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REVIEW OF THE STOCK ASSESSMENT OF BIGEYE TUNA IN THE EASTERN PACIFIC OCEAN

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A STOCK STRUCTURE FOR BIGEYE TUNA IN THE EASTERN PACIFIC OCEAN

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CONTENTS

1. INTRODUCTION

Here we review all the information that supports heterogenous spatial structure for bigeye tuna in the eastern Pacific Ocean (EPO), and we propose a spatial stratification to be used in a spatial model for the population dynamics of bigeye in the EPO .

The one-area model currently used to assess the bigeye stock in the EPO has shown a persistent two-stage pattern in recruitment, with much larger recruitments after the mid-1990s, coincident with the expansion of the purse-seine fleet that fishes on floating objects in the equatorial EPO west of the Galapagos Islands. At the same time, the main longline fleets have retracted their operations towards the west and south. The indices of abundance for the stock assessment are obtained only from the Japanese longline fleets in the central and southern areas, which are not the main areas of operation of the purse-seine fleets fishing on tunas associated with floating objects. This causes a "spatial mismatch" in the model as the increased catches of the purse-seine fleet do not translate into the indices of abundance derived from the longline fleet. There is evidence from fisheries data of more localized dynamics that coincides with evidence from tagging data, and that indicates that the model misspecification may be resolved by using a spatial model (Aires-da-Silva and Maunder 2010; Valero *et al*. 2018).

2. EVIDENCE OF SPATIAL STRUCTURE

2.1 Tagging data

During 2000-2006, scientists of the Inter-American Tropical Tuna Commission (IATTC) staff made tagging cruises in the equatorial EPO (Schaefer and Fuller 2009). From 2008 to 2012, the IATTC staff participated in a regional tuna tagging program for the equatorial central and western Pacific Ocean undertaken by the Oceanic Fisheries Program of the Secretariat of the Pacific Community (Schaefer *et al.* 2015).

Those studies indicate that bigeye in the equatorial region move longer distances longitudinally than latitudinally. Most of the fish (95%) tagged at 95°W with conventional tags stayed east of 110°W (Figure 1). The fish tagged at 140°W with conventional tags moved preferentially eastward. The purse-seine effort east of 110°W is about 4 times greater than west of 110°W, which increases the likelihood of tagged fish being caught. Taking this into consideration, the quarterly movement rate eastward across 110°W for fish with conventional tags released at 140°W was estimated to be 0.159, while that eastward across 120°W was estimated to be 0.229, about 45% greater (Xu *et al.* in prep., Figure 1), indicating that the 110°W boundary is less traversed. The fish tagged with archival tags at 140°W also showed eastward movements. Similarly, those tagged with archival tags at 95°W stayed mostly east of 110°W (Figure 2). These results support a longitudinal boundary at 110°W for the spatial structure of bigeye tuna in the EPO. As the fish recaptured in those experiments were almost exclusively juveniles, conclusions based on tagging data are valid for fish of those ages.

Both the archival and conventional tag results show that bigeye tend to stay between 10°N and 10°S (Figures 1 and 2). A 5°S boundary may also be supported by the data. Of the fish that were tagged with conventional tags at 95°W from 2°N to 5°S and were at liberty more than 6 months, 2.4% moved south of 5°S and 0.5% moved south of 10°S. Of those tagged at 140°W, 7.1% moved south of 5°S and 1% moved south of 10°S. None of the most likely positions of the fish with archival tags are south of 10°S, but some are between 10°S and 5°S (Figure 2). Similarly, for the northern boundary, fish tagged in the equatorial region do not move north of 10°N.

Tagging studies in Hawaii (Itano and Holland, 2000, Howell *et al*. 2010) showed that fish tend to stay in the temperate areas and do not move to the equatorial areas of the EPO, and may occasionaly move to the central Pacific Ocean (Figure 3). Fish tagged in the equatorial areas have not been recovered by the Hawaiian fisheries. These results also support a northern boundary (Schaefer *et al.* 2015).

Unpublished tagging data from Japan indicate that bigeye tend to move along the meridians and stay at about the same latitude at which they were released. Of the 13 fish released north of 10°N and recovered, only one moved to the equator, the rest stayed north (Figure 4). Of the four fish released between 7°S and 10°S and recovered, one was recovered south of 10°S. Of the 15 fish released south of 10°S, nine were recovered south of that parallel, one around the equator, and five around 8-9°S. All fish released east of 110°W moved further east. These data indicate regional fidelity and a tendency for bigeye to move along the meridians (east-west). They also support a northern boundary with limited crossing movements, but a more porous southern boundary with fish diffusion across it.

In summary, the results from the tagging data support dividing the area between 10°N and 10°S from the areas to the north and south, with the caveat that not many tagged fish were released south of 5°S. The tagging data support an east-west split at 110°W.

2.2 Fisheries data

We assume that any spatial heterogeneity of bigeye tuna stock structure should result in differences in size composition and catch rate trends of fisheries in space, if the selectivity and/or catchability are constant over the area. Following this assumption, spatial pattern in length-frequency distributions and trends in catch per unit of effort (CPUE) from purse-seine sets on floating objects and longline fisheries were analyzed using a multivariate regression tree approach (see Lennert-Cody *et al.* 2013 for details of the methodology). The purse-seine and longline data were analyzed separately. In addition to spatial predictors (longitude and latitude), quarter was also included in the regression tree analyses to allow for identification of seasonal pattern.

