TOWARDS A CONCEPTUAL MODEL FOR YELLOWFIN TUNA IN THE INDIAN OCEAN

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SUMMARY

Yellowfin tuna (Thunnus albacares) is an important food source, employment, and livelihood for several nations worldwide. The last assessment model for this species was held in 2021, and estimated a stock status of overfished and subject to overfishing. The main goal of this document is to summarize the current knowledge on the biology of yellowfin tuna in the Indian Ocean and provide some advice relevant to the next stock assessment process. This document relies on three main references: the 2021 stock assessment report, the report of the panel review in 2023, and the findings of Langley et al. (2023) regarding recruitment and other aspects of this species, as well as recent papers on the biology of this stock. We also present analyses that provide novel insights into the dynamics of this species and the fishery. Finally, we present future research needs and hypotheses towards an implementation of a conceptual model for this stock, which is the first step of recommended good practices when implementing spatially structured assessment models (Goethel et al., 2023).

KEYWORDS

Yellowfin tuna, assessment model, conceptual model, Stock Synthesis

1. Introduction

Yellowfin tuna (*Thunnus albacares*) is an important source of food, employment, and livelihood for several nations worldwide. Due to its economic importance, this species experiences substantial fishing pressure, with global catches of about 1.4 million tons (Heidrich et al., 2023). Yellowfin is a fast-growing species widely distributed in the Indian Ocean (IO), where it is considered as a single stock. This species has a high metabolic rate and, therefore, it requires large energy supplies to fulfill the bioenergetics demands for movement, growth, and reproduction (Artetxe-Arrate et al., 2021). Spawning activity in the IO occurs in lower latitudes with warmer waters and mesoscale oceanographic activity, principally from December to March (Muhling et al., 2017). Juvenile yellowfin (> ~ 45 cm) can perform extensive migrations between spawning areas and feeding grounds in southern and northern areas of the IO (Fonteneau and Hallier, 2015).

The last assessment of this species in the IO was carried out in 2021 (Fu et al., 2021) and was implemented in the Stock Synthesis (SS3) platform (Methot and Wetzel, 2013). This last assessment assumed a single stock in the entire IO with four areas with different fisheries and data. For this configuration, a global stock-recruitment relationship is assumed, and recruits are apportioned among areas. For this assessment, recruitment was assumed to happen only in tropical areas. Biological features (e.g., natural mortality, growth, etc.) were assumed spatially invariant. The stock status was estimated to be overfished and subject to overfishing in 2021. The IOTC's Scientific Committee has identified a number of problems with the configuration of the assessments of this stock, and a comprehensive assessment review was carried out in 2023 by an international panel of experts (Maunder et al., 2023), which listed several recommendations for the next assessment process.

The main goal of this document is to summarize the current knowledge on the biology of yellowfin tuna in the IO and provide advice for the configuration of a new stock assessment. This document relies principally on three main references: Fu et al. (2021), Maunder et al. (2023), and Langley et al. (2023), as well as recent papers on the biology of this stock. We also present analyses that provide novel insights into the dynamics of this species and the fishery. Finally, we present future research needs and hypotheses towards an implementation of a conceptual model for this stock, which is the first step of recommended good practices when implementing spatially structured assessment models (Goethel et al., 2023). For an easier description of our results, we use the spatial stratification shown in Figure 1 throughout this document, which is not necessarily based on any type of biological or fishery information, nor suggest any type of stock assessment configuration.

2. Sexual maturity and spawning

Zudaire et al. (2022) provide the most recent review on the sexual maturity of YFT in the IO. They analyzed samples from a few data collection programs since 2009, principally from the purse seine fleet and western IO. The authors estimated the length at 50% maturity (L_{50}) by applying two different maturity thresholds depending on the oocyte development stage considered: physiological maturity (threshold established at cortical alveolar oocyte development stage) and functional maturity (threshold at initial vitellogenic oocyte development stage). The former method estimated L_{50} at 75 cm fork length (FL) and was used in the 2021 assessment, while the latter estimated 101.7 cm FL.

SS3 calculates the spawning biomass (SB) assuming that a fish of a certain length can contribute to the spawning biomass (i.e., should be able to reproduce) during a given time step (Methot and Wetzel, 2013). Based on this, the use of functional maturity as the threshold to determine a sexually mature fish may be preferable since it guarantees that the fish will inevitably reproduce during that time step (Pacicco et al., 2023; Zudaire et al., 2022); therefore, we recommend its use in the assessment model. The previous two stock assessment reports (Fu et al., 2021; Urtizberea et al., 2019) mentioned that the choice of this threshold did not largely impact the assessment results, but limited comparison was provided. The choice of the maturity threshold may have important impacts on the resilience capacity of this stock, as well as the reference points; therefore, we recommend a detailed evaluation of this decision.

Another factor to discuss for the next assessment is the inclusion of maturity information as length or age-specific. In the 2021 assessment (Fu et al., 2021), maturity-at-length was converted to maturity-at-age and then included in the assessment model. Although Fu et al. (2021) mention that the use of maturity-at-length or -age produced

minimal effects on results, that conversion depends on other biological parameters (e.g., somatic growth) that may be changed in future assessments or vary among model configurations. In order to avoid that dependence, we recommend using maturity-at-length.

Zudaire et al. (2022) also examined the sex ratio and found it to be close to 1:1 for most of the small and intermediate size classes (smaller than 115 cm). However, males dominated the samples for sizes larger than 150 cm, probably due to differences in growth between sexes (Farley et al., 2023). The current evidence suggests that the assumption of a sex ratio of 0.5 in the assessment model is adequate.

Regarding spawning activity, Zudaire et al. (2022) found that spawning occurs all year round, with higher activity from November to February. Also, the largest batch fecundity estimates (i.e., number of oocytes released) were observed in the largest females. In SS3, we can approximate this spawning behavior through two approaches:

  • Use year as the model time step and model seasons (e.g., four seasons) within years. This approach estimates recruitment using the stock-recruitment (S-R) relationship once a year and then distributes the estimated recruitment among seasons.
  • Use quarter as the model time step. This approach estimates recruitment every quarter using the S-R relationship. This approach was used in the 2021 assessment.

While the latter approach may represent more realistically this species' spawning behavior, the number of parameters are substantially more than the former approach, so model estimation problems might arise. We recommend an exploration of both approaches.

Spatially, evidence suggests that the main spawning areas are located in the equatorial region, between 15°S and 10°N (Reglero et al., 2014); however, spawning activity is also reported in other areas such as the Oman Sea (Hosseini and Kaymaram, 2016) or the Bay of Bengal (Kumar and Ghosh, 2022) but with distinct seasonal spawning patterns. Likewise, spawning activity has been reported in the eastern IO (Nootmorn et al., 2005), with similar seasonal patterns as the one observed in the western IO (Hartaty et al., 2021; Zhu et al., 2008). All this evidence suggests that there may be spawning activity in a large portion of the Indian Ocean, especially in tropical areas. This last point has important implications for the recruitment configuration in the assessment model since it might define the areas with recruitment apportionment and areas with no recruitment.

3. Movement

The 2021 assessment model configured reciprocal time-invariant movement between areas R1-R2, R1-R4, and R3-R4, with different rates for young and adult fish. Other movement configurations were tested but produced minimal effects on model outputs (Fu et al., 2021). In order to inform movement rates, the 2021 assessment incorporated tagging data from the Indian Ocean Tuna Tagging Programme (IOTTP) and the Regional Tuna Tagging Project-Indian Ocean (RTTP-IO) from 2005-2009. In these programs, more than 50 000 fish were released, mainly in the western IO. Almost all recoveries were close to the release locations, but a few recoveries also happened in the eastern IO, southwestern IO, and Arabian Sea. The purse seine fleet recovered most of the tags but the set type was unknown for some of them.

Probably due to low recoveries in areas different than the western IO, the 2021 assessment estimated negligible movement rates between R1-R4, and relatively low movement rates (< 0.15) between other areas. One aspect of consideration when including tagging data in SS3 is that tag information should be specified by age, which is not available for most fish. Therefore, a conversion from length to age is required, which depends on the used growth curve. In addition, some caveats of this tagging data have already been identified, such as the unknown mixing period, reporting rates, and tag loss. Due to these caveats, Maunder et al. (2023) recommended an external exploration of the tagging information using spatiotemporal models to inform the stock assessment model about mortality and abundance (Mildenberger et al., 2023).

The use of tagging data in a spatially stratified stock assessment model is important because it can provide direct information on movement rates among areas. However, the incorrect parametrization of movement can hamper the model performance and produce biased outputs (Goethel et al., 2015). Movement parameters are usually highly correlated with recruitment estimates since the model will be able to fit observed data by either moving fish or creating new recruits (Cadrin et al., 2019). When movement dynamics are uncertain, previous studies have found

that estimating flexible movement (i.e., time or age-varying) in stock assessment models may produce less biased results than ignoring movement (Goethel et al., 2015; McGilliard et al., 2015; Punt et al., 2017).

Using the 2021 assessment and assuming recruitment only in the tropical area of the western IO (area 1 in the 2021 assessment), Langley et al. (2023) explored different movement configurations, including time-varying parametrizations, and concluded that the configuration used in 2021 was the most parsimonious. Also, Langley et al. (2023) found consistency between the Dipole Mode Index (DMI) and the movement rates between western and eastern IO. Given the notable seasonality in the ocean conditions in the IO (Schott and McCreary, 2001), it is reasonable to explore distinct movement rates, if present, among seasons in the assessment model, which can be explored further during the next assessment.

