SCIENTIFIC COMMITTEE
FIFTEENTH REGULAR SESSION

Pohnpei, Federated States of Micronesia
12-20 August 2019

A conceptual model of skipjack tuna in the Western and Central Pacific Ocean (WCPO) for the spatial structure configuration

WCPFC-SC15-2019/SA-WP-11

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Summary

In this document, we attempted developing a conceptual model of skipjack tuna in the western and central Pacific Ocean (WCPO) for stock assessment that shows hypothesis of spawning area, migration patterns and reproductive traits, that are the basic information to take into account for spatial structures as well as model configurations. In addition, CPUE trends, size distributions and tag release and recapture mainly extracted from Japanese data are briefly described in the spatial structure used in the 2016 stock assessment and candidate spatial structure based on the conceptual model is described in this document.

Introduction

MULTIFAN-CL, an integrated model, is the main model used for stock assessment to determine stock status in the Western and Central Pacific Ocean (WCPO) that allows spatial structure, which can estimate movements rate among areas directly from tag-integrated approach (Fournier *et al.*, 1998). Tag-integrated models provide an ideal method for incorporating spatial structure into stock assessment models (e.g. Goethel *et al.*, 2015). Model consider animal movement keep track of numbers by age/size by area and allows some proportion of the animal by age/size to move from one area to another area in each time step.

Spatial structure for the skipjack stock assessment in the WCPO has been changed in last five assessments, 2005, 2010, 2011, 2014 and 2016. The area in 2005 assessment contains six spatial regions (Langley et al., 2005; **Fig.1a**) as used in CPUE standardization study (Ogura and Shono, 1999), and enlarged to include the domestic fisheries of the Philippines and eastern Indonesia. The assessment model area in 2010 and 2011 comprises three regions in order to reduce model complexity (**Fig. 1b**), with a single region north of 20°N, and two equatorial regions 20°S to 20°N, with the western equatorial region from 120°E to 170°E, and eastern equatorial from 170°E to 150°W. There is also an advantage that is the southern boundary which is also same as the bigeye and yellowfin tuna regional structures (Hoyle *et al.*, 2010 and 2011). The assessment model area in 2014 and 2016 comprises five regions (**Fig. 1c**), with a single region north of 20°N, and four equatorial regions between 20°S to 20°N. This change was because of reducing uncertainty of catch by Indonesia, Philippine and Vietnam and large-scale tagging project in the Bismarck and Solomon Seas (Harley *et al.*, 2014; Rice *et al.*, 2014). These areas do not always coincide with the skipjack biological and ecological background. Additionally, 2016 assessment was done in the alternative spatial structure as one of sensitivity (**Fig. 1d**). In this case, the region in the northern region was divided into three regions; as a result, one region in subtropical was added. This regional structure was based on the previous research on tagging or larvae distribution (Kiyofuji and Ochi, 2016), however, it was not robust enough to fully explain the distribution of catch or migration of fish among the defined areas.

Ying et al. (2011) addressed the importance of considering spatial structure in the fisheries management. Guan *et al.* (2013) used a simulation approach to evaluate the consequences of misspecifying spatial structure and migration during the assessment process and results showed overestimation of SSB and underestimate of fishing mortality. To avoid complexity of model parameterization in the spatially-explicit model, most assessment account for spatial structure using the "area-as-fleets" approach as a single-stock assessment (e.g. Waterhouse *et al.*, 2014). This approach involves estimating separate selectivity patterns for each spatial region to share the effects of differences among areas in the distribution of animals by age/size (e.g. Punt, 2019a) as results of animal movement. Punt (2019b) provided a guidance as a "tentative best practice" should start with a conceptual model with hypotheses of stock, sex, age, etc. In the case of skipjack, it should be noted that the biological parameters (growth, natural mortality and fecundity) may differ among areas though the target species distribute homogeneously across areas such that size/age compositions among the area are expected to be similar.

In this document, we attempt to develop a conceptual model for skipjack tuna in the WCPO that shows hypothetical spawning area, migration patterns and reproductive traits. These features are basic information to take into account when defining the spatial structures of the species as well as it helps us to set appropriate model configurations. In addition, CPUE trends, size distributions and release numbers in the recapture area are displayed in the 2016 area and alternative spatial structure proposed for the stock assessment in 2019.

Overview of skipjack fisheries in the WCPO

The primitive pole-and-line fisheries targeting skipjack in Japan started from the Edo era (around 1,600s), operated in very near shore using rowboats. With motorized engines, fisherman started to expand their fishing ground to south (subtropical and tropical areas) from the waters around Japan in 1960s (**Fig. 2**). At the beginning of this southward expansion, the fishing grounds were formed around the Ogasawara Islands and Northern Mariana Islands mainly in summer and autumn seasons (Kiyofuji *et al*., 2018). As these areas were often affected by frequent occurrences of typhoon, fishermen were forced to move to southern areas further south of 10°N, the area characterized by calmer weather conditions that lead to more stable operation of the fisheries. At the same time, the issues of maintaining live baits and increasing fuel prices had certain effects on reducing number of distant water fleet resulted in catch decrease. Japanese government made it obligatory to submit logbook in 1972, and since then the format of which has been unmodified.

Decadal fishing locations by the offshore (OS) and distant water (DW) JPN pole-and-line fisheries (JPN PL) were summarized in Kiyofuji and Okamoto (2013), as range of fishing grounds has been contracted due to decrease of number of vessels. While the number of vessels has been decreasing, fishing technology has been advanced to improve fishing efficiency. One of the important implementations of the technological innovations for the JPN DW PL (conventionally defined as of vessel size larger than 200 gross registered tonnage) are the low temperature live bait tank, onboard NOAA meteorological satellite image receiver, radar for bird searching and sonar for detection of fish schools. On the other hands, purse seine (PS) fisheries started their operation in 1980s and having been growing rapidly both in their fishing efficiency and capacity. Their main fishing grounds are mainly in tropical are between 10°S and 10°N in latitude (Fig.7.1.2 in William, P. and Reid, C., 2018). Recent skipjack catch by PS fisheries is about 1.6 million metric tonnes. Recent catch trend by the JPN coastal troll shows decreasing trend (Fujioka and Kiyofuji, 2019) and the CPUE from several unique troll vessel also shows similar trends (Kiyofuji *et al.*, 2015), while JPN coastal PL shows gradual increase.

The historical fishing ground formation in the WCPO shows that the fishing ground expanded to south from the water near Japan mostly by the JPN PL fisheries. The recent fishing ground can be separated into mainly three regions; the western tropical area including Indonesia and Philippine with small-scale fisheries (120°E–135°E, 10°S–10°N); central Pacific ocean with mainly large scale PS by several distant countries and small portion of PL fisheries (135°E–150°W, 10°S–10°N) and northern area with PL, domestic PS and small-scale fisheries (120°E–180°E, 25°N–40°N; **Fig. 6(a)**). Interestingly, catches in the area between 10°N and 25°N are relatively smaller compared to the areas mentioned above.

Biological background and relevant information

Uncertainty associated with insufficient knowledge of skipjack population structure would lead to misspecification of spatial structure resulted in producing large assessment errors, related to biomass estimates and management measures. Skipjack regarded to be one single stock in the entire Pacific Ocean which is one of the different stocks in major three oceans (Atlantic, Indian and Pacific). While the previous research shows possibility of population differences within the Pacific Ocean based on the combined analysis of biochemical and population genetics (e.g. Fujino and Kang, 1968), further analysis is necessary to clearly specify the population structure in the entire Pacific by using nuclear DNA markers. Therefore, as there are no clear and concrete evidences of stock separations in the Pacific, it is reasonable to assume that skipjack tuna in the WCPO is one single stock at this stage.