2.2.1 Purse-seine data from floating-object sets

Tree analyses were applied to data for 2000 – 2017. The tree analyses of CPUE trends were unstable and thus not considered further. The tree analysis of the length-frequency distributions supports a split at 110°W (Table 1). The length composition of the catch west of that meridian is dominated by smaller fish, while to the east of that meridian, the range of lengths in the catch is broader (Figure 5). For the area east of 110°W, the analysis identified another longitudinal partition at 90°W, and for the area west of 110°W, an aditional longitudinal partition at 125°W (Table 1). The areas west of 110°W have smaller fish, with a mode below 50 cm. The area between 110°W – 90°W has a mode at 50 cm or larger, there are some fish above 100 cm. In the area from 90°W to the coast there is a wide distribution of sizes, dominated by fish larger than 100 cm in several years, but with a large proportion of fish smaller than 50 cm mostly after 2012 (Figure 5).

2.2.2 Longline data

The available CPUE and size-composition data for longline fisheries come from the Japanese fleets (commercial vessels and training vessels) and were split into two periods. Only the commercial fleet's data were used. The first period is from 1975 to 1991, when the Japanese longline fleet operated in a wider area of the EPO, and a late period from 1996 to 2016, after the expansion of the purse-seine fleet and retraction of the longline fleet towards the western part of the EPO. In general, in the early period the fleet used from 10 to 12 hooks between floats, whereas in the late period the number of hooks between floats ranged from 16 to 17, after a couple of years of transition (Lennert-Cody *et al*. 2014). Changes in the number of hooks between floats have varied spatially, as well as temporally (Figure 6). There have been some changes in the species composition of the Japanese longline catch, as well. For example, in recent years there was an increase the proportion of albacore catches off Peru and Ecuador, and in the tropical EPO, and a decrease in the proportion of bigeye off Peru and Ecuador (Satoh *et al*. 2017, SAC-08-05a presentation).

Although multivariate tree analyses were applied to data from both time periods, the results of the analyes for the early period are considered more representative because of the greater spatial coverage of the EPO, compared to that for the later period. The analyses for the early period support a longitudinal partition at 110°W (Table 2). West of that meridian, those data support latitudinal partitions at 10°N and 10°S; south of 10°N, the second best partition was at 5°S. East of 110°W the data support a partition at 15°S.

An analysis of the deviations from the overall mean of the nominal CPUE per quarter in space shows that the area east of 110°W and south of 10°S is more homogeneous than if the area was expanded to south of 5°S (Figure 7), during quarters 1 and 3.

3. ASSUMPTIONS FOR THE SPATIAL STRUCTURE FOR THE NEW BIGEYE TUNA MODEL

Based on the evidence from the tagging data in conjunction with the supporting information derived from the early Japanese longline data, as well as from the purse-seine data on floating objects, the first spatial partition of the EPO should be 110°W. For the area west of 110°W, there is evidence for several latitudinal partitions. A split at 10°N is suggested based on the evidence from the tagging data and the longline data. The tagging data also suggest that the fish from the area around Hawaii do not mix, or mix at negligible rates, with those from the equatorial area, and thus the longline catches from the area north of 10°N should not be considered in the spatial stock assessment model for bigeye tuna in the EPO. The area north of 10°N has a negligible amount of purse-seine catch (Figure 8), and therefore all purse-seine catches coming from this area could be added to the area south of 10°N. The 10°N boundary also coincides with the assumption the Western and Central Pacific Fisheries Commission made in its 2017 assessment of bigeye tuna (McKechnie *et al* 2017), which provides a practical support for this boundary as it could facilitate development of a Pacific-wide assessment model in the future.

South of 10°N and west of 110°W, a southern boundary for the equatorial EPO is partially supported by the tagging data (Figures 1, 3 and 4). However, the tagging data do not extend much beyond 5°S, making it difficult to use these data to establish exactly the best latitudinal boundary. The analyses of the longline data support a boundary at 10°S, which would also coincide with the boundary used in the Western and Central Pacific Ocean (WCPO) assessment (Table 2). Therefore, for the area west of 110°W, we suggest boundaries at 10°S and 10°N should be implemented, following from analyses of tagging data, longline data, and the practical consideration that these boundaries coincide with boundaries used in the the WCPO bigeye tuna assessment, which could facilitate a Pacific-wide assessment in the future.

For the area east of 110°W, we suggest a latitudinal boundary at 10°S. The tagging data east of 110°W suggest a northern boundary (Figures 1, 3). However, the catches of bigeye tuna by both purse-seiners and longliners since 1975 are small in this area. Therefore, as a simplifing assumption, a northern boundary should not be assumed east of 110°W. A southern boundary is partially supported by the tagging data (Figure 1, 3 and 4), however, as noted above, the precise location of this boundary is not possible to determine from these data. The tree analyses of the longline data support a boundary at 15°S, however, having a step change from 15°S east of 110°W to 10°S west of 110°W would be difficult to implement in the assessment (see Discussion below). Therefore, as a practical simplification, we suggest a latitudinal boundary at 10°S east of 110°W.

Finally, we interpret the results of the tree analyses of the longline and purse-seine data east of 110°W to indicate the southeast corner of the EPO (east of 90°W and south of 15°S) to be spatially distinct. The longline analyses suggest the best partition to be at 15°S (Table 2), while the purse-seine length-frequency analysis suggests the best partition to be at 90°W (Table 1). Given the spatial distribution of catches south of 10°S and east of 110°W, the results of these two analyses point to the need for a spatial treatment that separates the southeast corner of this region. We therefore suggest that for the area east of 90°W and south of 15°S, an "area-as-fishery" should be defined; *i.e.*, an area where different selectivity is assumed but is is not an explict area, that will require movement rates to be estimated. The selectivity assumption would accommodate the heterogeneity detected by the tree analyses. Movement rates could not be estimated at this time for thise areas as there is no tagging data available.

The spatial stratification proposed for the spatially-explicit stock assessment model is summarized in Figure 8, where the boundaries can be compared to the overall spatial distributions of longline and purse-seine catches. This configuration seems to delimit well most of the high CPUE areas for the Japanese fleet (Figure 9).