Previous reports (Fu et al., 2021; Maunder et al., 2023) have discussed the absence of intermediate lengths ($\sim$ 55 to 100 cm) in the length data of the purse seine (free school) fleet in the western IO. One hypothesis is that these fish might move to other areas. The Arabian Sea is of special interest since these fish ($\sim$ 55 to 100 cm) are caught by the gillnet fleet operating in this area. Another explanation might be that those fish of intermediate lengths are in deep areas where the purse seine gear cannot catch them or escape from it, therefore they are not seen in the catches. This hypothesis needs to be demonstrated by data and further studies, but there are a few reasons that support it. Yellowfin dwell preferentially in the surface mixed layer and the thermocline (Pecoraro et al., 2017), above 200 m approximately (Sabarros et al., 2015). There is evidence that younger yellowfin ($\sim$ 60 cm) inhabit deeper areas, where the purse seine gear does not act efficiently, than mature fish ($>\sim$ 100 cm) in other regions (Matsumoto et al., 2013). This behavior is possibly related to a shallower habitat of spawners to maximize the offspring's survival (Muhling et al., 2017). Ontogenic differences in vertical habitat utilization were also identified in the eastern Pacific Ocean for this species (Schaefer et al., 2011). We recommend considering these different hypotheses when implementing assessment configurations.

4. Growth

The 2021 assessment modelled somatic growth as changes in the mean size-at-age at the stock level using a growth curve estimated by Fonteneau (2008). This curve did not follow the traditional von Bertalanffy growth pattern, and was approximated by varying the growth rates (k parameter) by age in SS3. Using otolith readings, growth increments, and modal progressions from PS length data, Dortel et al. (2015) estimate comparable growth patterns. In a recent study, Farley et al. (2023) provided new growth estimates based on otolith readings validated with radiocarbon (Fraile et al., 2024), and used a two-stage von Bertalanffy curve to fit the age-length data. This last study is an update of a previous version presented in 2021 (Farley et al., 2021). Langley et al. (2023) tested the inclusion of the 2021 growth curve and found a substantial deterioration in the fit to the FS, LS, and BB length composition data. The new assessment process should test the updated growth estimates presented in Farley et al. (2023), which can be included either as fixed parameters or as priors.

Another approach to model growth in the assessment model is to freely estimate the growth parameters with the available data (e.g., length frequency). Age-length data from otoliths readings used in Farley et al. (2023) is available and the assessment analysts can also test its inclusion in the assessment model as conditional age-at-length (CAAL) data. CAAL data is important because it can inform growth and the stock age structure in integrated assessments (Lee et al., 2019). However, given the relatively low sample size in Farley et al. (2023), we do not expect that the age-length data will have large effects on assessment results, also because the temporal coverage is limited to a few years, and the data is available only for the purse seine, longline, and gillnet fisheries. In addition, there is no discrimination between the set type for the purse seine fishery (i.e., free school or log school), so the assessment analysts should assign the fleet for those observations.

4.1. Length frequency analysis

We implemented an algorithm to identify modes in a length frequency sample using finite mixture models (McLachlan et al., 2019). We also performed a length frequency clustering analysis (Lennert-Cody et al., 2010; Xu and Lennert-Cody, 2024) to identify areas or quarters with similar length compositions. These analyses were applied to the length frequency data by grid (5x5°) in the IOTC database, only for the LS, FS, and LL fleets (see Table 1 for fleet definitions) due to their larger sampling sizes.

The LS fishery contained length data principally from the western IO, but there were several grids with information from the equatorial region of the eastern IO. We noted a strong seasonality in the identified modes (Figure 4). The youngest cohort in the fishery is observed in quarter 2 after 2000, but it is absent in previous years. We also noted a modal progression of young cohorts throughout quarters, and we can even identify a modal progression throughout quarters of older cohorts (> 90 cm) between 1990 and 2010. Quarter 1 and 4 displayed a narrower and wider range of modes, respectively. These seasonal patterns were also found in the clustering analysis, which splits the length frequency patterns among the four quarters while no spatial differences were identified (Figure 5 and Figure 6). We also examined changes in the spatial center of gravity of the LS fleet by quarter, and noted that this fleet tends to move northwards along the year (Figure 7), probably following the currents and the dispersion of floating objects.

The FS fishery also contained data almost exclusively from the western IO. We could identify a seasonal pattern in the modes for older cohorts between 1990 and 2010; however, this was less evident after 2010. We can even track some young cohorts over seasons with a similar pattern to the one observed in the LS fishery (Figure 8). The clustering analysis split the length structure between quarter 1 and 2, and one area north of 0° (dominated by small fish) and one area south of 0° (with higher dominance of large fish) in quarter 3 and 4 (Figure 9 and Figure 10). The center of gravity of this fleet did not display clear spatial patterns throughout the year (Figure 11).

The LL fishery was the fleet with the best spatial coverage of length information. As observed for the purse seine fleets, we could identify a seasonal progression of modes larger than 90 cm, especially before 2000 (Figure 12). Smaller modes were observed during quarter 1 and larger modes during quarter 4. We also noted that modes larger than 150 cm were more frequent after 2000. The clustering analysis explained less than 10% of the variance in the length frequency data, and generally found two areas with similar length compositions: north of 20°S and south of 20°S, which were consistent over quarters. However, when analyzing the length frequencies among these clusters, we did not visually find clear differences over space, but the difference among seasons was more clear (Figure 13 and Figure 14). Over decades, this fleet has moved its center of gravity towards the western IO, with no distinguishable seasonal pattern (Figure 15).

4.2. Growth variability

Temporal and spatial variability in somatic growth is present in several fish stocks (Thorson and Minte-Vera, 2016) including tunas (Ashida et al., 2018), and may have an important effect on management quantities (Stawitz et al., 2019). Given the vast area of the IO with contrasting environmental conditions, it is expected to find some degree of spatial differences in the population mean length-at-age of yellowfin. However, considering growth spatial differences in the assessment model may be challenging since most of the length frequency and age-length information come from the western IO Figure 2. The longline fleet could provide some information about spatial differences in growth since it covers most of the IO. However, the clustering analysis did not show clear spatial patterns of the length frequency of adults. Regarding temporal variability, we did not observe large differences in the identified modes among decades for the analyzed fleets, which might indicate a low temporal variability in growth.

The variation of lengths at age is another aspect relevant to the assessment model. It is commonly modelled from two parameters: the standard deviation of lengths at a young age, and the standard deviation of lengths at a old age, although other parameterizations exist. These parameters account for variability in growth among individuals, variability in the spawning timing, size-selective mortality, among others. The mode analysis presented previously might be useful for getting information about initial values for these parameters, but caution is recommended since the observed modes in the length frequency data are affected by fleet selectivity. Finally, sex-specific growth has been identified (Farley et al., 2023), especially for older fish (Figure 16). Assessment analysts should consider implementing configurations with sex-specific growth since it may improve model fits, but also considering that this may increase model complexity.

5. Stock structure

Artetxe-Arrate et al. (2024) presented an updated review of the yellowfin stock structure in the IO using available information regarding spawning behavior, tagging, otolith chemistry, parasite, and genetic data. Timing of spawning and larval distribution surveys suggest that this stock spawns in most parts of the tropical IO (Reglero et al., 2014); however, there is still a lack of evidence of spawning in southern areas. Tagging data suggest that fish have high

movement rates in the western IO and some evidence from the western IO to the Arabian Sea, but it cannot provide evidence of significant movement between western and eastern IO. Caveats of tagging data was already described above. Otolith chemistry data suggest that fish in the western IO were born in this area and provide some evidence that at least some fish in the Arabian Sea come from the western IO. Parasite composition and abundance display clear differences between fish in the Indonesian archipelago and the Maldives (central IO), which suggests limited movement between these two areas. Genetics suggest spatial heterogeneity, with differences in fish between the Arabian Sea/Bay of Bengal areas and areas south of 0° (Barth et al., 2017; Kunal et al., 2013). Also, there is evidence of gradual genetic differences between the Arabian Sea and the Bay of Bengal.

To sum up, the available studies provide evidence of:

- Larval presence both in the eastern and western IO.
- Genomic differentiation between fish in the Arabian Sea and other areas of the IO.
- Fish have high movement rates, but there is no clear evidence of large-scale movements from the western to the eastern IO or viceversa.
- Fish may move between the western IO and the Arabian Sea.
- Fish inhabiting the western IO are mainly composed of fish recruited from this area.
- Limited exchange of fish between central and eastern IO.

Studies like Artetxe-Arrate et al. (2024) aimed to investigate the structure of fish stocks are quite important when implementing assessment configurations, and have a large impact on management outcomes (Cadrin et al., 2019). Based on the current evidence, a spatial structure of yellowfin in the IO is supported; however, the degree of movement between areas needs to be further investigated. Based on Goethel et al. (2023), the following stock structures could apply for yellowfin in the IO:

a. Panmictic population. In this case, there is movement of juveniles and adults, as well as larval connectivity among areas. Spawners can reproduce in any area regardless their origin. Spatial heterogeneity in biological features might be present. Density dependence in recruitment is assumed to occur at the population scale.

b. Metapopulation with multiple sub-populations. In this case, there is also movement of larvae and later stages among areas, but the degree of larval connectivity will determine if the density-dependence in recruitment occur at the metapopulation scale or a local scale.

c. Multiple unit population with natal homing, also known as sympatric population structure. In this case, there is reproductive isolation but there could be some overlap among populations. Spawners will mainly reproduce in their area of origin.

Biological and genomic studies presented in previous sections and the spatial variability in ocean conditions in the IO suggest that spatial heterogeneity for the IO yellowfin population is likely. We still need more information to strongly support one of these three structures. However, the available evidence so far may suggest that a sympatric structure (i.e., multiple units with natal homing) is more likely. Simulation experiments have shown that assuming area-specific stock-recruitment relationship when uncertainty exists on the stock structure is a safer option (Punt, 2019). We particularly recommend investigating the degree of larval connectivity and natal homing behavior of this species. A previous study found larval connectivity in tunas between the western IO and southwestern IO Gamoyo et al. (2019), but there is no information at a wider spatial scale.

6. Selectivity

The 2021 assessment considered length-based selectivity for purse seine fisheries (FS and LS) and age-based selectivity for other fleets. Unless ontogenic movement is clearly identified in the stock, selectivity should always be considered a length-based process (Francis, 2016). We recommend modelling length-based selectivity for fleets with length composition information, especially for the LL fishery since length information is available for many years. For other fleets with low sample sizes of length frequency data, we recommend evaluating the impacts of using age or length-based selectivity. If the effect on model outputs is minimal, age-based selectivity might be enough, which would also help to decrease the model complexity.