Growth Stage (morphological characteristics)

It is also necessary to describe growth stage of skipjack in terms of size, morphologic characteristics, days after hatching (Tanabe, 2002) and sampling gear (**Fig. 3a**). The growth stages are defined as follows. The length of larvae is smaller than 1.0 cm and age within 10 days after hatching. Yolk sac is present or absent. The number of rays in each fin is fewer than those of adults. It is assumed that they do not swim at this stage. Range of juvenile size is between 1.0 cm and 10cm approximately, which is equivalent to 10–40 days after hatching. Yolk sac is absent. The number of rays in each fin is similar to that of adults. Morphological characters of adult fish (e.g., silvery abdomen, large number of gill rakers) gradually appear. Young skipjack is approximately between 10–20cm as age of 40–90 days after hatching. Although morphological characters of adults are observable, the conspicuous longitudinal dark bands on abdomen is not clear yet. Immature fish is approximately in a range of 20 cm to 40 cm as age of 90 days–one year after hatching. Their gonad is in undeveloped phase. Approximate size of matured skipjack is approximately more than 40 cm as age of more than one year after hatching. Their gonad is developed, and the fish in this stage can partially contribute to spawning activity.

Growth

Growth is a fundamental biological process along with reproduction and mortality and an important biological parameter for stock assessment that determine the production of populations. A growth model describes change in length and weight as a function of age and is used in stock assessment to convert length measurements in the catch data to age, thus an incorrect growth model can adversely affect the estimated age structure of the population. For tunas including skipjack, Murua *et al*. (2017) reviewed growth studies and summarized and validated growth models in the all oceans and mentioned that growth in skipjack is rapid compared with other tuna species. **Fig. 3(b)** shows the growth model of skipjack in the WCPO derived by several different studies, which revealed that different growth rates were apparent in the same region.

Analysis of otolith daily increments has been applied as growth estimates. However, large measurement errors have been reported due to complexity of otolith microstructure of this species (e.g., Sardenne *et al*., 2015). Estimating age and growth of this species is an important scientific role that should be achieved to accurately assess this stock because still large uncertainties remain in the current stock assessment model (e.g. McKechnie *et al*., 2016; Ochi *et al*., 2016). In the WCPO, the growth model was estimated by two different otolith procedures and observations. Focusing on the growth stages, Tanabe *et al*. (2003a) inferred that the daily increments are available to read as otolith rings in juvenile skipjack for age determination by surface reading. From young to adult stages, following two methods were considered: 1) thin-slicing method (read the micro-increments on the cross section cut along the transversal axis direction, Adam *et al*., 1996; Leroy, 2000; Sardenne *et al*., 2015); 2) etching method (dissolve the distal face of otolith with 10% hydrochloric acid to expose the micro-increments, Wild and Foreman, 1980; Uchiyama and Struhsaker, 1981; Wild *et al*., 1995; Tanabe *et al*., 2003b; Kayama *et al*., 2007). Daily increment formation of otolith used in the thin-slicing method is commonly recognized in some species of gebys *Thunus* (Wild and Foreman, 1980; Wild *et al.*, 1995; Stéquert and Conand, 2004; Sardenne *et al.*, 2015). However, daily increments were not recognized on the marginal zone of otolith by the thin-slicing method in young to adult skipjack [250–570 mm in Fork Length (FL)]. Moreover, large measurement errors have been reported due to some complexity of otolith microstructure of this species, leading to the conclusion that the number of increments of otolith rings is not suitable for the age determination of skipjack (Adam *et al.*, 1996; Sardenne *et al.*, 2015). On the other hand, the etching method targeting young to adult skipjack tuna (180–710 mm FL) has been confirmed to be applicable to detection of daily formation of the microstructures on the marginal zone by observation of oxytetracycline (OTC) marked otoliths extracted from recaptured individuals (Tanabe *et al.*, 2003b; Kayama *et al.*, 2007). However, no documents with respect to the procedure for etching method analysis targeting juvenile to adult skipjack have been reported previously and thereby detailed description of otolith procedure for age determination was reported (Tanaka *et al.*, 2017). Additionally, spatially different growth according to fish movement has direct effects on the stock assessment results if the model assume size-structured population dynamics. While Aoki *et al.* (2018) already indicated different growth and reproduction depending on migration routes in the WCPO by the Dynamic Energy Budget-Individual Based Model (DEB-IBM), further investigations are necessary whether different growth among areas can be identified or not through biological observations.

Averaged body weight calculated from 46 years of historical JPN PL logbook is shown in **Fig. 4**. Overall, skipjack with body size less than 3kg were identified in the north of 30°N mostly during quarter 2 and 3. This is due to seasonal migration of smaller individuals from subtropical to northern area (Kiyofuji *et al.*, 2019b). Larger individuals ranging between 4 and 10 kg likely aggregated in the subtropical area from 140°E to 160°W with gradually increase in size towards east. In tropical area, around 4 kg individuals appeared. It should be noted that the size segregation of skipjack would be useful information to consider spatial structure for the stock assessment (**Fig.6(b)**). Kinoshita *et al.* (2018) addressed model-based cluster analysis using average fish weight and CPUE obtained from JPN PL logbooks for accurate and practical area definition to use in the stock assessment. The study was conducted to solve the issue of mixed-size or -age of fish especially in northern area recognized in the assessment in 2016, which would be inconsistency in CPUE in that area, leading to incorrect biomass trend estimates.

<u>*Spawning area and potential*</u>

Skipjack spawning area has been inferred indirectly by larvae distribution from several ship surveys (e.g., Nishikawa *et al.*, 1985) and occurrences of matured female skipjack (Asano, 1971; Naganuma, 1979). As age of the collected skipjack larvae by ship surveys was assumed to be a few days after hatching based on the laboratory observations (Ueyanagi, 1974) and their less ability of swimming compared to juvenile or older, the area of larvae occurrences could be equivalent to the spawning area, where is presumed to be formed in area between 35°N and 24°S in latitude with sea surface temperature (SST) is 24°C or warmer as appropriate indicator for spawning (Ueyanagi, 1969). Spawning potential is likely higher in tropical and lower in the higher latitude (Ohashi *et al*., 2019) where skipjack visit and leave in their seasonal migration. The high mobility of this species and their needs for feeding even during spawning season leads to the inhabitation of spawning capable females in the temperature lower than suitable for spawning. **Fig. 5** show averaged temperature in quarters for the entire target area with different area definitions (a) and among each area (b). Different temperature can drive the productivity in each region resulted in overall productivity of a stock.

Based on the skipjack larvae and spawning female distributions in the WCPO and the seasonal temperature changes, tropical area is considered the main spawning area while spawning potential become smaller gradually and recruit occurs occasionally in higher latitude are due to seasonal temperature warming (**Fig.6(c), (d) and (e)**). This implies that the recruitment among areas should be different also as well as the area-specific spawning potential.

Movement

Fujino (1970) first proposed the existence of two main seasonal migration routes: one from the south to Japan area along the Nansei Islands and the other following the Pacific coast of Japan, along the Northern Mariana–Izu–Ogasawara Islands to the coastal area and the northwestern waters around Japan (**Fig.6(f)**; grey arrows). Their migration rate between areas and their underlying migration route remain a concern to improve fisheries management (Phillips *et al.*, 2018). A new and comprehensive migration route of this species in the WCPO was observed from the results of a large tagging project (Kiyofuji et al., 2019b). Three major potential routes were observed with strong skipjack residency along; (i) the Kuroshio in the Nansei Islands, and with seasonal northward movements along (ii) the Kyushu-Palau ridge and (iii) the Izu-Ogasawara Islands. During northward migration, the tagged skipjack experienced several specific physical oceanographic structures such as in the Kuroshio recirculation area (the subtropical mode waters), the Kuroshio Current near the coast of Japan, the Kuroshio Extension and the Kuroshio–Oyashio transition area (**Fig.6(f)**; red arrows).

Candidate spatial structure for the skipjack stock assessment in the WCPO

Fig. 6 summaries all sections mentioned above; (a) fisheries, (b) average body weight of skipjack obtained from JPN PL logbook, (c) larval distribution modified from Nishikawa *et al.* (1985), (d) schematic illustration of spawning potential based on Ohashi *et al* (2019), (e) example of SST distribution (See **Fig. 5**) and (f) movement patterns indicated by Fujino (1972) and Kiyofuji *et al.* (2019b). Skipjack habitats are limited in temperature 18°C range warmer than 18°C, whereby the norther and southern most limit would be 40°N and 30°S, respectively. The main fishing area, i.e. tropical area, could be main spawning area as 24°C SST of the appropriate spawning indicator shows. While spawning capable female would migrate towards the north and south in the subtropical and temperate areas due to their seasonal migration, their spawning potential in the northern areas could be smaller than the main spawning areas in the tropical. The larvae distribution research suggest that the hatching area might be skewed to the western and central Pacific than eastern Pacific. Combining the insights mentioned above with the size segregation derived from the averages of body size of the JPN PL logbook data, it is reasonable to use the area definition shown in **Fig. 7(b)** for the skipjack assessment in the WCPO, which is expected to reduce inconsistency among data such as CPUE, size and tagging data. CPUE trends, size distributions, release and recapture of tagged fish are summarised in **Fig.8, 9 and 10**, respectively. Detailed descriptions of these results can be found in Kinoshita *et al*. (2019), Kiyofuji *et al*. (2019) and Vincent *et al*. (2019).