4. DISCUSSION

In this study, we propose spatial stratification assumptions based on evidence about regional dynamics from tagging data and spatial pattern in fisheries data, as well as some practical considerations, to be used in the spatial-explicit stock assessment model for bigeye tuna in the Eastern Pacific Ocean. Most of the boundaries are supported by multiple data sources. Some of the boundaries are not as clear as others and it was necessary to make decisions based on practical considerations. The "step" in the partition of the southern boundary (15°S east of 110°W and 10°S west of 110°W) is also supported by the oceanographic characteristic of the area, that is highly influenced seasonally by the Humboldt current that comes south from the coast of South America and turns towards the west seasonally, but is not practical to include in a spatial model because there is no tagging data that could be used to estimate to estimate movement rates. Instead, it we propose that the southeast corner, west of 90°W and south of 15°S, be considered a "fishery", so to accommodate the heterogeneity by using a separate selectivity function.

All the other three tRFMOs that manage tropical tunas have used spatial models to assess bigeye tuna at some point. Like in the EPO, in all three oceans the purse-seine fleets that set on floating-object-associated tunas seem to concentrate in areas with oceanographic conditions consisting of a mix of currents where high productivity exists (Indian Ocean - around Madagascar, Atlantic Ocean – close to Senegal, Pacific Ocean - around and west of the Galapagos Islands). The models from the three t-RFMOs in general separate the tropical and the temperate areas, and two models also split the equatorial area logitudinaly (Indian Ocean and Western and Central Pacific Ocean) (Figure 10).

Atlantic Ocean: The spatial model used as one of the candidates to assess the bigeye tuna stock in the Atlantic (Schirripa, 2016) mainly separated the tropical and temperate areas and considered a northern area North of 25^{o}N, a central area between 25^{o}N and 15^{o}S, and a southern area south of 15^{o}S. The model was not fit to tagging data considering that they were very limited and uninformative about movement. The current stock assessment model is a one area model (Report of the 2018 ICCAT bigeye tuna stock assessment meeting).

Indian Ocean: The IOTC implemented its first SS3 spatial model for the assessment of bigeye tuna in 2016 (Langley, 2016). The model has four areas and is fit to tagging data, indices of abundance and length composition, conditioned on the catches. The spatial structure is defined by temperate regions between south of 15°S and north of 35°S, and an eastern and western region in tropical areas, split at 80°E . The western region is further subdivided in two sub regions (north and south of the equator). The regions were defined to partition the spatial distribution of the main fisheries.

Western and Central Pacific Ocean: WCPFC has been using a spatial model for a long time, implemented in Multifan-CL. The most recent assessment (McKechnie *et al*, 2017) had 9 areas. The equatorial areas were defined based on the recent tagging study by Schaefer *et al* (2015) and were redefined to be between 10°N and 10°S, instead of 20°N to 20°S as it was done previously. This structure was also proposed to reflect the spatial division of the equatorial purse seine fishing zone and areas dominated by longline fishing. The model is fit to a large tagging dataset.

5. REFERENCES:

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TABLE 1. Results from the tree analysis of length-frequency distributions of the purse-seine catch from sets on tunas associated with floating objects. Shown are the best three partitions at each step in the analysis. “Scaled improvement” refers to the improvement in explaining heterogeneity in the data attributable to a partition of the data at a particular value of one of the predictors, scaled so that the maximum improvement has a value of 1.0.

Region	Scaled improvement	Rank
(a) EPO		
115ºW	0.948	2
110º W	1.000	1
100ºW	0.884	3
(b) West of 110ºW		
130ºW	0.778	3
125ºW	1.000	1
120º W	0.834	2
(c) East of 110ºW		
100ºW	0.856	2
95ºW	0.804	3
90ºW	1.000	1

TABLE 2. Results from the tree analyses for the early Japanese longline data, for length-frequency distributions only, CPUE trends only, and simultaneous analysis of both. Shown are the best three partitions at each step in the analysis or lower ranking partitions for one of the two data types that correspond to a better partition option for the simultaneous tree analysis. “Scaled improvement” refers to the improvement in explaining heterogeneity in the data attributable to a partition of the data at a particular value of one of the predictors, scaled so that the maximum improvement has a value of 1.0. “Cyclic quarters 134;2” indicates a partition on quarter where quarters 1, 3 and 4 are grouped together, and separate for quarter 2.

Region	Length-frequency	Rank	CPUE trends	Rank	Simultaneous tree	Rank
	Scaled improvement		Scaled improvement		Scaled improvement	
(a) EPO						
25°N			0.583	2		
10°N			1.000	1	0.611	2
15°S	0.865	2			0.603	3
120°W			0.457	3		
110°*W*	0.817	3	0.441	4	0.629	1
100°W	1.000	1				
(b) West of 110°W						
30°N			0.381	3		
25°N			0.537	2		
15°N	1.000	1				
10°N	0.764	2	1.000	1	0.999	1
5°N					0.462	2
5°S	0.709	3				
Cyclic quarters 134;2					0.437	3
(c) West of 110°W and south of 10°N						
0°			1.000	1	0.752	3
5°S	1.000	1	0.625	3	0.813	2
10°S	0.835	2	0.967	2	0.901	1
Cyclic Quarters 134;2	0.795	3				
(d) East of 110°W						
15°S	1.000	1	0.451	6	0.725	1
20°S	0.672	2				
90°W	0.586	3	0.785	2	0.686	2
Quarter 2			1.000	1	0.677	3
Quarter 3			0.578	3		

