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Tuna longline fishing around West and Central Pacific seamounts

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Executive Summary

This study used tuna longline logbook data to look for higher catch rates of tuna species close to seamounts, to identify those seamounts with significantly higher catches, and to quantify the seamount contribution to Pacific Ocean tuna catch. We found that a significant number of seamounts throughout the Pacific Ocean are targeted by tuna longline fleets. Adopting some conservative assumptions, this study concluded that at least 5-10% of the seamounts in the Pacific show significantly higher CPUE values for at least one tuna species and that seamounts may be responsible for an annual longline catch of as much as 25 thousand tons for three species combined. This study identified at least 43-69 seamounts that exhibit increased yellowfin fishing yields in the Pacific, 30-61 that increased bigeye catches and 27-69 that increased albacore catches. Seamounts enhancing tuna yields were found throughout the study area with a great proportion lying within national EEZs. This study did not show clear temporal changes on the seamount potential to enhance fisheries yields over the period from 1965 to 2007. Furthermore, our analyses showed increased proportions of the longline catch being taken from seamounts in recent years. Seamount aggregations, areas as well as any other aggregation points such as FADs, atolls or islands, may lead to hyperstability of catch rates caused by tuna shoaling behavior and range contraction during stock declines and should be carefully accounted for in any analysis of spatial catch rate data.

Introduction

Tuna is one of the most important world marine fish resources accounting for nearly 10% of the global marine fisheries catches by landed weight (FAO, 2009) and 20-30% by landed value (Sumaila et al., 2007). The largest tuna fisheries target skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), bigeye (*Thunnus obesus*) and albacore (*Thunnus alalunga*) and account for about 70% of the global tuna catch (Lawson, 2008; FAO, 2009). The Western and Central Pacific Ocean (WCPO; area managed by the Western and Central Pacific Fisheries Commission, WCPFC) is by far the most important tuna fishing ground, contributing about 50% (2.4 million tonnes in 2007) of the global tuna catches (Lawson, 2008) using predominately purse seine, longline and pole-and-line gears.

Over the last decade there has been considerable debate on the sustainability of these fisheries and the ecosystem upon which they are dependent. Seamounts have been hypothesized as important aggregating locations for tunas and other pelagic species (Holland and Grubbs, 2007; Litvinov, 2007; Morato et al., 2008) and proposed as potential locations for special conservation measure to help protect these fisheries from potential over-exploitation. In the WCPO, the status of the tuna stocks varies amongst species. Current stock assessments indicate that overfishing is occurring on the bigeye stock and that the adult component of the stock may be overfished (Langley et al., 2008). Yellowfin tuna is fully exploited with significant probability of overfishing (Langley et al., 2007). On the other hand, overfishing is not occurring on skipjack and some increases in catch may be sustainable (Langley and Hampton, 2008). Current stock assessments also indicate that the albacore stock is not overfished but there are significant uncertainties in the assessment (Hoyle et al., 2008). Major management concerns in the region include a general increase in effective fishing effort, the impact of purse seining on juvenile bigeye and yellowfin, longline catches of adult bigeye, and increasing illegal, unregulated and unreported (IUU) fishing by vessels of both members and non-members of the WCPFC (FAO, 2009).

Seamounts are important topographic features of the ocean bottom and their influence on local abundances of many commercial demersal species is well documented (Clark et al., 2007; Marques-da-Silva and Pinho, 2007; Watson et al., 2007). Their importance for pelagic fish has been only demonstrated for a small part of the northeast Atlantic, in the Azores EEZ (Morato et al., 2008) and the

contribution of seamounts to global fisheries catch is still poorly estimated. Watson et al. (2007) tried to assess the global seamount catch by allocating catch statistics to spatial cells and by intersecting this modeled distribution with a map of known seamounts. With this method, they estimated that about 10% of yellowfin tuna catch, 4% of bigeye, albacore and skipjack were caught in the vicinity of seamounts. This method, however, is highly dependent on the catch allocation algorithm at a too large spatial scale to capture seamounts association, and the habitat affinity index which is to some extent subjective.