Another factor to explore is time-varying selectivity. Our length frequency analysis showed a strong seasonality in the length frequency observations for the LS, FS, and LL fleets. Since the spatial distribution of grids with length information does not largely change among seasons, the high seasonality in length data might be most likely caused by changes in the fish availability to the fishing gear (i.e., some cohorts are more available since they are more abundant). On a longer time scale, we noticed changes in the observed lengths for some fleets. For example, a young cohort appears in the LS length frequency data in last two decades Figure 4, and a lower presence of large fish is observed in the FS fishery over the years Figure 8. We recommend exploring if time-varying selectivity for the most important fleets (i.e., those with larger sample size) improves the fits to compositional data.

7. Other components

The parameters of the length-weight (L-W) relationship ($W = aL^b$) were updated in 2016 using information from more than 20 000 fish sampled since 1987 (Chassot et al., 2016). These parameters were used in the 2021 assessment. Zudaire et al. (2022) also estimated these parameters using data from the GERUNDIO and EMOTION programs, which were similar to the ones estimated in Chassot et al. (2016) despite the much lower sample size. Also, Zudaire et al. (2022) did not find differences between males and females. There seems to be consistency between both estimates, and we recommend continuing to use the L-W parameters provided by IOTC (Chassot et al., 2016).

The sample size of length compositions was assumed to be constant (input sample size of 5) for all fleets and years and had a relatively lower weight with respect to other model data inputs (Fu et al., 2021). This approach assumes that all length frequency observations have equal weight; however, there are clearly some fleets with better sample size and spatial coverage than others (Figure 2). This difference should be included in the model since might have a large influence on the assessment results. Ideally, the input sample size should derived from the number of sample units (e.g., number of sampled vessels, number of trips or sets) that represent the statistical power in the data. The number of fish sampled, commonly used for tuna assessments, is not necessarily an indicator of statistical power (e.g., all fish could come from a single fishing trip) (Stewart and Hamel, 2014); however, in most cases that is the only information available. In addition, using the number of fish sampled can overrepresent some observations due to large differences in sample size between fleets. One approach to deal with this problem is to use the number of fish sampled on a logarithmic scale as done in other Regional Fisheries Management Organizations (RFMOs). Another factor to consider when specifying the input sample size is the spatial coverage of length samples due to there is a couple of fleets with sampling areas restricted to coastal zones.

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Zudaire, I., Artetxe-Arrate, I., Farley, J.H., Murua, H., Kukul, D., Vidot, A., Razzaque, S., Ahusan, M., Romanov, E., Eveson, P., Clear, N., Luque, P., Fraile, I., Bodin, N., Chassot, E., Govinden, R., Ebrahim, A., Shahid, U., Fily, T., Marsac, F., Merino, G., 2022. Preliminary estimates of sex ratio, spawning season, batch fecundity and length at maturity for Indian Ocean yellowfin tuna (No. IOTC-2022-WPTT24(DP)-09). Indian Ocean Tuna Comission.

9. Tables

Table 1: Fleets included in the 2021 assessment model

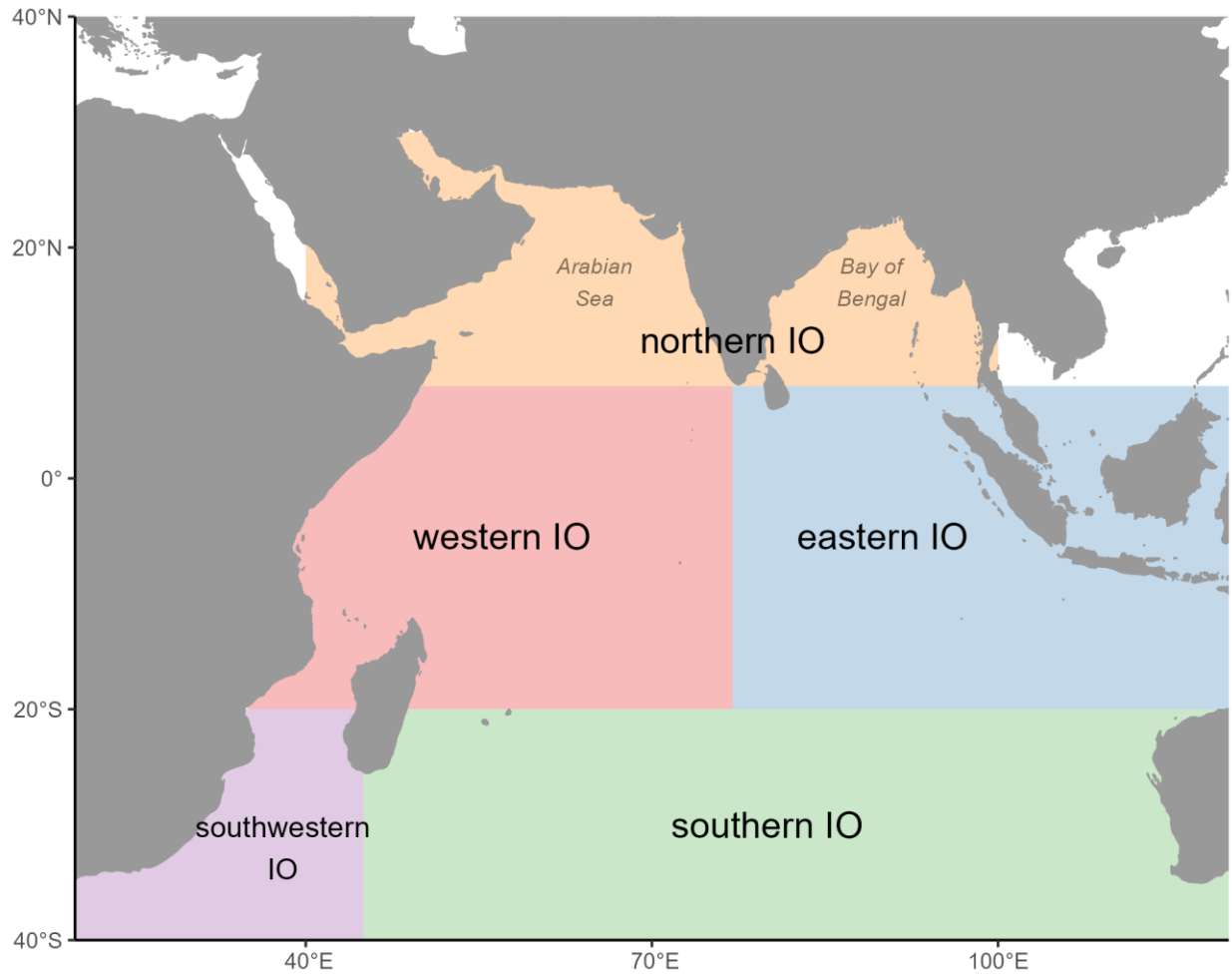| Fishery name	Fishery code
Longline (fresh tuna)	LF
Longline (distant waters)	LL
Purse-seine (free school)	FS
Purse-seine (FADs)	LS
Baitboat	BB
Gillnet	GI
Handline	HD
Troll	TR
Others	OT