Figures

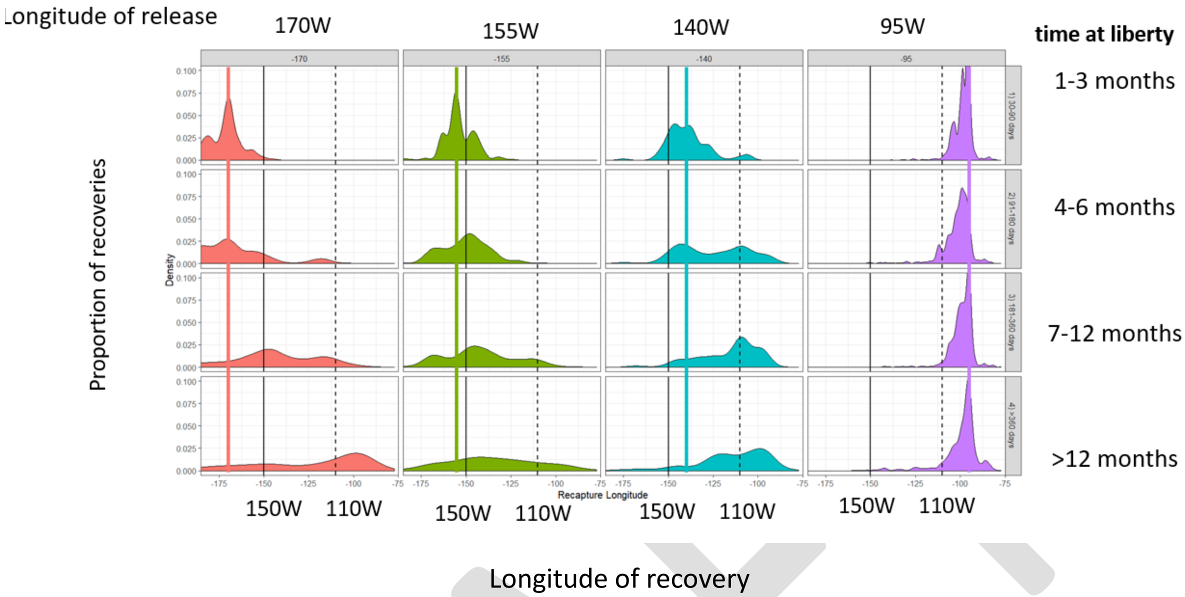

FIGURE 1. Movements of bigeye tuna inferred from conventional tag recoveries, for fish released and recovered between 95°W and 170°W, by time at liberty. The dashed vertical line indicates 110°W, and the solid vertical line the IATTC boundary at 150°W. Source: data from Schaefer *et al* (2015) and Schaefer and Fuller (2009).

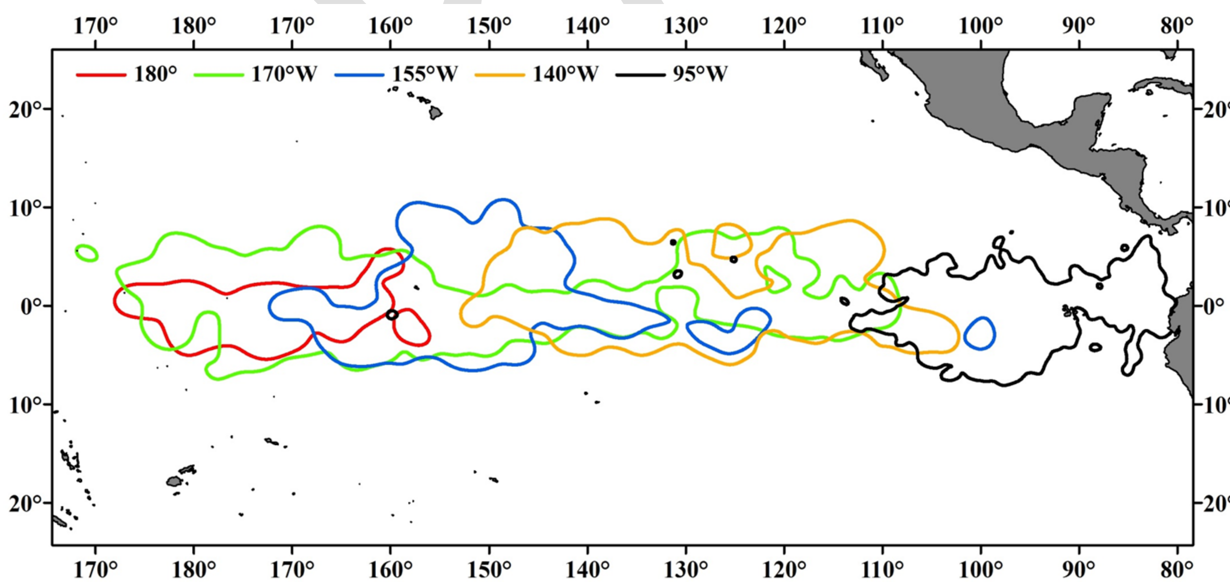

FIGURE 2. 95% volume contours, calculated from a kernel density function for all archival tag position estimates using a 1° search radius and a 0.01° output cell size, for fish with more than 30 days at liberty released at 180°W (*n*=2), 170°W (*n*=15), 155°W (*n*=15), 140°W (*n*=16) and 95°W (*n*=98). Source: data from Schaefer *et al* (2015) and Schaefer and Fuller (2009).