Following summaries needed to be consider at the SC15;

1. It is appropriate to use the spatial structure shown in Fig. 7(b) at the present understanding of skipjack tuna in the WCPO as a conceptual model based on historical fisheries changes, occurrence of skipjack size, different spawning potential among regions and movement.
2. An adequate reproductive parameter and recruitment should be considered in each area, especially in marginal areas (at least in the northern area) where their spawning potential is relatively low because of their seasonal migration which is limited by the lower tolerance of temperature. Specifically, the reproductive parameter should be considered in overall WCPO with the data in their spawning season only. In addition, different recruitments among areas should be considered. While recruitment in tropical and subtropical likely occurred in all season, that in temperate is only in summer which corresponds to quarter 3.

Following future research also need to be considered to improve skipjack stock assessment in the WCPO

1. Evaluate the spatial structure in tropical area whether it is necessary to be divided into two areas (west and east) or not.
2. Explore size data including areas from 5 to 8 to investigate size segregations in the WCPO.
3. Further investigation of sex ratio is required with respect to smaller and larger size than previously reported to evaluate whether sex-disaggregated growth model should be implemented or not.
4. Further investigation is necessary to evaluate whether different growth among areas can be identified or not.

5. Evaluate otolith reading protocols for growth study to establish reliable aging method for skipjack.
6. Further samples for reproductive trait investigation should be collected in each area as current sampling area is biased due to its fishery-dependent sampling, in particular in the east of area 2, 4, 5, 6 and 8 where shows smaller sample sizes compared to others.
7. Develop and evaluate use of a large-scale PS index in the tropical area to represent trends of skipjack population fluctuation rather than the JPN DW PL.
8. Further consideration of collaborative tagging project to represent age/size specific movement rate in the WCPO as well as estimating a precise abundance index.
9. Explore “area-as-fleet” approach in single-area model

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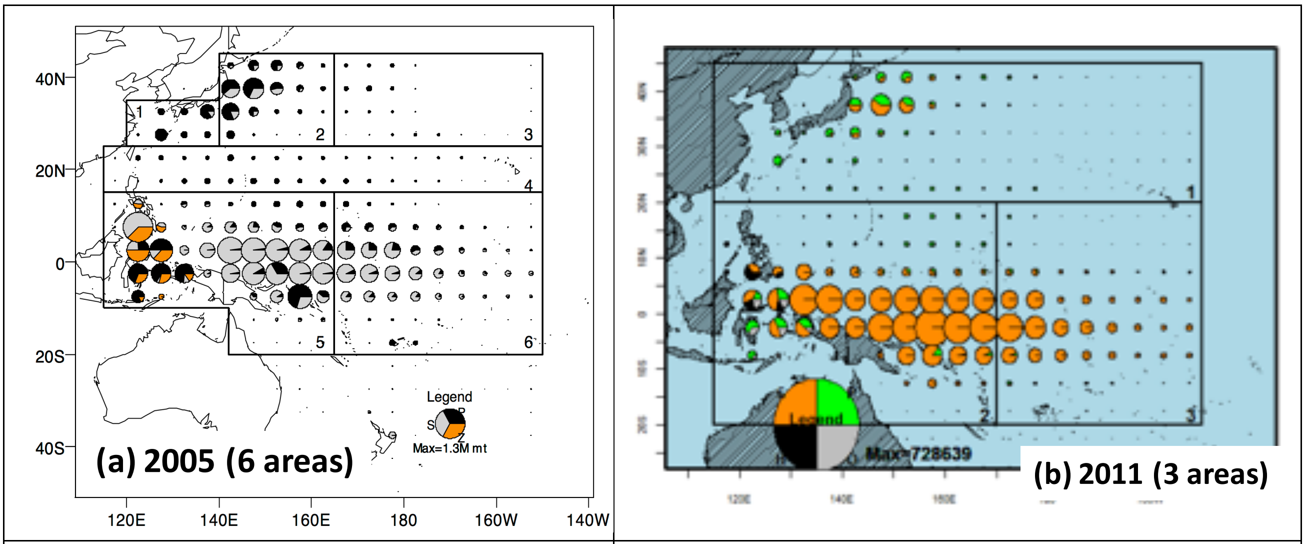

(c) 2014 and 2016

(d) sensitivity in 2016

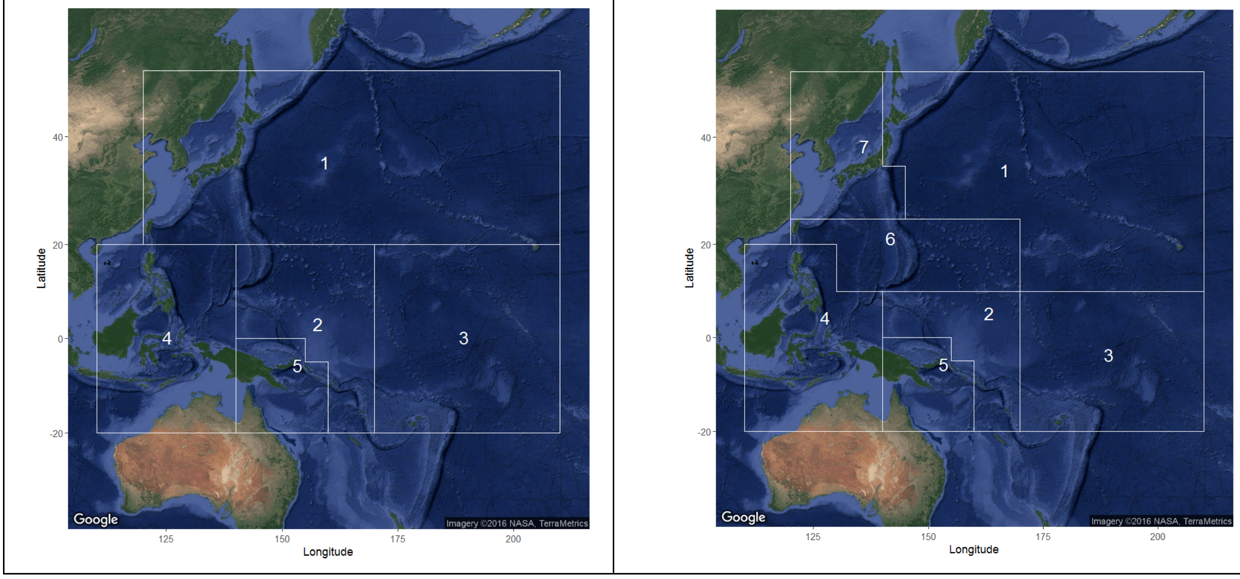

Figure 1. Spatial structures used in the skipjack stock assessments in the WCPO. (a) 2005 and 2008 (6 areas), (b) 2011 (3 areas), (c) 2014 and 2016 (5 areas) and (d) an alternative spatial structure as one of sensitivity runs in the 2016 assessment (McKechnie *et al.*, 2016).