10. Figures

Figure 1: Delimited zones in the Indian Ocean (IO) used in this study. This delimination does not necessarily follow any biological or fishery criteria.
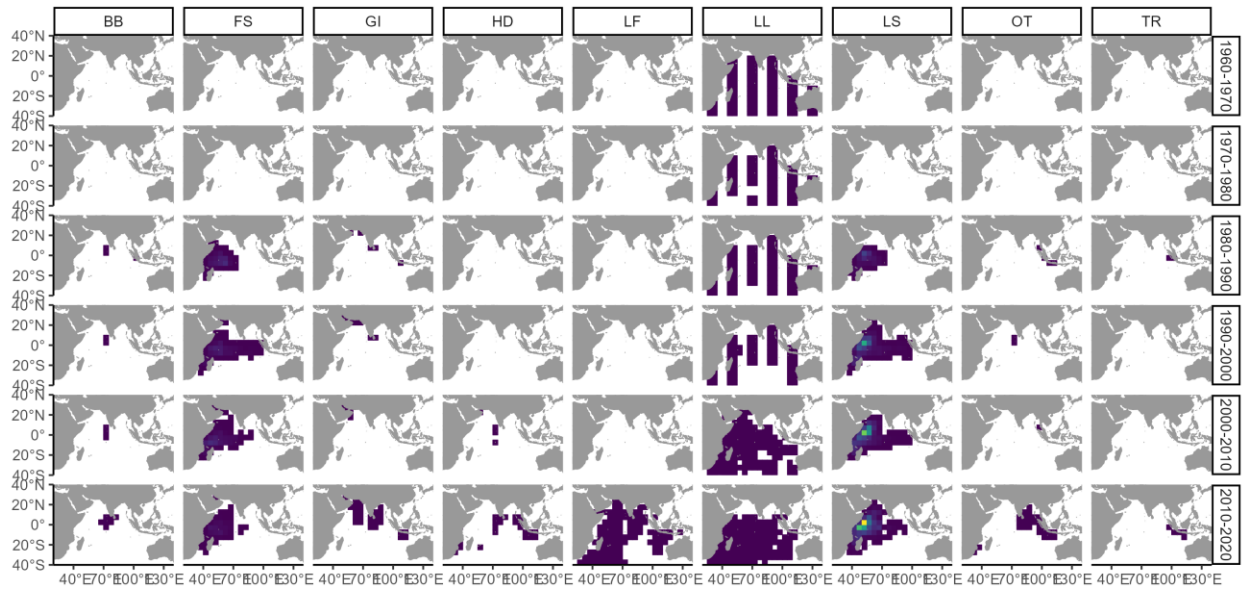
Figure 2: Sample size of length frequency per grid, decade, and fleet.
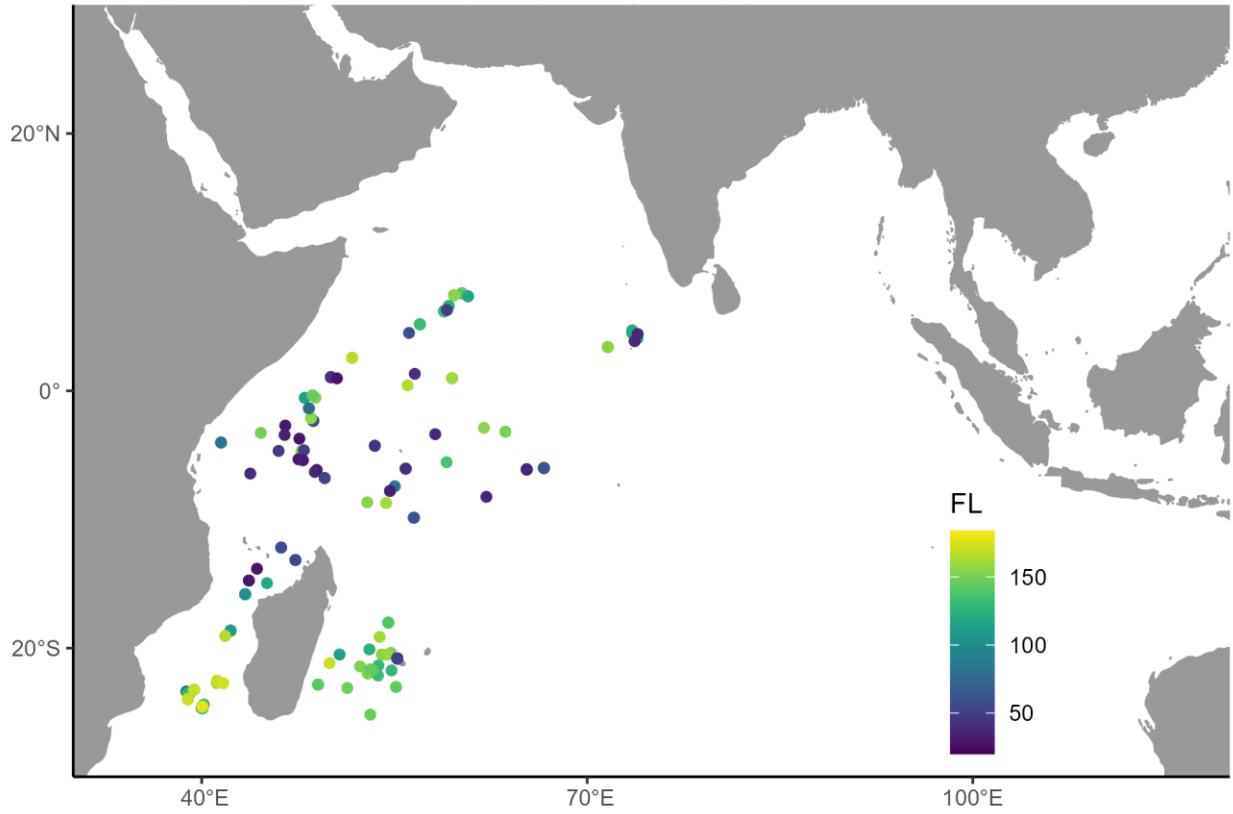
Figure 3: Age-length sampling locations. Fork length (FL) is shown.
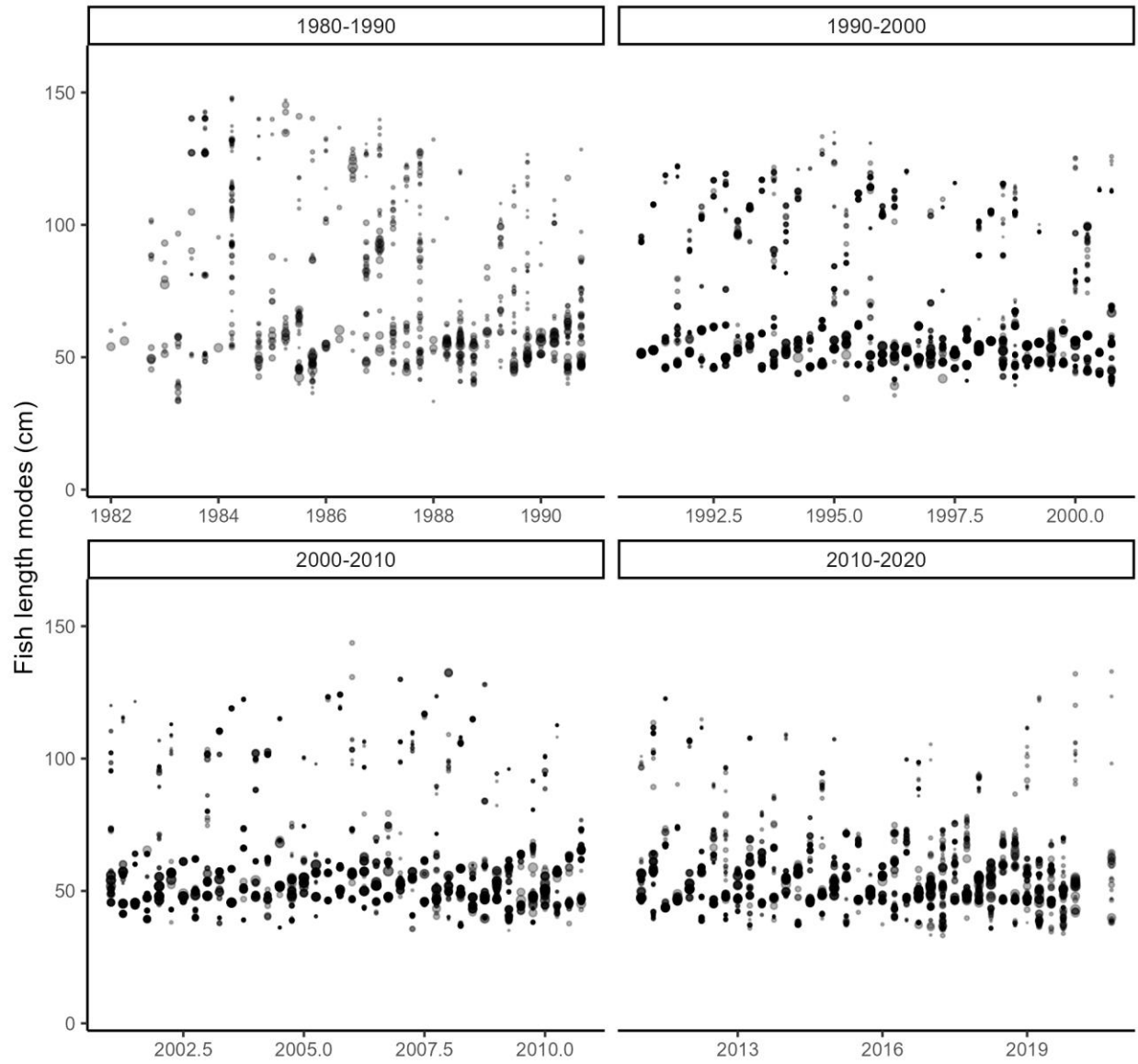