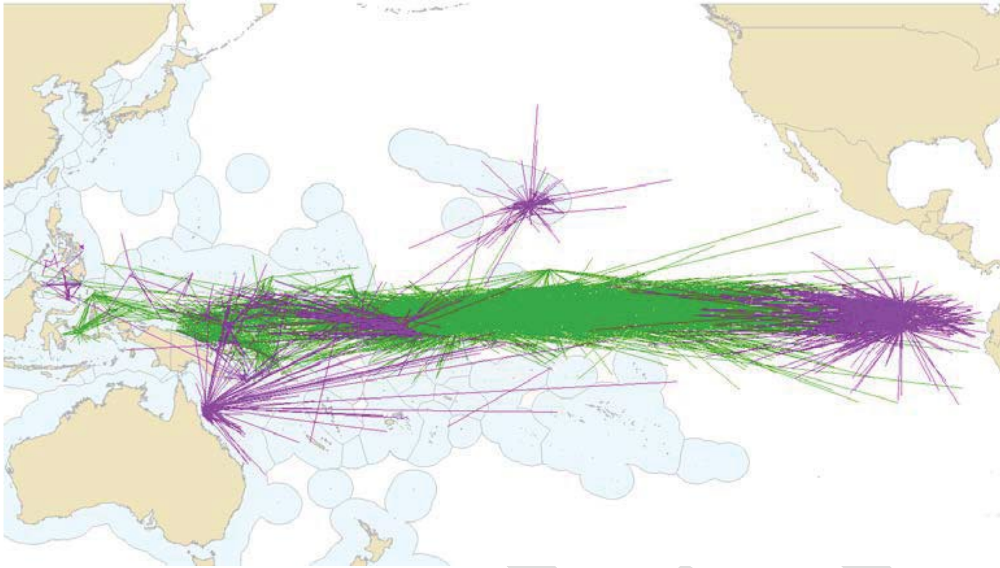

FIGURE 3. Straight-line displacements of bigeye tuna in the Pacific Ocean, derived from conventional tagging data from multiple programs reviewed during the [Workshop on Pacific Movement and Distribution](#) (Honolulu, Hawaii, USA, April 2014). Source: Western Pacific Regional Fishery Management Council 2014)

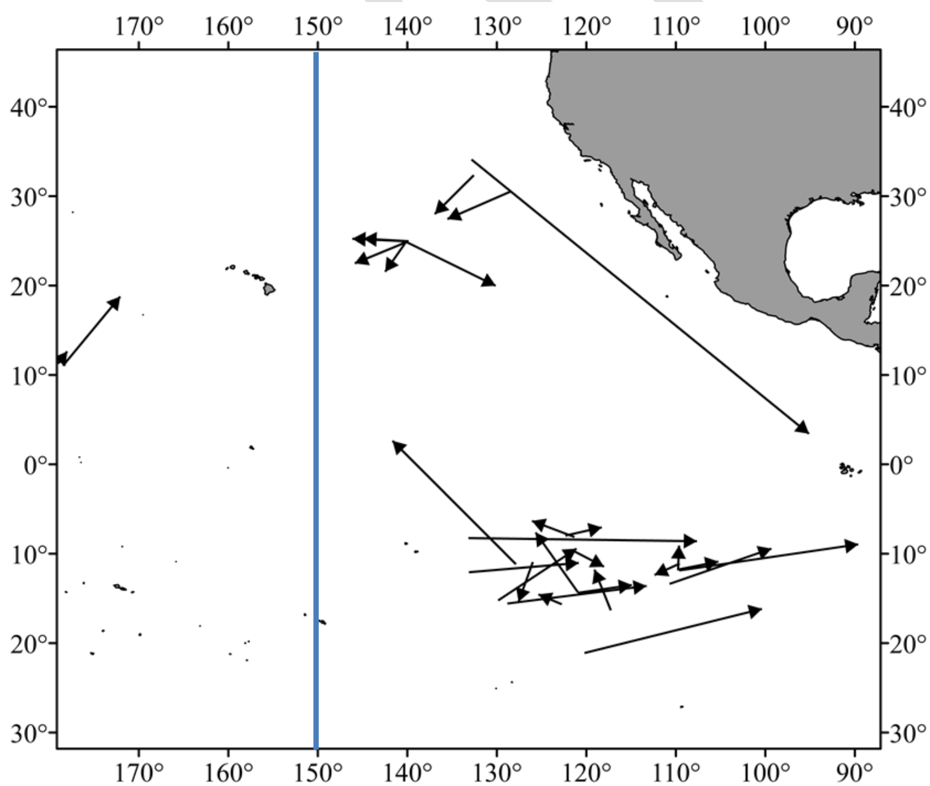

FIGURE 4. Straight-line displacements if bigeye tuna derived from conventional and archival tagging done by Japan from 1998 to 2012 (unpublished data, personal communication from K. Satoh, Far Seas Fisheries

Research Laboratory, Japan). The solid blue line is the IATTC boundary at 150°W.

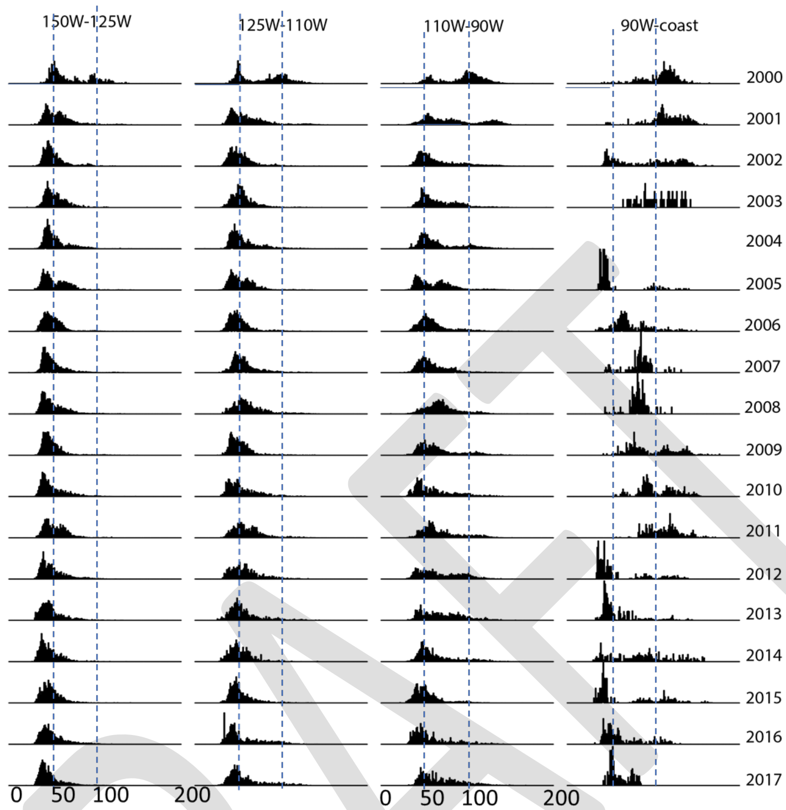

FIGURE 5. Length-frequency distributions of the purse-seine catch on floating objects, by year, for each of the four area identified in the tree analysis. The blue dashed lines indicate lengths of 50cm and 100cm.