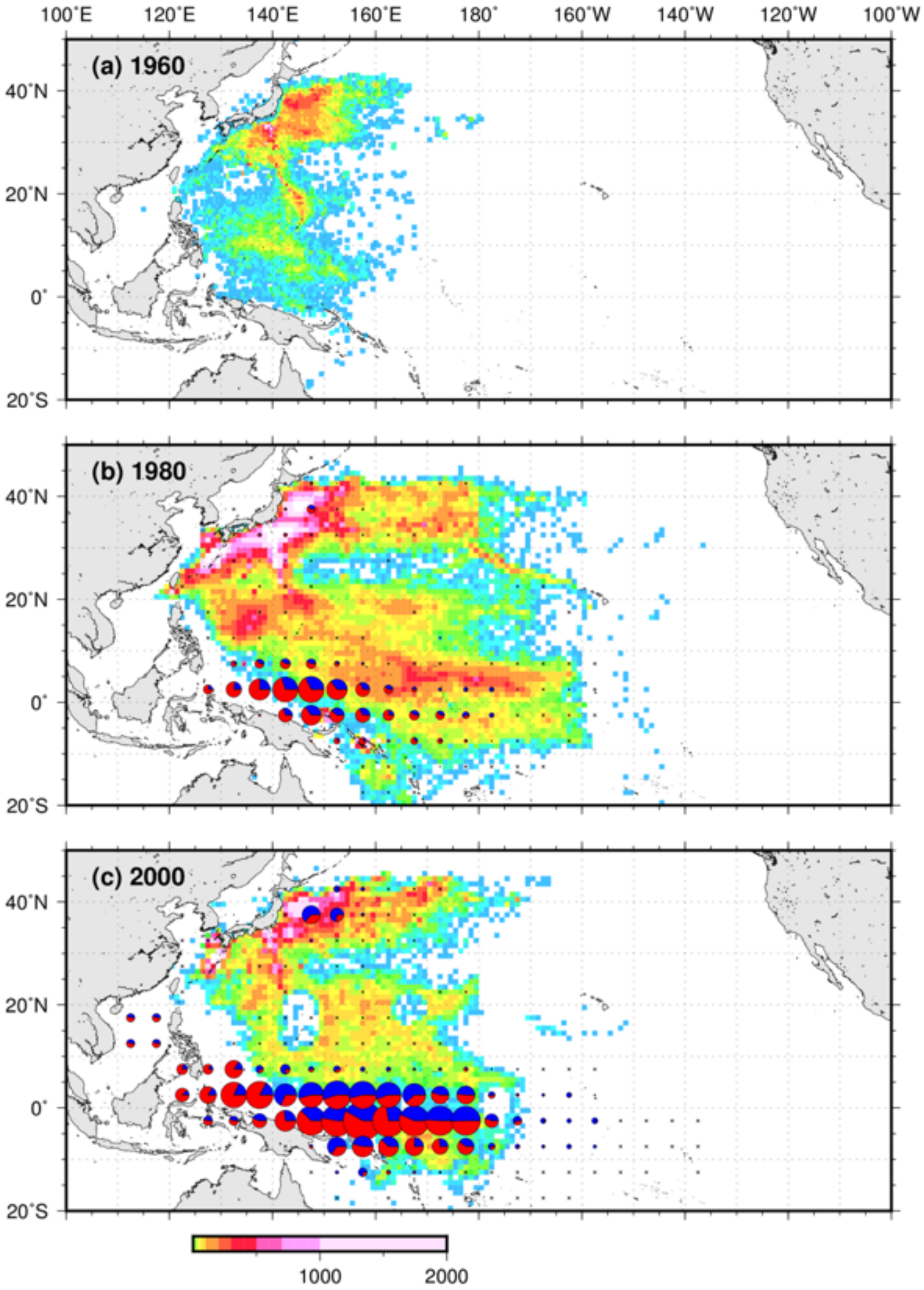

Figure 2. JPN PL effort distribution with 1 × 1 degree (color tile plot; number of vessels) and PS skipjack catch with 5 × 5 degree (circle; red: unassociated, blue: associated) in (a) 1960s, (b) 1980s and (c) 2000s.

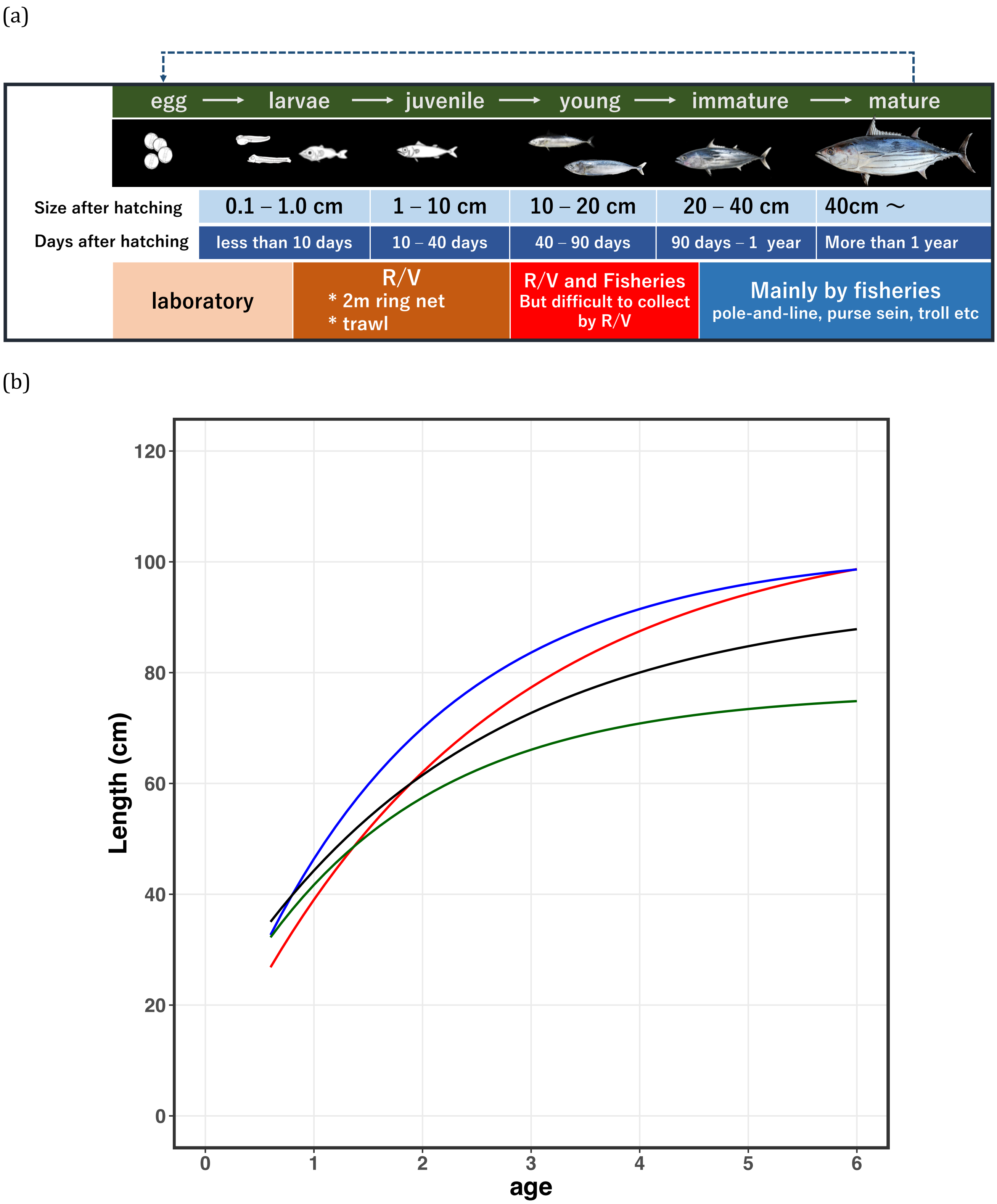

Figure 3. (a) Growth stage of skipjack with size, days after hatching and sampling gear. Size and days after hatching for egg and larvae growth phase are based on the literature by Ueyanagi *et al*. (1974). Juvenile and young phase are based on the literature by Tanabe (2002). (b) Estimated growth curves for skipjack tuna in eastern Pacific Ocean from length frequency data (red), in central Pacific Ocean from otolith (blue), western Pacific Ocean estimated from otolith (black) and estimated from length frequency data (green). These curves were reproduced from the supplemental information from Murua *et al*. (2017)