Figure 4: Modes in length frequency by grid for the LS fishery (back circles). Modes are shown by quarter and decade.
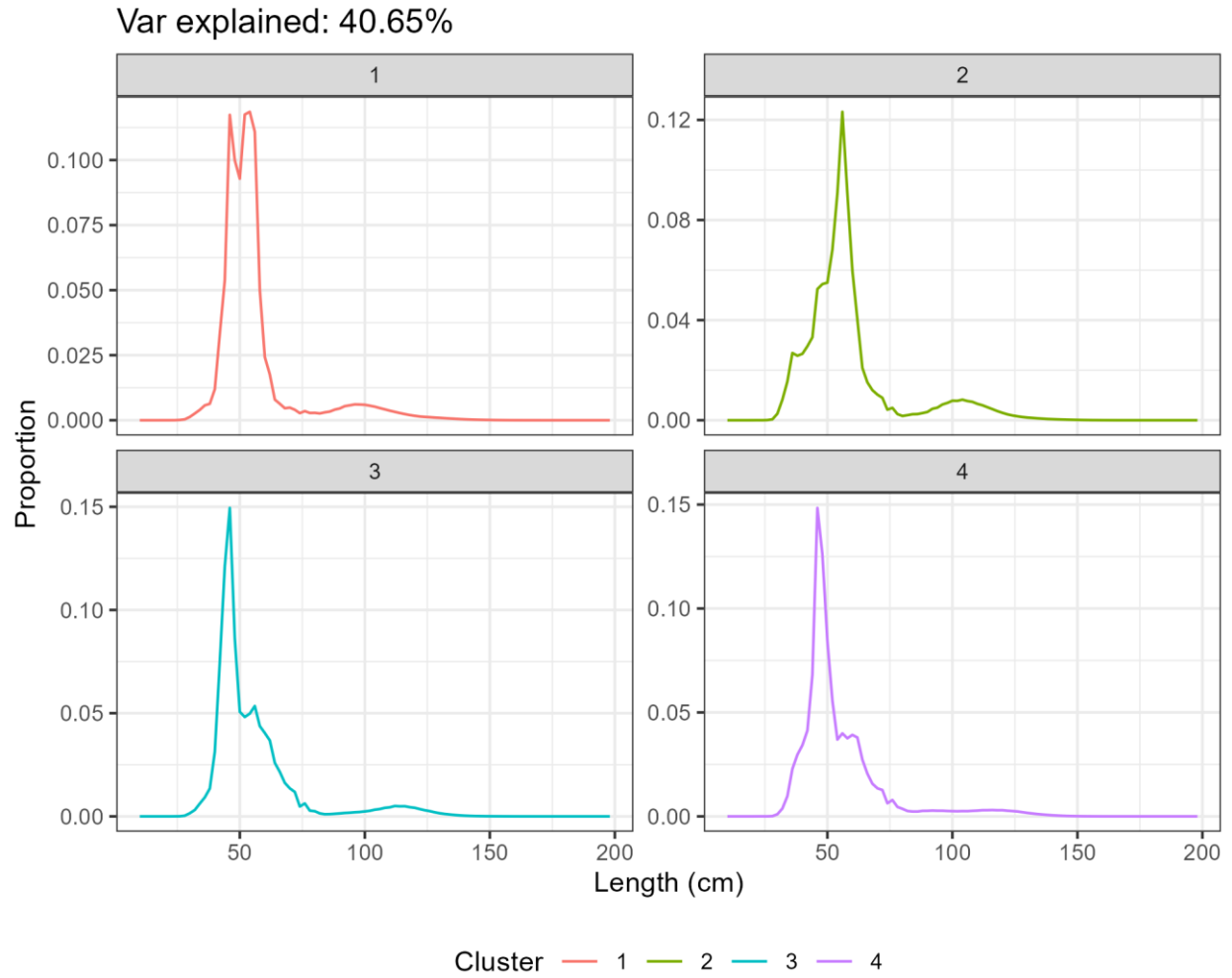
Figure 5: Clustering of length compositions for the LS fishery. Panels correspond to quarters. Four clusters were identified and split by quarter (colors).
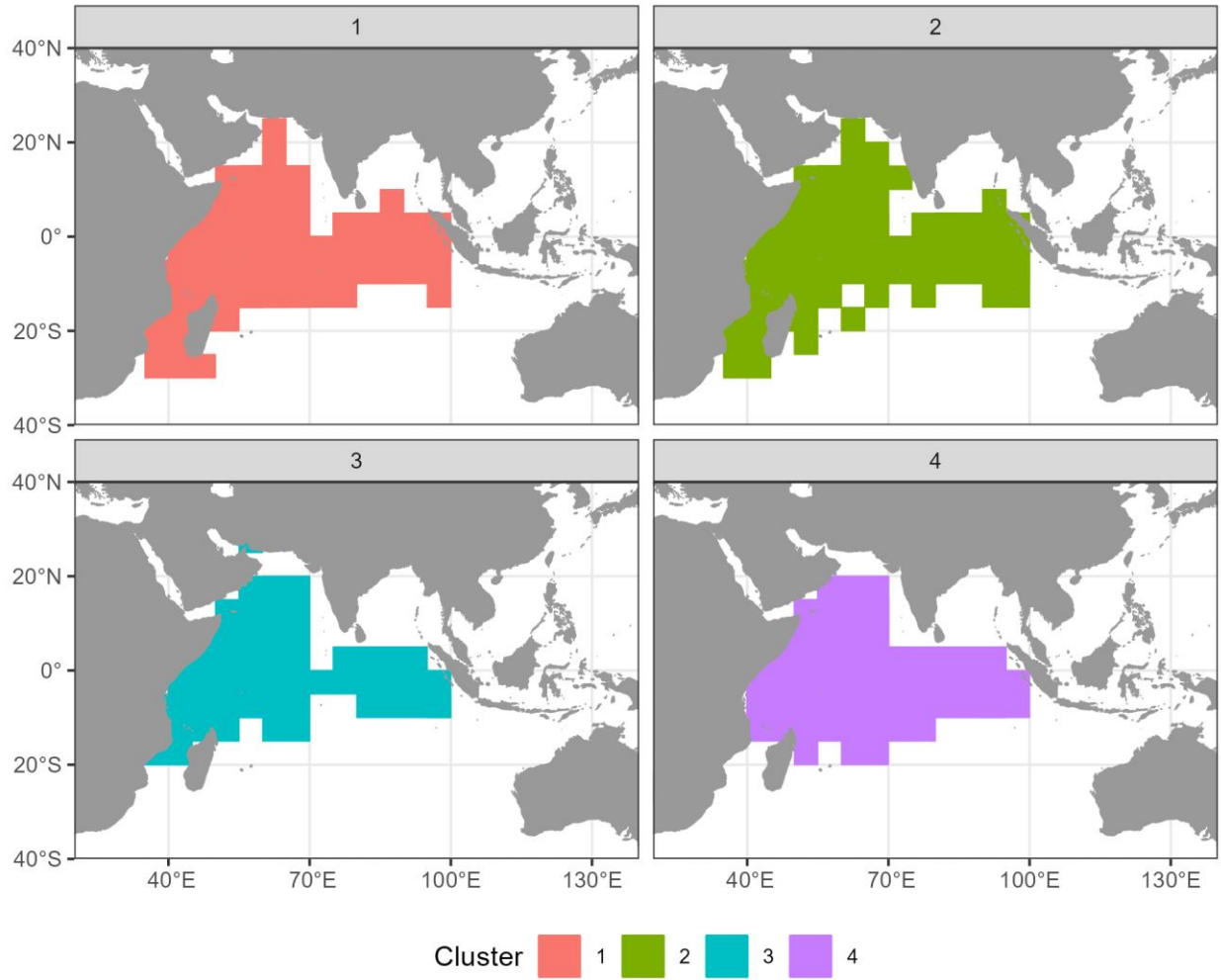