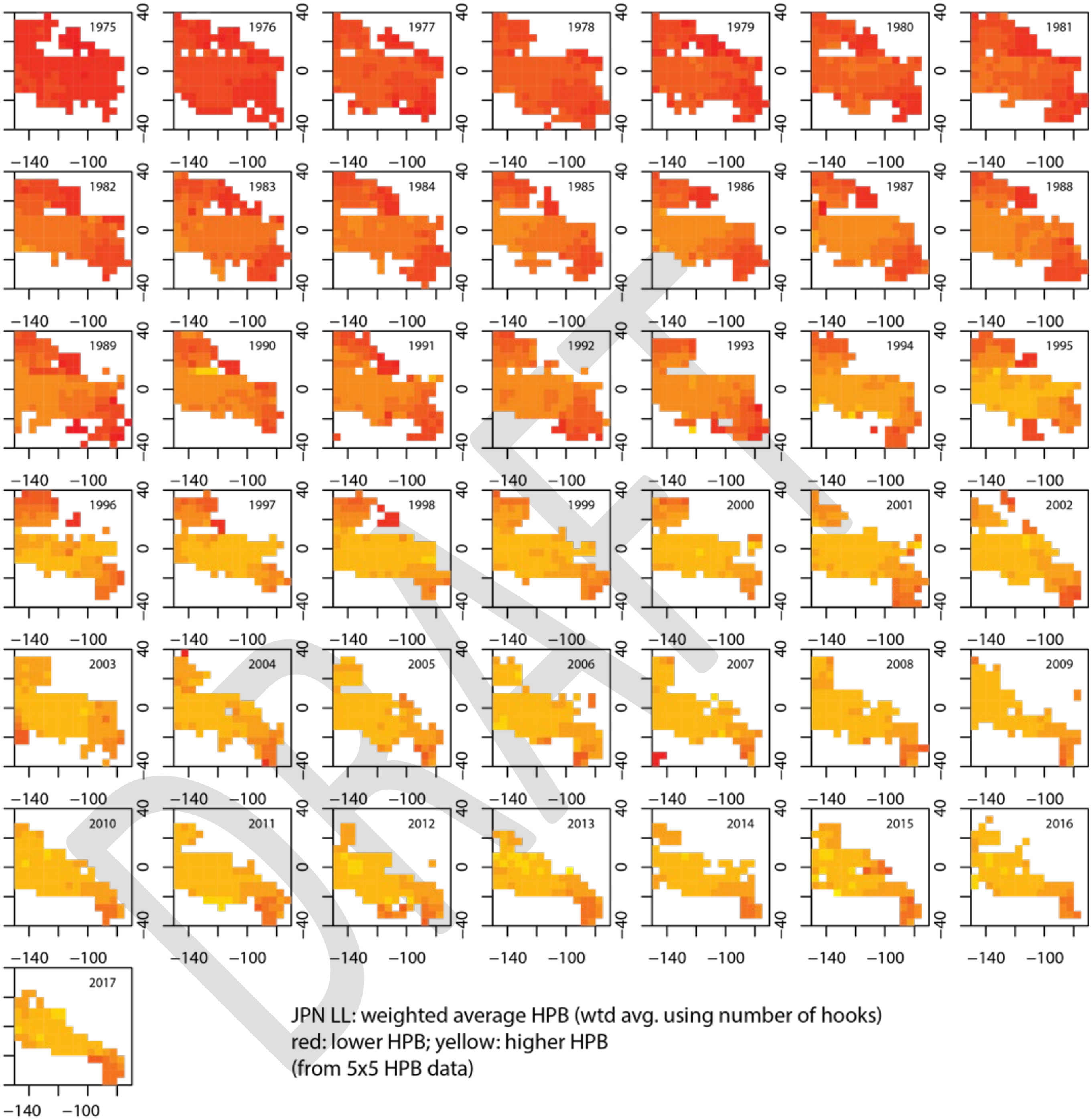

FIGURE 6. Spatial distribution of weighted average of hooks per baskets for the Japanese longline fleet by year