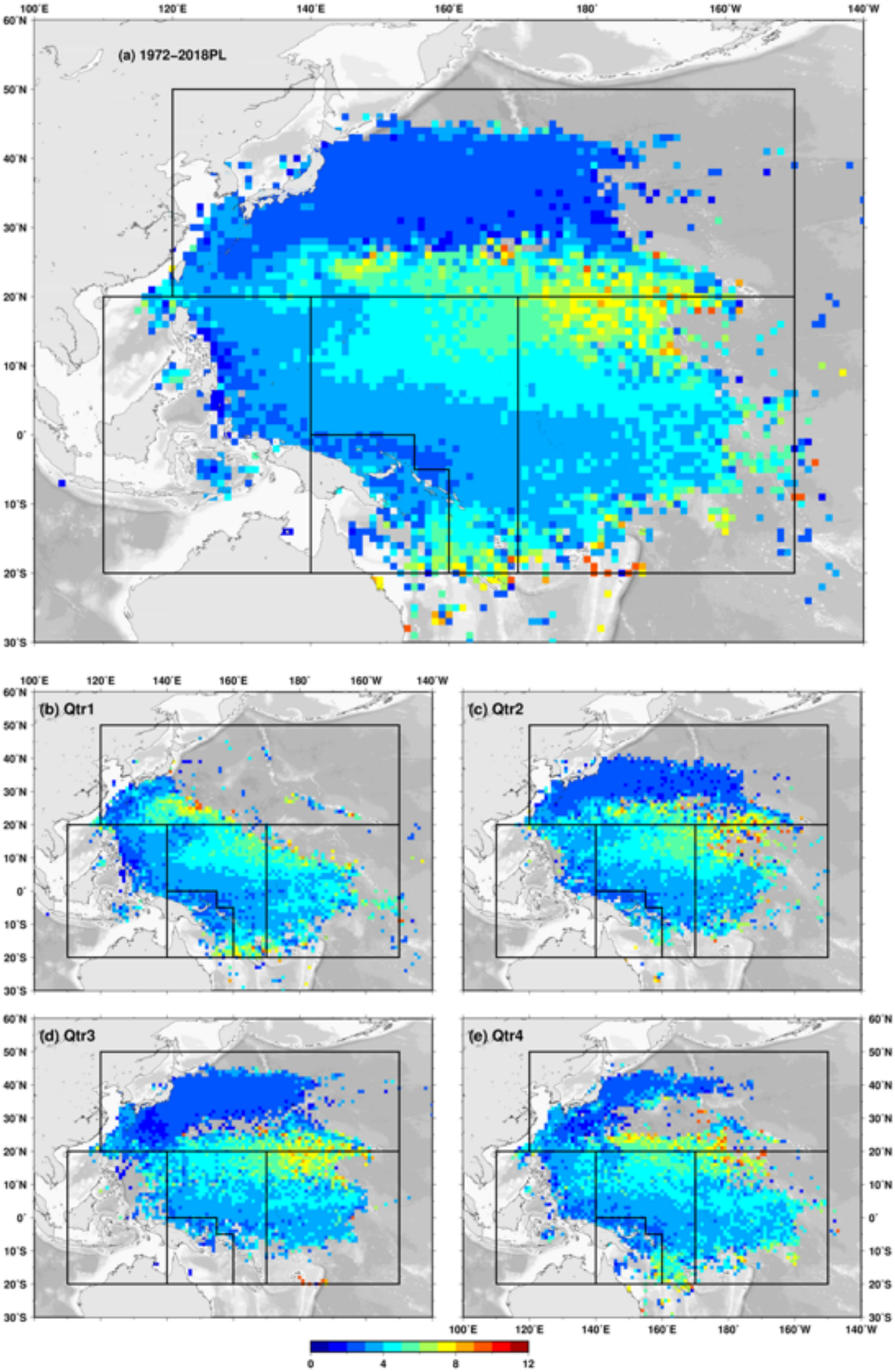

Figure 4. Average skipjack body weight based on JPN PL logbook from 1972 to 2018 (a) and each quarter (b–e). Black solid lines show boundaries of the stock assessment area used in 2016.

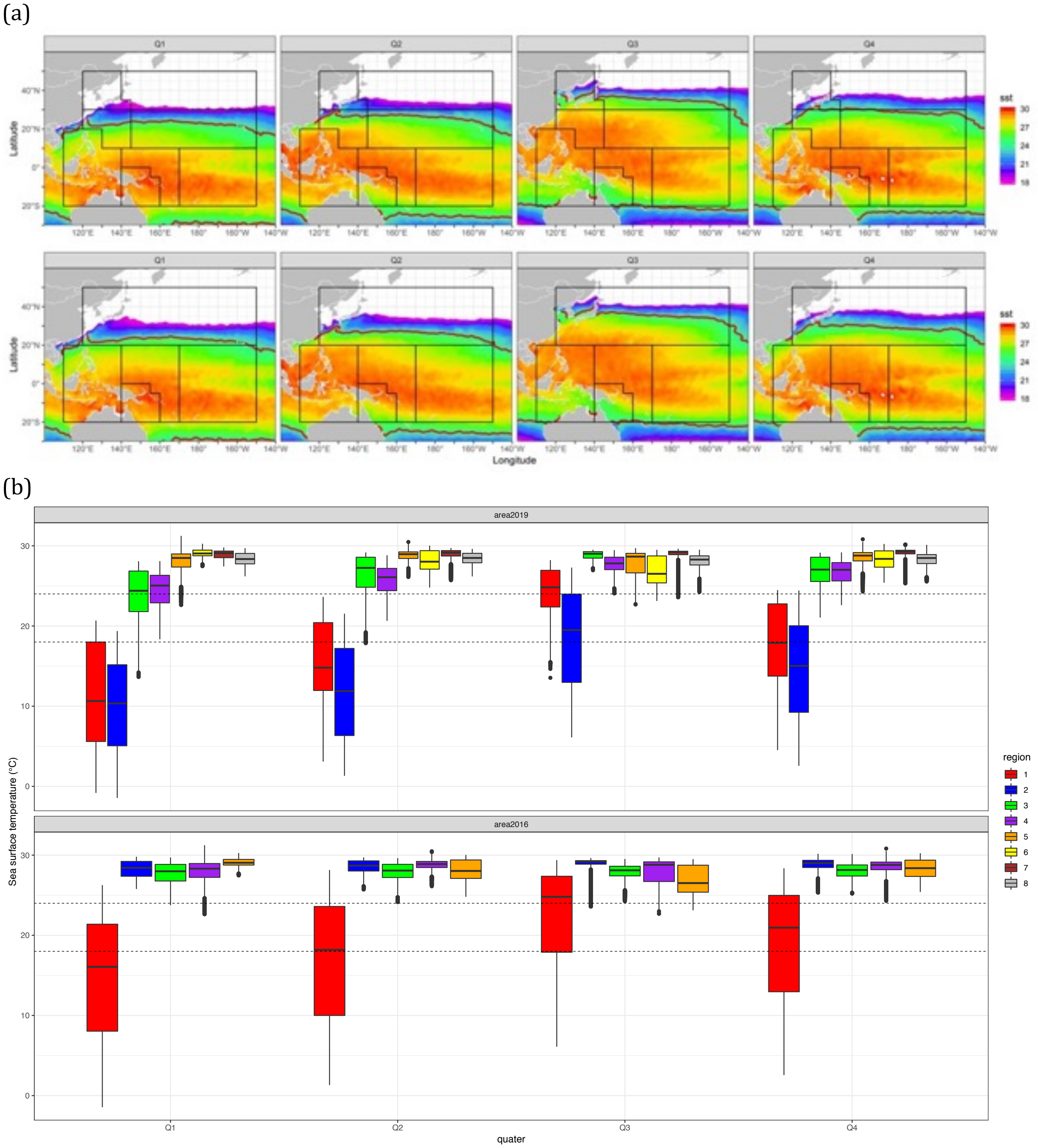

Figure 5. (a) Averaged sea surface temperature (SST) in the western and central Pacific Ocean (temperature lower than 18.0°C are not displayed as it is the lower thermal limit for adult skipjack (Kiyofuji *et al.*, 2019)). Red line shows 24°C isotherm as an index of spawning temperature. (b) Quarterly averaged SST in each stock assessment area. Dotted lines show temperatures of 18°C which is the lower thermal limit and 24°C as the spawning index. Upper and lower figure in both (a) and (b) represent stock assessment area in 2016 and proposed in 2019, respectively.