In the Pacific Ocean region, tuna fish or fishing has been reported in association with seamounts but no analyses of tuna fishing around these features have been performed at an ocean basin scale. Associations with seamounts have been observed for bigeye tuna, yellowfin tuna and albacore (Yasui, 1986; Anon., 1994, Holland et al., 1999; Itano and Holland, 2000; Sibert et al., 2000, 2003; Klimley et al., 2003; 2005; Musyl, et al. 2003; Beverly et al., 2004) in the region, but only from four specific seamounts: Cross, Capricorn, Emperor and Espiritu Santo seamounts. The Emperor Seamount chain (Hawaii), for example, has a long history of tuna fishing around its features. The Japanese fleet has been longlining for albacore since 1938 and fishing with pole-and-line since 1973 (Yasui, 1986). Pole-and-line catches in this seamount chain represented 5 to 25% of the total albacore landings by Japanese vessels. Cross seamount, also in Hawaii waters, is another well known seamount in the Pacific that has become a handline and deep longline fishing ground for bigeye and yellowfin tuna in the 1990's (Beverly et al., 2004; Itano and Holland, 2000). The handline fishery on the Cross Seamount was based on high catch rates of juvenile fish. In the western and central Pacific Ocean there are fewer reported examples of tuna fishing around seamounts. The exception is the longline fishing experiments in Tongan waters where catch rates were found to be much higher close to Capricorn seamount when compared to the open ocean (Anon., 1994). During these experiments catch rates on Capricorn were 12.7 tuna per hundred hooks (mainly bigeye and yellowfin) while open ocean sets averaged 1.9 tuna per hundred hooks (mainly albacore).

To examine the hypotheses that oceanic pelagic species are associated with seamounts we use a spatially explicit 47 year time-series of longline catch data, and a recently validated and spatially explicit seamount occurrence dataset for the Pacific Ocean to 1) look for higher catches of tuna species close to seamounts, 2) identify seamounts with significantly higher catches close to their summits relevant to identify hotspots for fishing industry, and 3) quantify the seamount contribution to Pacific Ocean tuna catches overtime.

Material and Methods

Seamounts in the Pacific. The numbers and locations of Pacific seamounts have been determined by several authors but the dataset by Kitchingman and Lai (2004) and Kitchingman et al. (2007) is one of the most complete and this dataset has been validated for part of the Pacific Ocean by Allain et al. (2008) by cross checking its seamount positions with other datasets available for the Pacific region. This process was able to remove atolls and islands that had been incorrectly classified as seamounts. It also added seamounts that were not detected by Kitchingman and Lai (2004) algorithm but were detected in other datasets (e.g. Seamount Catalog <http://earthref.org/SBN>, GEBCO <http://www.gebco.net>, Volcano NGDC <http://www.volcano.si.edu>, or NGA underwater features <http://earth-info.nga.mil>). The final datasets produced a list of 4021 underwater features in a defined area of the Western and Central Pacific Ocean.

In this work we used an extension of the Allain et al. (2008) seamount dataset so it covers a larger area of the Pacific Ocean (50°N-50°S and 105°E-95°W). This included all validated seamounts in Allain et al.

(2008) plus all validated seamounts in the same database (SPC database) that lie outside of Allain study area (n= 6022), plus those from Kitchingman and Lai (2004) that lie in the area missing from the previous datasets (n= 1908), minus those seamounts lying in the Indian Ocean. The final seamount list used in this study includes 7741 of these features (Figure 1)

Tuna fisheries longline catch data. The Secretariat of the Pacific Community (SPC) maintains a Catch and Effort database (CES) on industrial tuna fisheries in the WCPO. This database has been extensively used for research and monitoring purposes such as assessing the state of exploitation of the tuna stocks. CES contains data from daily catch and effort logsheets provided by over 20 member countries. It has information on vessel trip, date, GPS position of the fishing operation, the effort and configuration of the gear expended in that fishing operation and the catch for each species taken (see details in Williams, 2001). CES currently has over 2.5 million records from 1960 onwards covering longline, purse seine, pole and line and troll fishing gears. The quality of logsheet data increased substantially in recent years (Lawson et al., 2002). Problems have existed in the past with the reporting of catches on logsheets for certain fleets. However, the reporting in recent years appears to have little biased (Lawson et al., 2002).

All longline sets from the period 1960-2007 and for the area 50°N-50°S and 105°E-95°W were extracted from the SPC's catch and effort system. The final dataset contained 1.8 million sets (Figure 2). Catch by species was returned as numbers, estimated weight, and discarded fish. Date and geographic location of the set, numbers of hooks, flag and fleet of the fishing boat were also extracted. Studying catch data in relation to seamount positions presents two major challenges. The first is common to any large scale study on seamount and lies in deciding what seamounts are and where they are located. The second lies in the quality of the fisheries data for the specific purpose of quantifying seamount-associated catches. For example, the position of a longline set represents only a rough approximation of where the gear is actually fishing since one set can be more than 100km long and the logsheet will contain only one lat/long position.