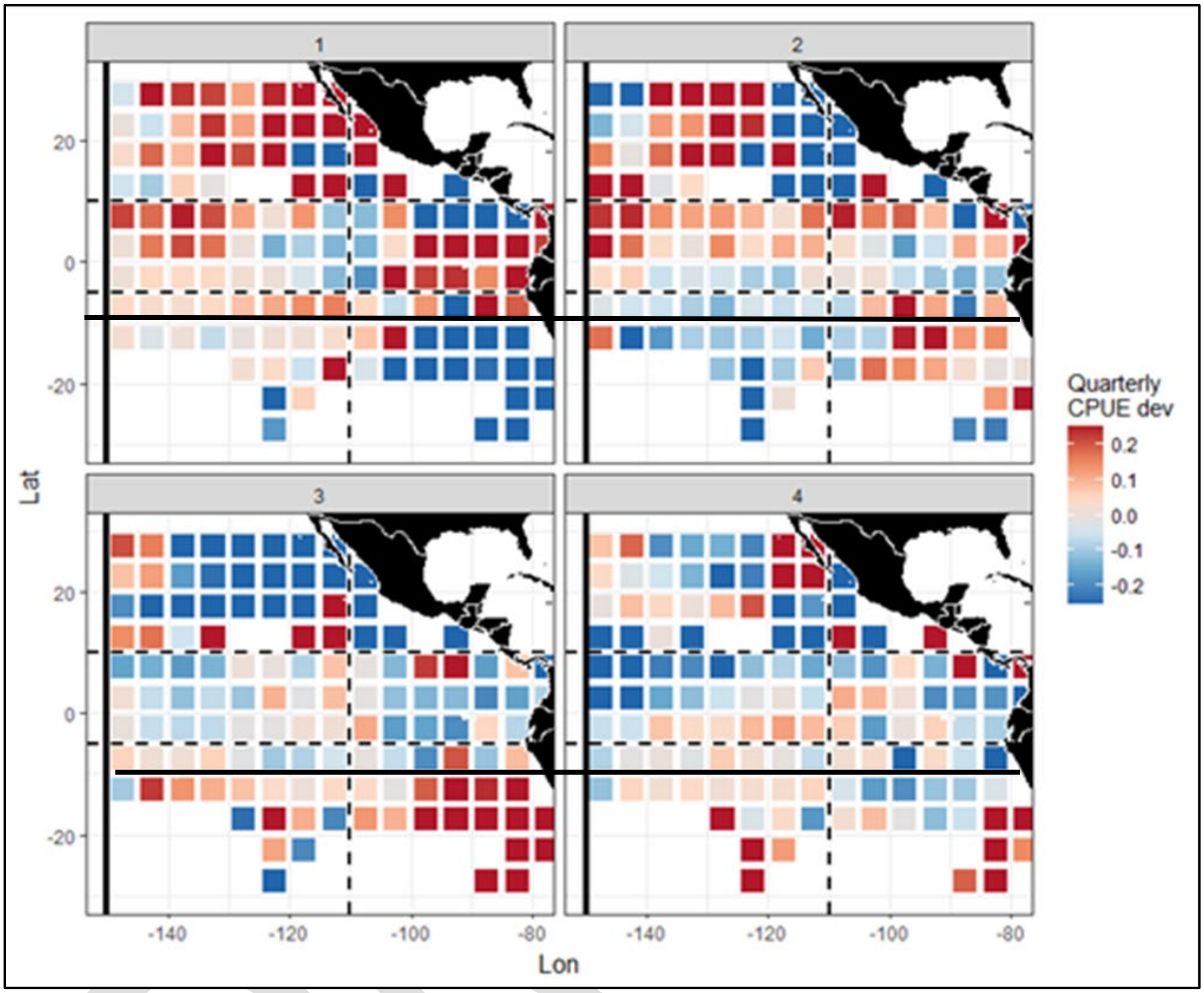

FIGURE 7. Deviations from the overall mean of the nominal CPUE of the Japanese fleet for the early data (1975-1991). The dashed horizontal line south of the equator is at 5°S and the solid line is a 10°S.