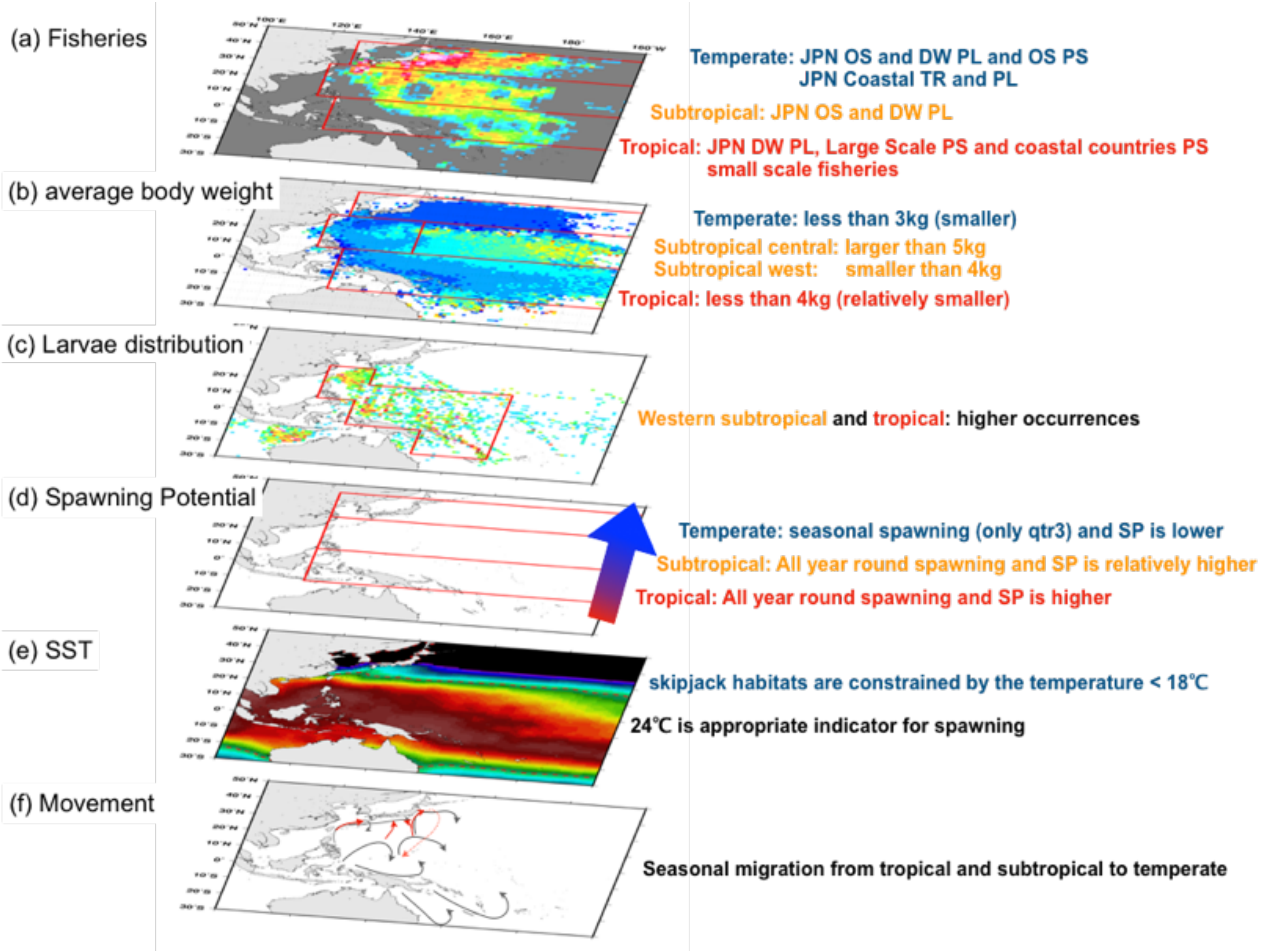

Figure 6. Spatial characteristics of (a) Fisheries, (b) average body weight from the JPN PL logbook, (c) larvae distribution modified from Nishikawa *et al*. (1985), (d) spawning potential from Ohashi *et al*. (2019), (e) sea surface temperature (SST) and (f) movement patterns modified from Fujino (1972; black and gray arrows) and Kiyofuji *et al*. (2019; red arrows).

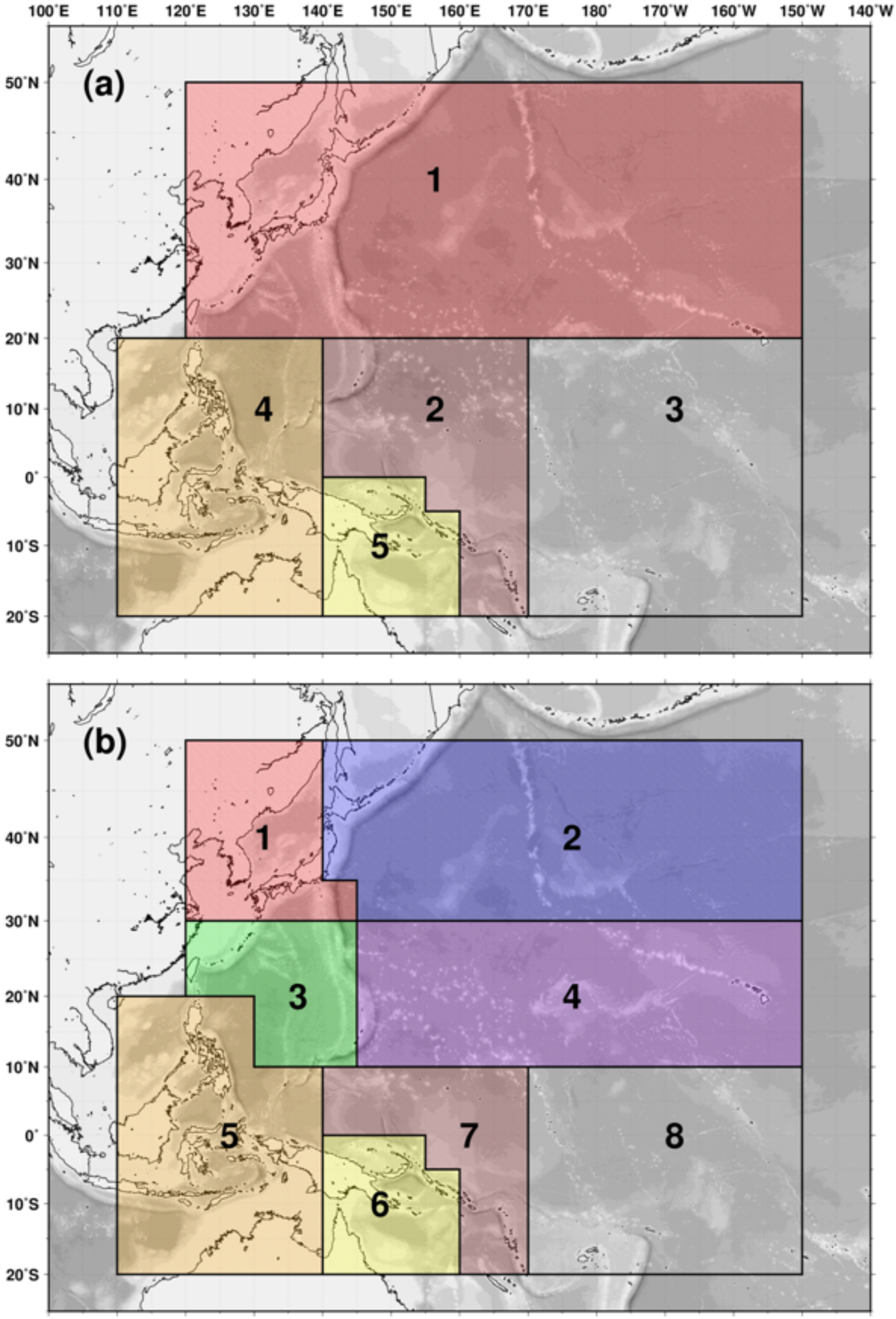

Figure 7. (a) Spatial structure used in the WCPO skipjack assessment in 2016. (b) Candidate spatial structure in the WCPO skipjack assessment in 2019.