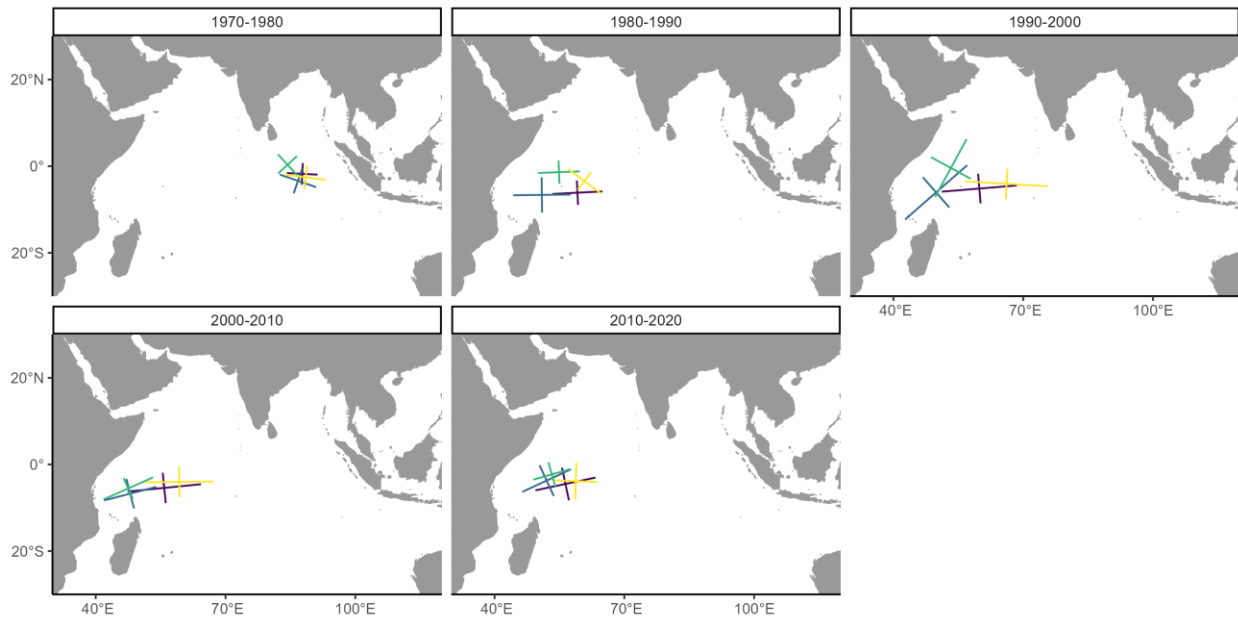Figure 6: Clustering of length compositions for the LS fishery shown over space. Panels correspond to quarters.
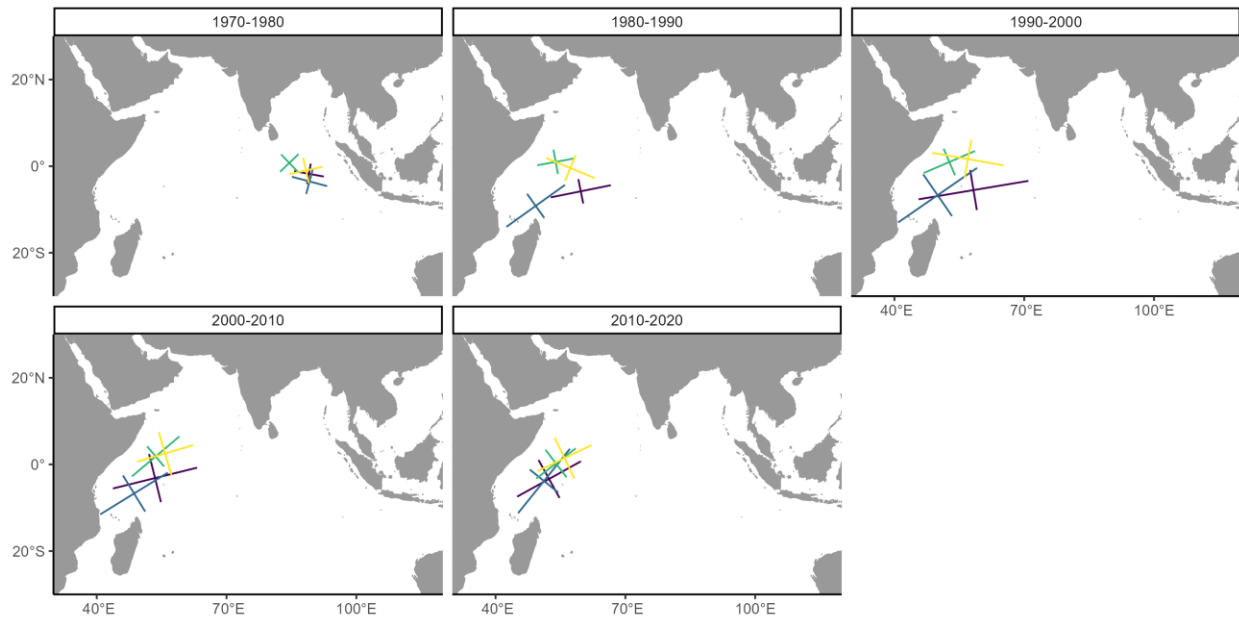
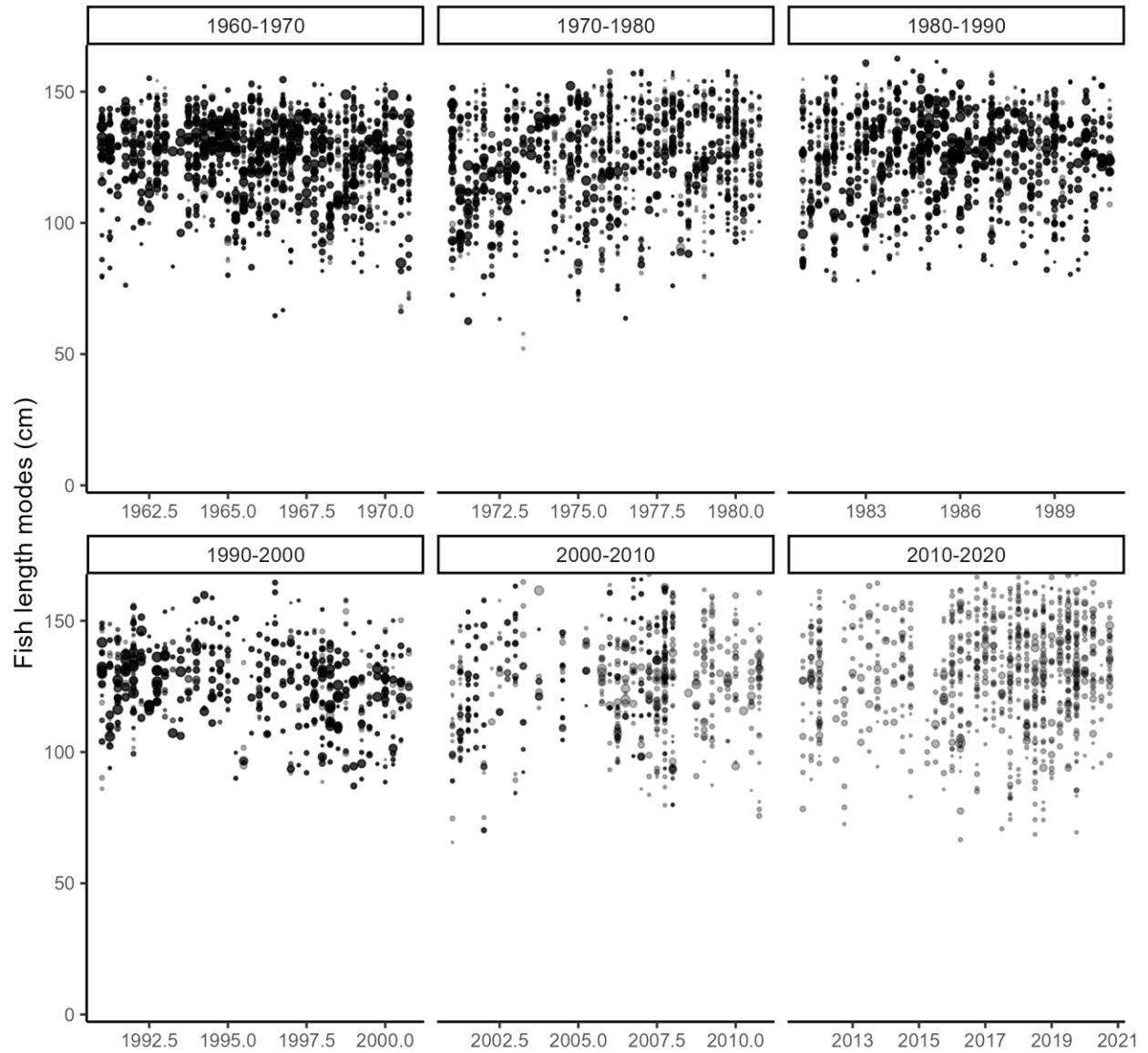Figure 7: Center of gravity of catches for the LS fleet by decade.
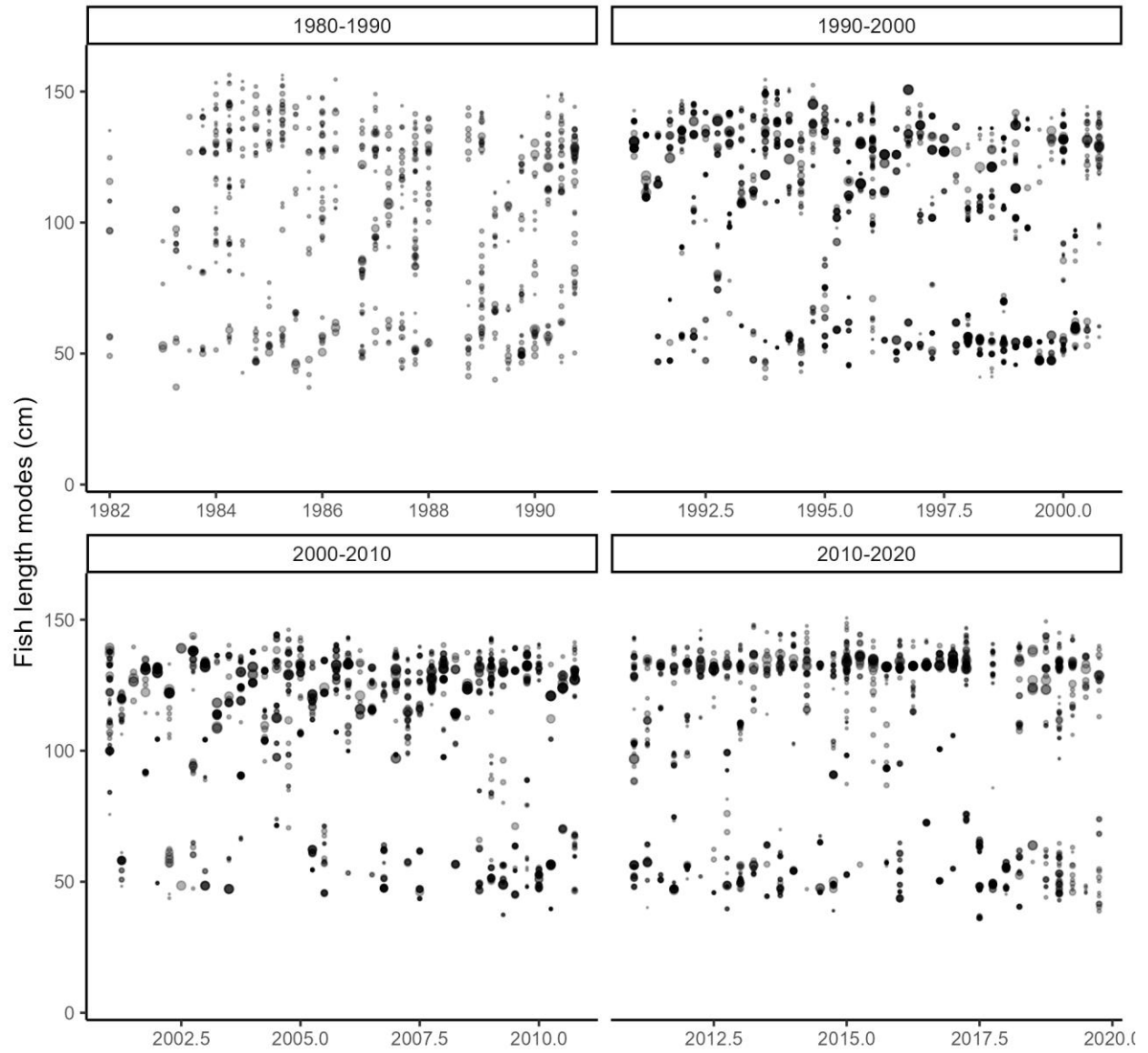
Figure 8: Modes in length frequency by grid for the FS fishery (back circles). Modes are shown by quarter and decade.