Distance of longline sets to closest seamount. The distance (d) of each longline set to the closest seamount was estimated using the simple spherical law of cosines:

$$d = \text{acos}[\sin(\text{lat}_1) \cdot \sin(\text{lat}_2) + \cos(\text{lat}_1) \cdot \cos(\text{lat}_2) \cdot \cos(\text{long}_1 - \text{long}_2)] \cdot r.$$

Only sets that were located within 100km from any seamount summit were selected, i.e. 1.051.463 sets or rows. This selection was done to reduce the number of rows for computing proposes and because we were interested in looking at data points close to seamount summits. Those longline sets farther than 100km are unlikely to be under the influence of the seamount itself (Morato et al., 2008). From the 7741 seamounts in the dataset only 4465 had longline sets within 100 km from their summits.

Standardization of longline logsheet data. Fisheries catch data are usually influenced by many factors in addition to fish abundance, including fishing fleet, fishing location, year, season, moon phase, and many environmental conditions. Consequently, catch data are usually standardized to remove the impact of such factors. Generalized linear models (GLM) are the most common method for standardizing catch and effort data (Maunder and Punt, 2004) and assume that the expected value of a response variable is related to a linear combination of explanatory variables (Guisan et al., 2002). In the present study we used GLM techniques to standardize yellowfin, bigeye and albacore catch data for longline sets

performed within 100km from any seamount summit (n=1.051.463). Longline sets were allocated to 7 seven areas to allow computing.

The natural logarithm of the catch in numbers +1 was used as the response variable. After trying different sets of explanatory variables, it was decided to use year, moon phase, month (as a proxy for annual variability), geographical areas (lat5 + long5), and vessel type (described by flag and fleet) as categorical variables and number of hooks as a continuous variable. A Gaussian family of error distributions with identity link function was used and the common analysis of variance (ANOVA) for generalized linear model fits and drop tests were performed. The drop test computes the single explanatory variables that can be maintained or dropped from the model:

$$\ln(\text{Catch}_n + 1) \sim \text{Year} + \text{moon phase} + \text{lat5} + \text{long5} + \text{flagfleet} + \text{effort}$$

Years included in the standardization were 1960 to 2008, but the latest being incomplete. Moon phase was divided in 8 categories from New to Full. To calculate the moon phase for each longline set, the reference New Moon date was assumed as 18/01/1950 at 7:00 a.m. and the moon period assumed as 29.5². The geographical areas used in the standardization were squares of 5 degrees latitude and longitude³. Vessels were categorized based on their flag and fleet type but a combination of the two was used. Effort was measured as the number of hooks in each longline set.

Analyses of the GLMs residuals. In order to identify seamounts with significantly higher catches close to their summits the residuals of the GLMs were analyzed against the distance of each longline set to the nearest seamount. Linear and quadratic models were then fitted for each tuna species to the whole data and to each seamount. Seamounts showing significant regressions and a negative slope were selected. Additionally, residuals from the average catch in number were estimated for each distance interval 0-100, bin size 10, for each seamount. Negative linear or logarithmic models were fitted to each of the 4465 seamounts and for each species separately. A short Visual basic for Applications (VBA) code was developed to perform the analyses. Furthermore, one-way analyses of variance (ANOVA) were performed to test for significant differences between mean Catch residuals at different distances from each individual seamount. When significant F-test values from the ANOVA were found, the Dunnett's post hoc multiple comparison test was used to determine what distance bin mean catch residuals were significantly higher than the overall mean catch residuals, the control mean (Morato et al., 2008).

A set of criteria was defined to select seamounts showing significant higher catches close to their summits (Table 1). Seamounts were considered to have a significant impact on tuna catch if (1) had more than 100 longline sets in their vicinity ($n \geq 100$); (2) longline sets in at least 6 out of the 10 distance bins (blanks < 5); (3) if showed a significant linear or quadratic regression ($p < 0.05$) with a negative slope ($b < 0$) on the residuals of the catch in number (distance to seamount vs residuals of Catch in numbers); (4) if showed a significant linear or logarithmic regression ($p < 0.05$) with a negative slope ($b < 0$) on mean residuals at different distances bins (10 km distance bin vs Mean residuals of Catch in numbers); (5) if showed significant differences between mean catch value at different distances ($p < 0.05$) and (6) showed 1, 2 or 3 significant (Dunnett Q test) higher residuals close to the seamount (<40km) than the overall mean (Q_{10}, Q_{20}, Q_{30} and $Q_{40} > q'$).