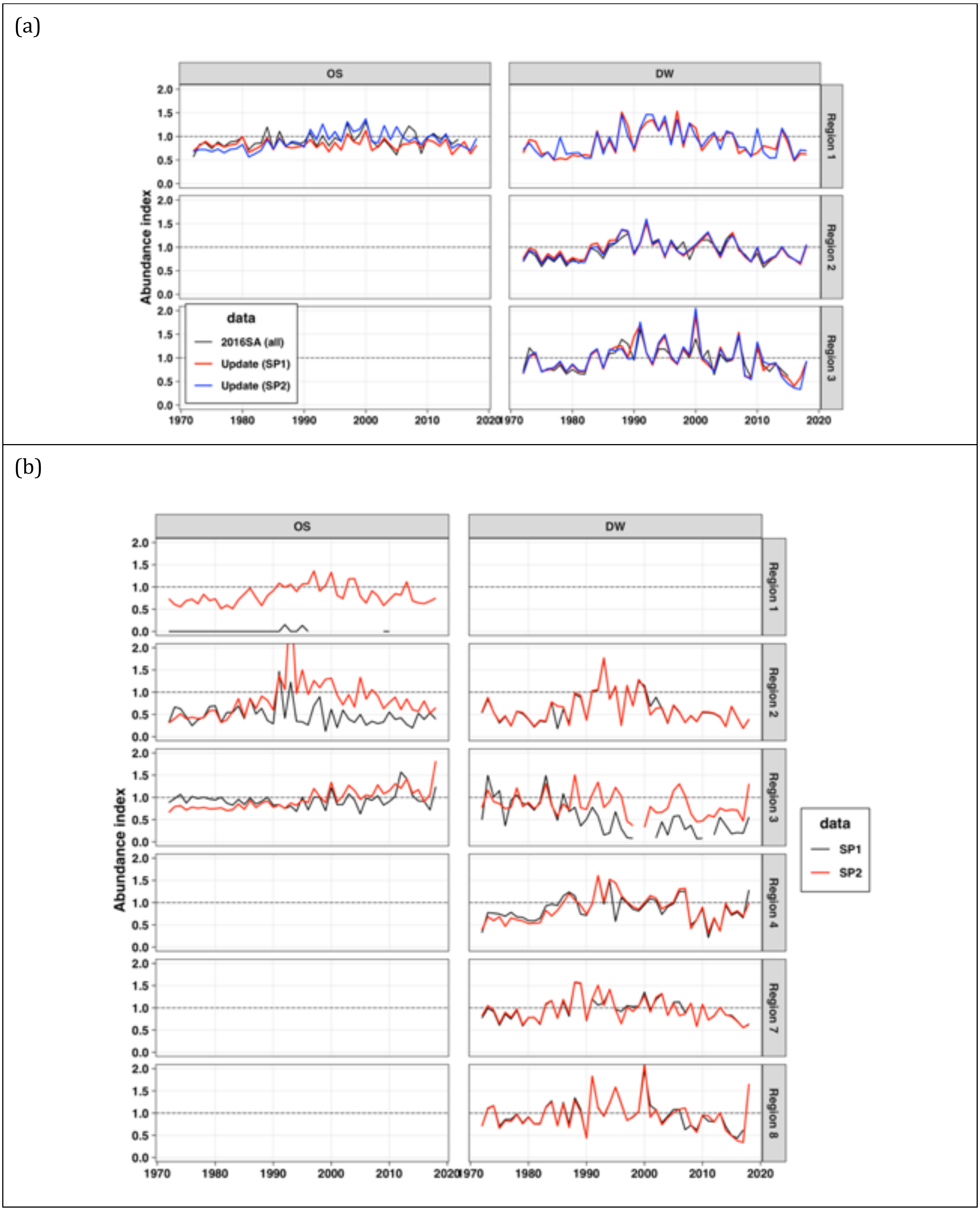

Figure 8. Abundance indexes of JPNPL obtained according to the 2016 stock assessment area (a) and the alternative spatial structure (b) using the delta-GLM model (See Kinoshita *et al*., 2019).

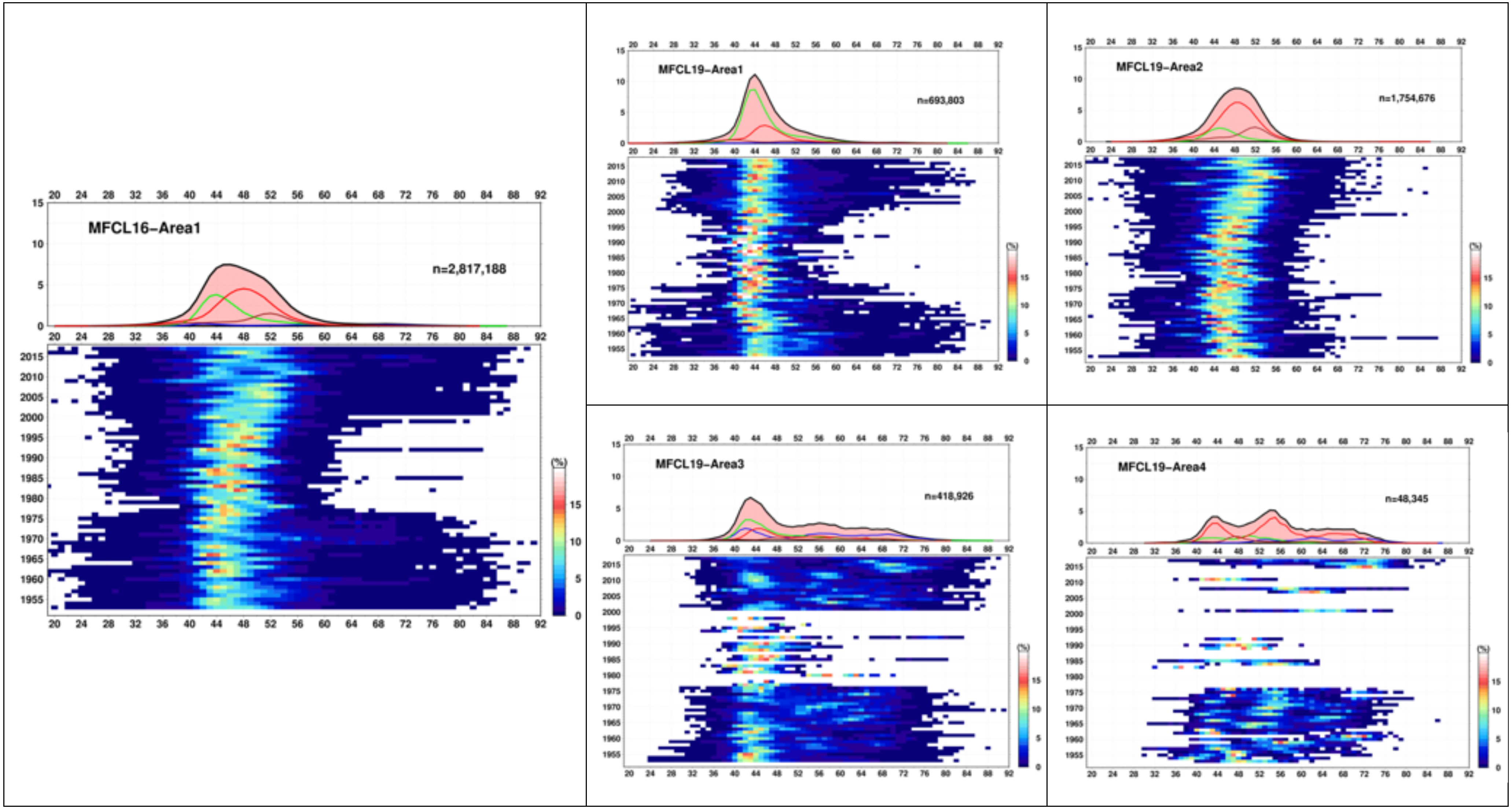

Figure 9. Overall skipjack size distribution (histogram) and year-length plot in each assessment region. The fish were caught by the Japanese commercial pole-and-line fisheries. Left: Region 1 in 2016 skipjack assessment; Right 4 panels: region 1–4 in of the 2019 proposed assessment regions for 2019 stock assessment (See **Fig. 3**). Black lines indicate overall size distribution, and blue, green, red and brown lines represent size by quarter from 1 to 4. Note that quarter is defined by every three months from January, April, August and October.