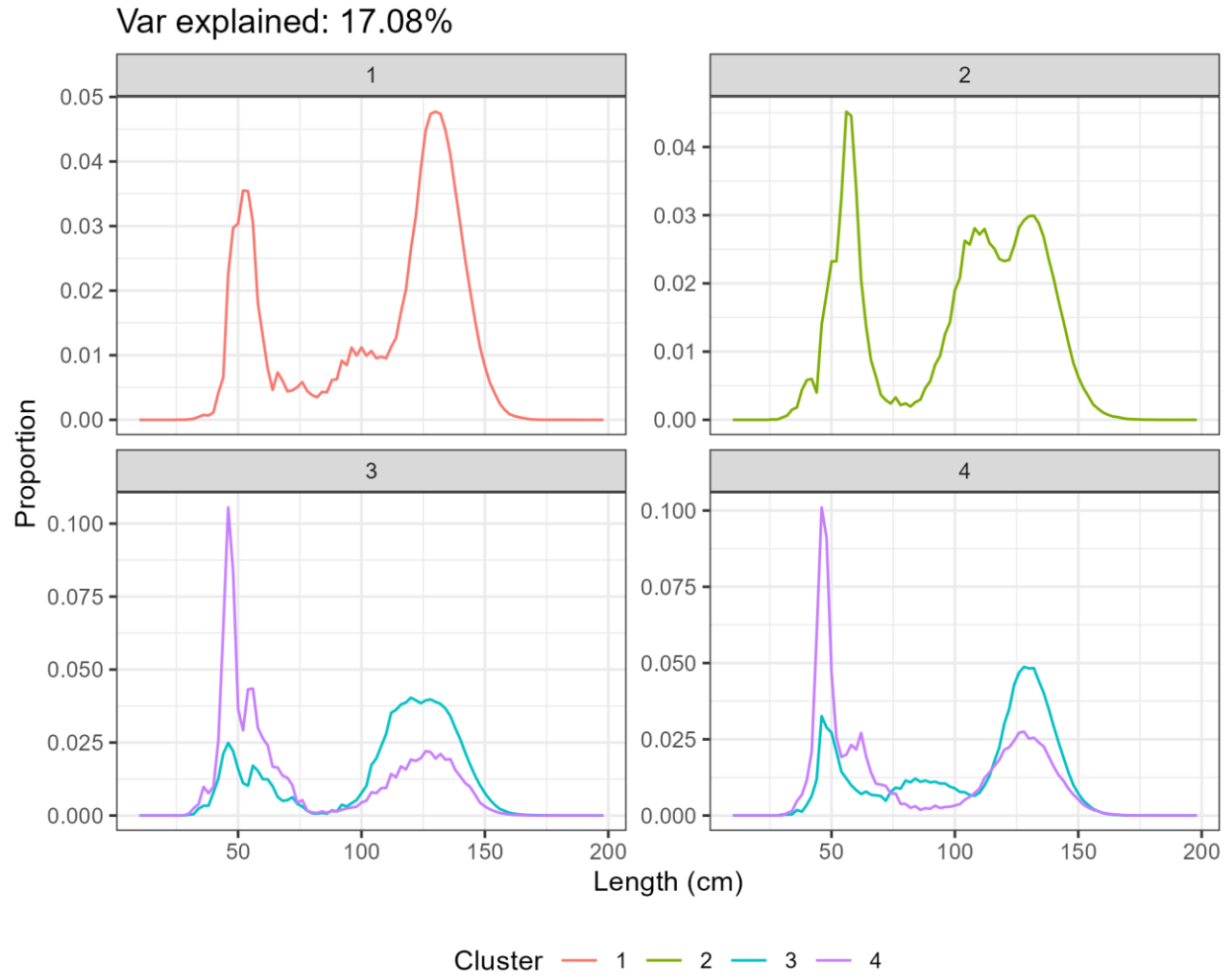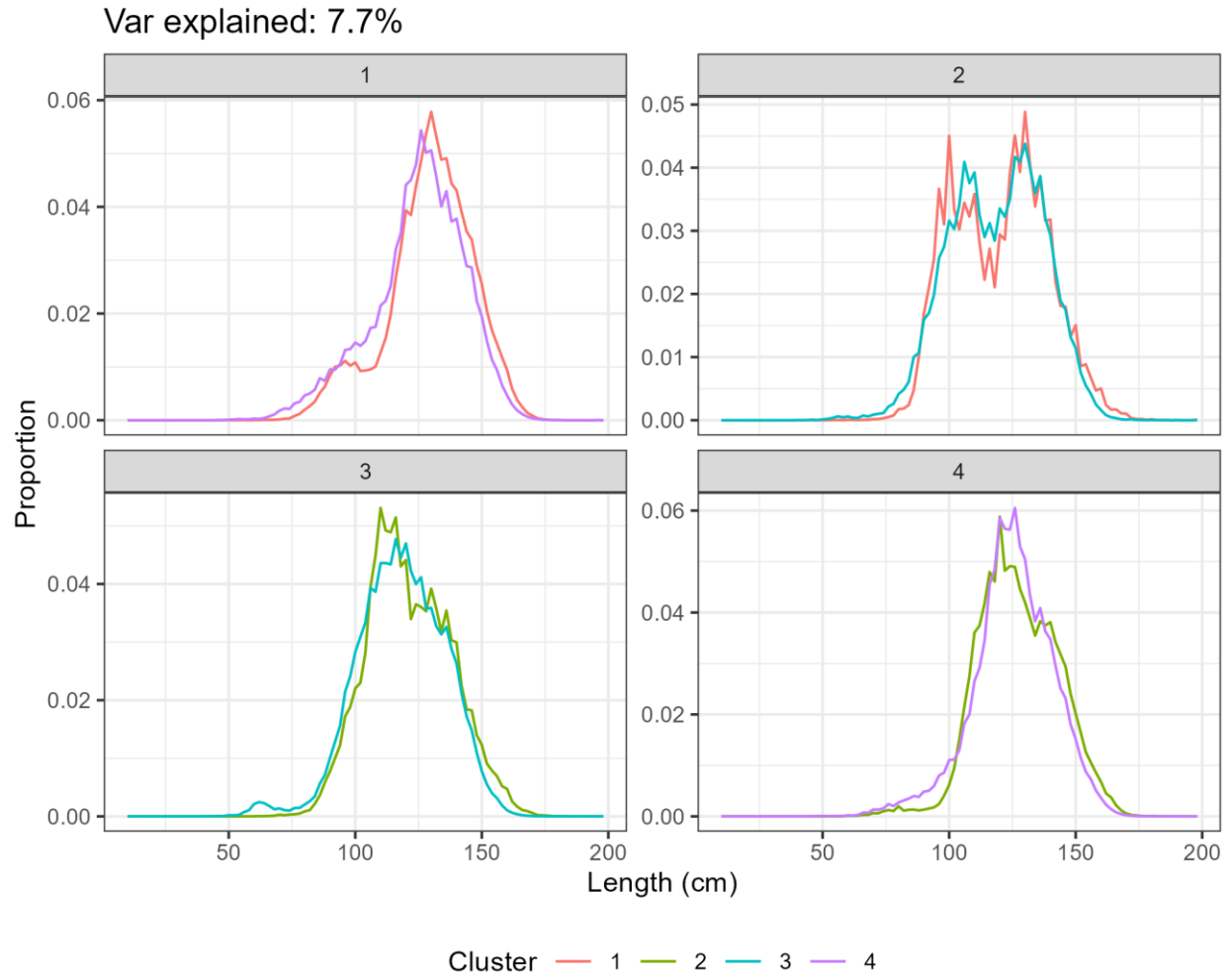
Figure 9: Clustering of length compositions for the FS fishery. Panels correspond to quarters. Four clusters were identified and split by area and quarter (colors).
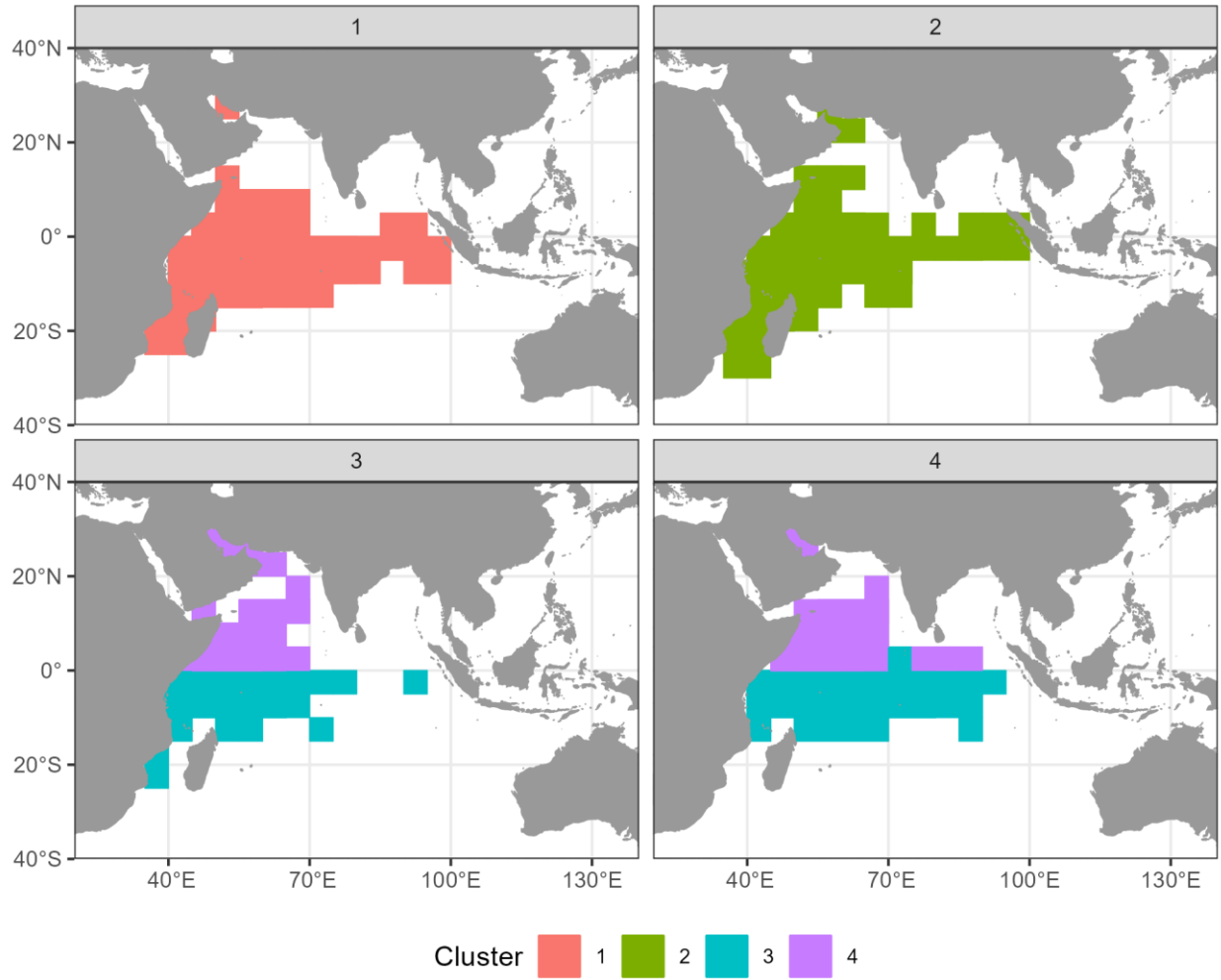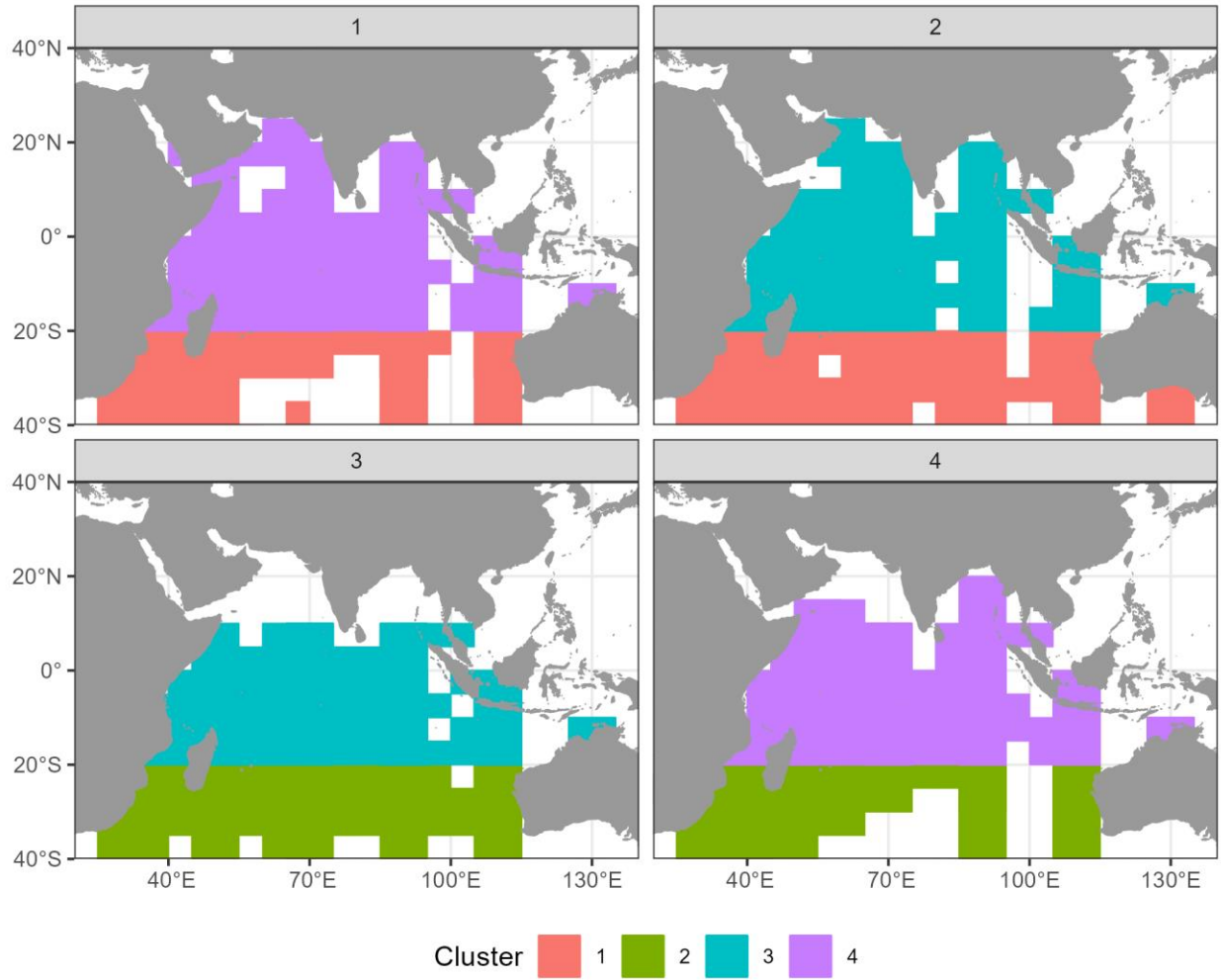
Figure 10: Clustering of length compositions for the FS fishery shown over space. Panels correspond to quarters.

