellow, and white indicates no samples.

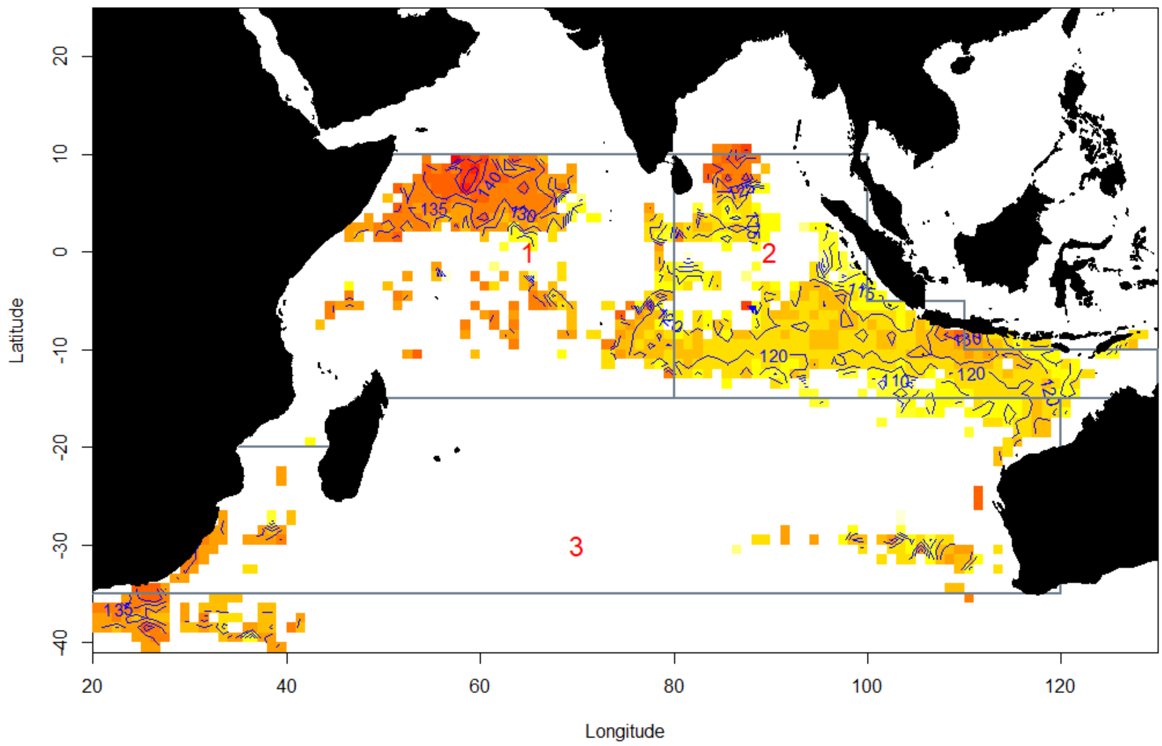

Figure 17: Bigeye predicted mean lengths per stratum from a model fitted to 1 x 1 length data. Red indicates larger fish than yellow, and white indicates no samples.