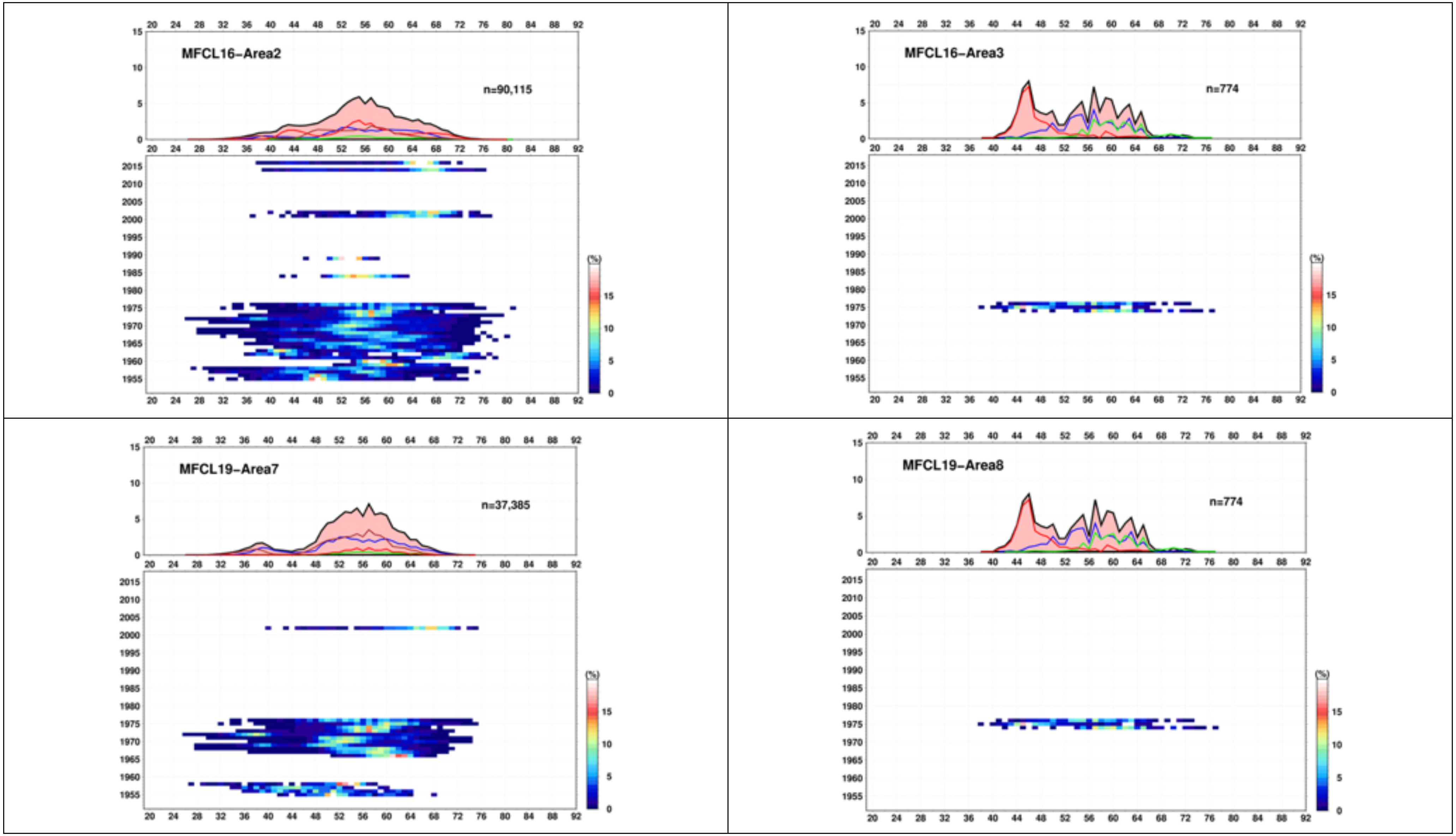

Figure 9. Continued. In different area definitions. Upper two panels are area2 and 3 of the 2016 assessment area; lower two panels are area 7 and 8 of the proposed area in 2019, respectively.

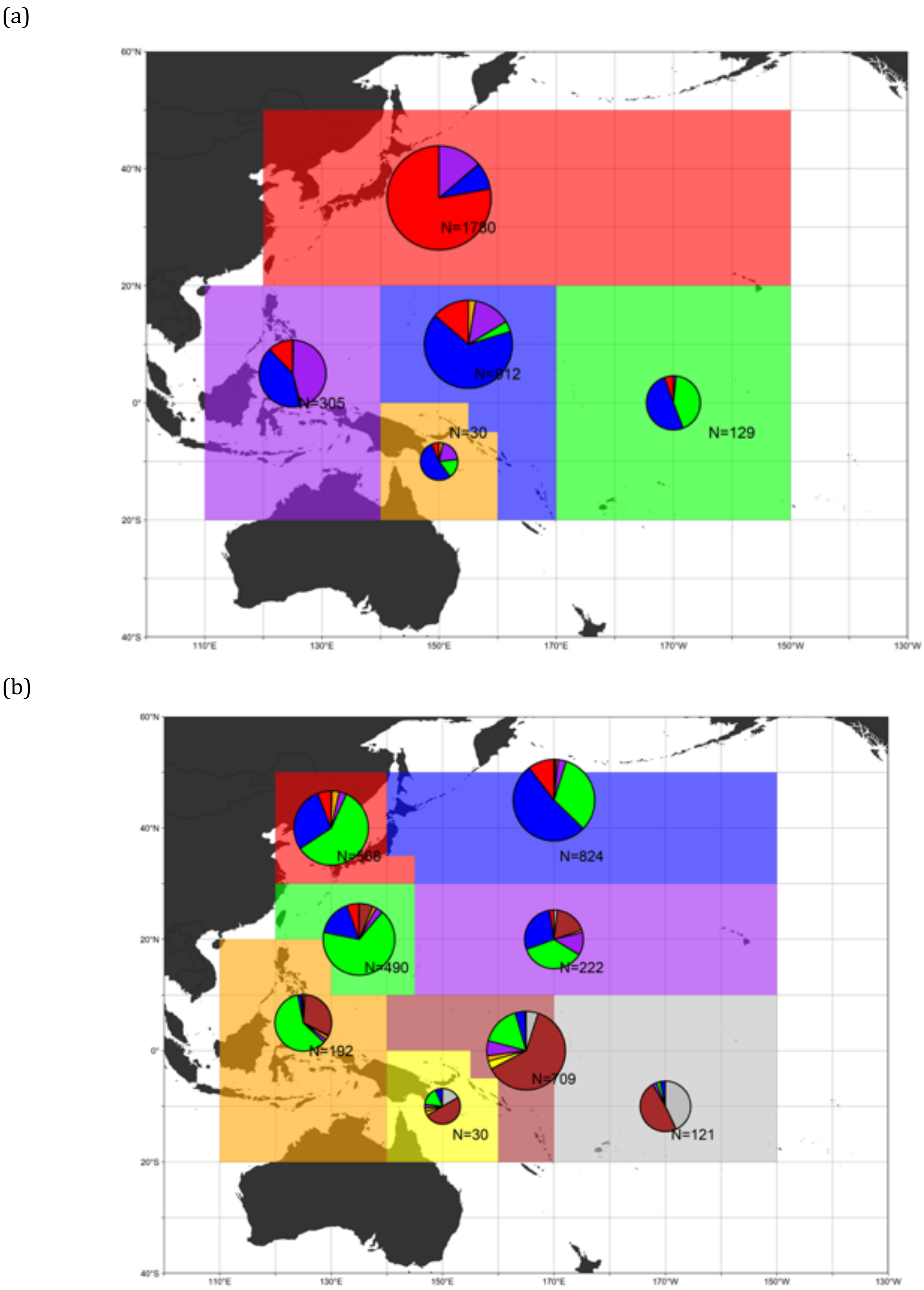

Figure 10. Comparison of number of recaptured tags and the regions where tags were originally released. (a) 2016 stock assessment area. (b) proposed area definition in this study (Fig. 7). (See Vincent *et al.*, 2019) Note that this figure is created based on Japanese data only.