Figure 11: Center of gravity of catches for the FS fleet by decade.

Figure 12: Modes in length frequency by grid for the LL fishery (back circles). Modes are shown by quarter and decade.

Figure 13: Clustering of length compositions for the LL fishery. Panels correspond to quarters. Four clusters were identified and split by area and quarter (colors).

Figure 14: Clustering of length compositions for the LL fishery shown over space. Panels correspond to quarters.
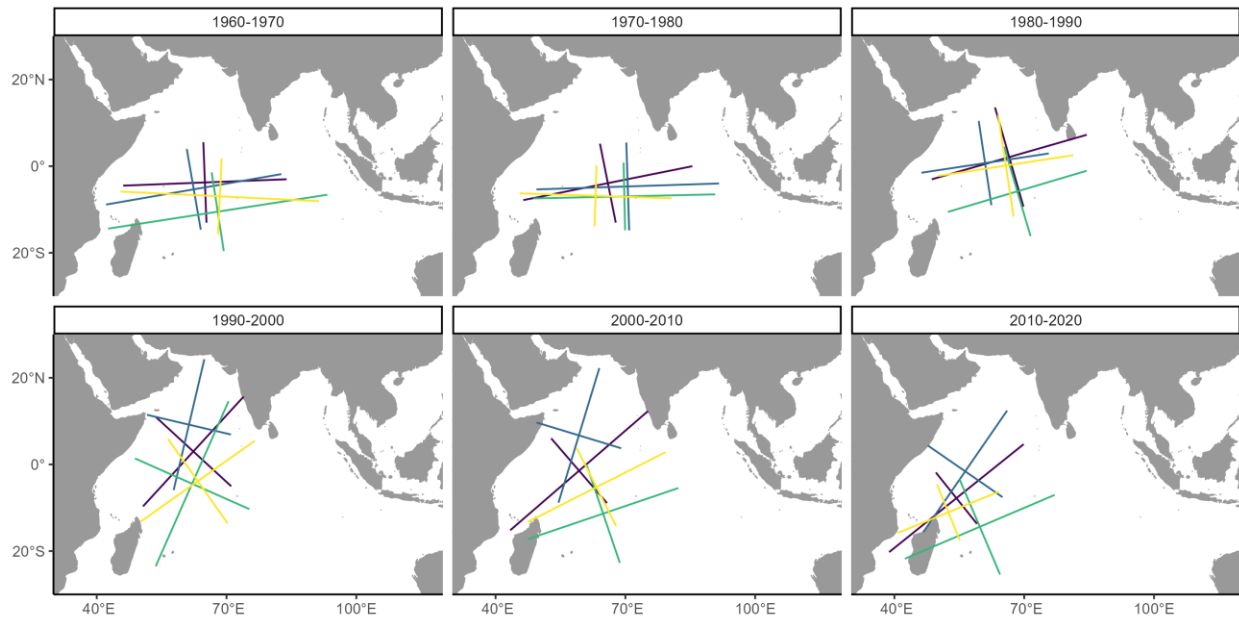
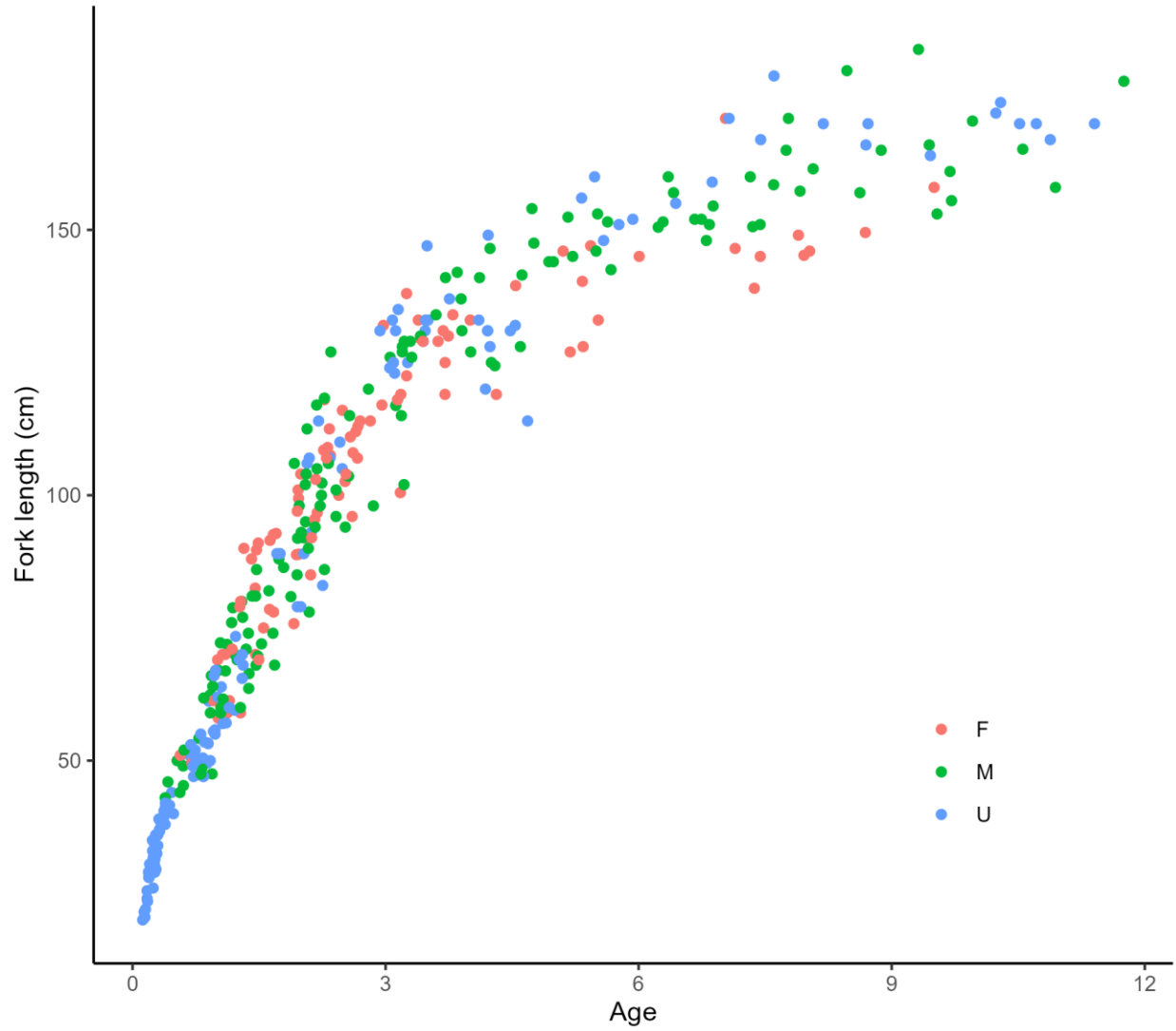Figure 15: Center of gravity of catches for the LL fleet by decade.

Figure 16: Observed length at age (years) by Farley et al. (2023) differentiated by sex (F=females, M=males, U=undefined).