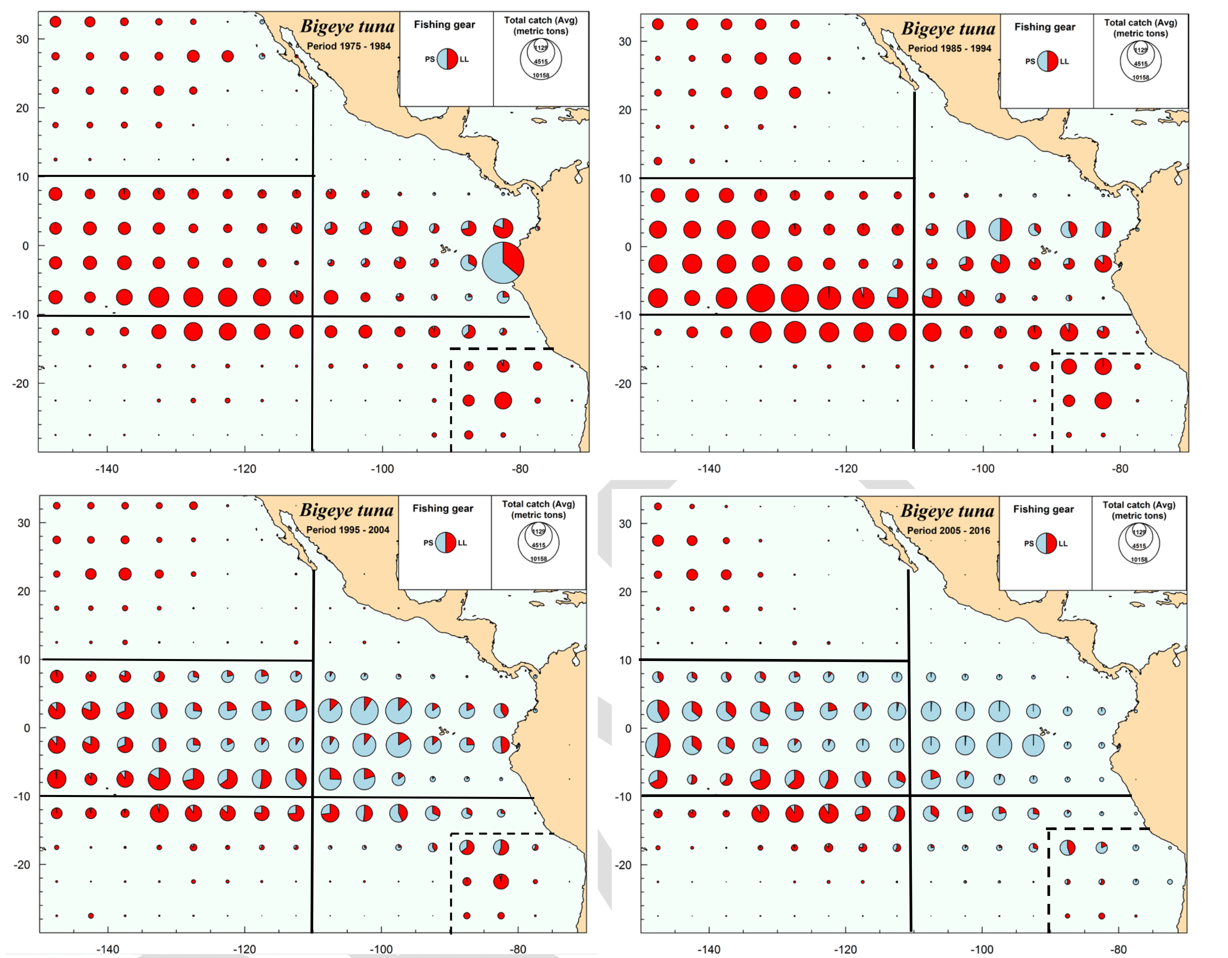

FIGURE 8. Catches of bigeye tuna from longlines and purse-seine in the eastern Pacific Ocean from 1975-2016, with the final spatial structure configuration in the last panel (2005-2016).

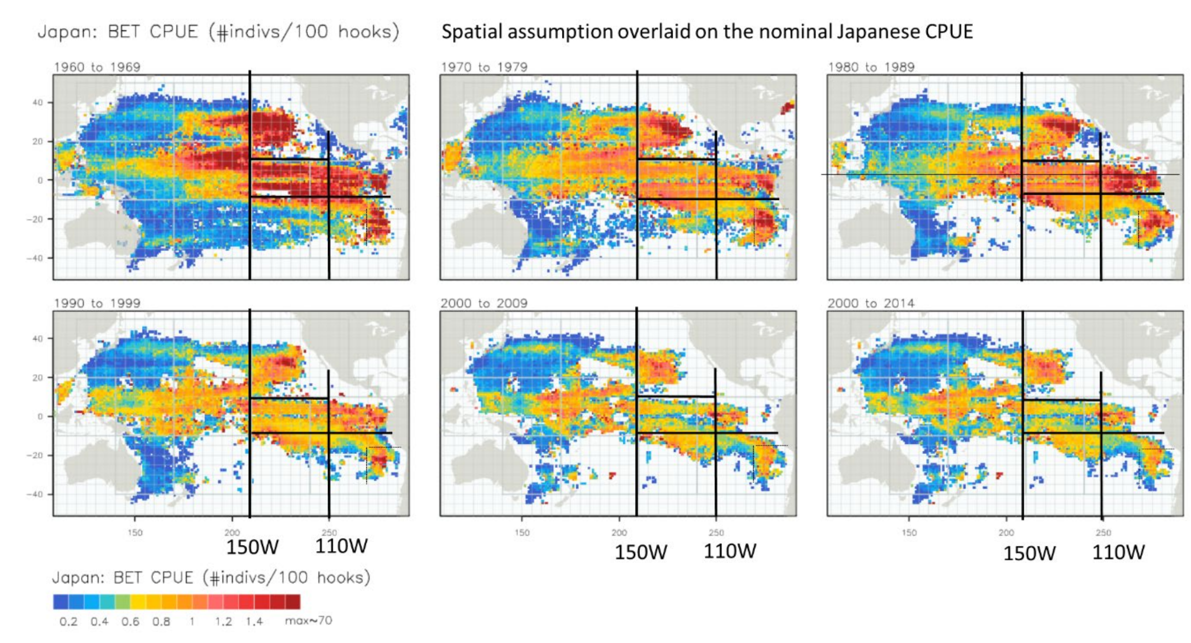

FIGURE 9. Spatial assumptions overlaid on the maps of nominal CPUE for the Japanese longline fleet over time (Source: McKechnie *et al* 2015)

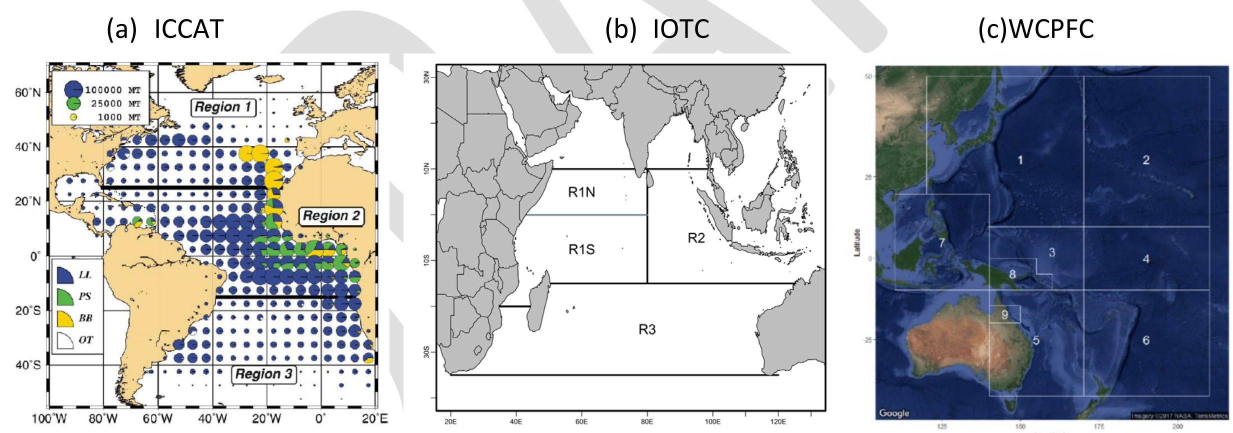

FIGURE 10. Assumption of spatial structure assessment models of bigeye tuna: (a) Atlantic (Schirripa 2015), Indian Ocean (Langley 2016) and Western and Central Pacific Ocean (McKechnie *et al* 2017).