² Moon period= 29.53058867. The Excel formula is =INDEX(\$D\$2:\$D\$9,MOD(ROUND(MOD(\$A5-\$B\$2,\$B\$1)/\$B\$1*8,0),8)+1) where D2:D9= Moon phases, A5= Date with unknown moon phase, B1= Moon Period, and B2= reference New Moon date

³ The Excel formula is =ROUNDUP(I2/5,0)*5

Overtime trends in seamounts effect. In order to investigate changes over time in the seamount effect on tuna catches, we estimated the average slope and intercepts of the regressions (residuals of the GLMs against the distance of each longline set to the nearest seamount) for each year for the period 1965 to 2007. In these analyses we used only those longline sets that were performed around significant seamounts, as detected by the methods described above. With this, we expected to investigate changes in the slopes and intercepts of the regressions over time. Steeper negative slopes and higher intercepts will indicate stronger effects of seamounts while positive or close to zero slopes and negative intercepts will indicate that seamounts are no longer enhancing tuna catches.

Quantifying tuna seamounts catch. After selecting seamounts that significantly increased the longline catch as described above we quantified the proportion of the standardized longline catch that was fished within 100km to their summits. These proportions were then extrapolated to the entire WCPO area to estimate the total longline catch of tuna species around WCPO seamounts.

Results

Exploration of CES database. The SPC's catch and effort database contained 1.8 million sets mostly concentrated in the area 10°N-10°S and 140°E-160°W (Figure 2). Areas with high levels of fishing effort were the SE coast of Australia, Fiji, Federal States of Micronesia, and Solomon Islands. The average fishing effort, as the mean number of hooks in each longline, also varies spatially. This indicates different gear configurations used in different areas with common patterns being a higher number of hooks per longline at higher latitudes and smaller gears in equatorial region. In the WCPO, the spatial distribution of catch per unit of effort varies amongst species. Yellowfin tuna mean CPUE during 1960–2007 were higher in the western region of the Pacific Ocean. Bigeye tuna CPUE's peaked in equatorial regions while albacore peaked at higher latitudes. These patterns clearly match the natural distribution of these species in the Western Pacific region (Langley et al., 2007, 2008; Hoyle et al., 2008).

Standardization of longline logsheet data. Pseudo- R^2 values for most GLM were approximately 0.40. For yellowfin, pseudo- R^2 values ranged from 0.35 to 0.52, while for albacore ranged from 0.26 to 0.84 and for bigeye 0.31 to 0.53. These values were in the range of GLM models fits for standardization of tuna catch data (Su et al., 2008). All explanatory variables were highly significant for all species with the exception of "Moon" for albacore in area 7. The residuals were used as a measure of the difference between the observed sample and the fitted GLM. This measure allows quantifying the catches that were higher than predicted by the regression models. Thus, positive residuals identify those catches greater than predicted by the GLM and negative residual values those catches smaller than predicted. Most of the residuals were close to zero meaning small or no difference between the predicted and the observed catches (Figure 3).

Analyses of the residuals. The analyses of the residuals for the whole dataset revealed different patterns between species. If considering all seamounts and catch data, yellowfin tuna showed somehow higher catches close to seamounts as revealed by significant (ANOVA with Dunnett test) higher residuals for the 10 and 20 distance bin intervals (Figure 4). For bigeye tuna, the patterns were not clear while for albacore significant higher residuals were found away (≥ 70 km) from seamounts (Figure 4).

All 4465 seamounts considered in this study were screened for higher catches of tuna close to their summits, using multiple methods. Only 1780 had one hundred or more longline sets in their vicinity and 2760 had longline sets in at least 6 out of the 10 distance bins. Applying the two first criteria reduced the number of seamounts to 1663.

The number of seamounts showing significant higher catches of tuna in their vicinities varies between the methods used (Table 2) with more restrictive methods selecting fewer seamounts. The number of seamounts that were selected by at least one method and for at least one species was 640 (38%) of the seamounts with sufficient data to be screened, with 533 being located inside EEZs. From these, 310 seamounts were significant for yellowfin, 246 for bigeye and 219 for albacore.

Considering just the regression models on residuals of the catch data or regression models on aggregated residuals at 10km distance bins, the number of seamounts with higher catches were 459 and 467, representing 27.6% and 28.1% of the seamounts with sufficient data to be screened. The number of significant seamounts was higher for yellowfin tuna with 209 (12.6%) or 239 (14.4%) seamounts, followed by bigeye with 164 (9.9%) and 167 (10.0%) and albacore with 161 (9.7%) and 143 (8.6%) significant seamounts.

When considering the one-way analyses of variance with the Dunnett's post hoc multiple comparison test, the number of significant seamounts were much smaller. It ranged from 99 (6.0%) if accepting only one significant mean in the first four to 13 (0.8%) if accepting three out of four significant means. Note that this selection method also required significant regression models on aggregated residuals at 10km distance bins with negative slopes. With this method, the number of significant seamounts was smaller but also higher for yellowfin tuna (50 to 8), followed by bigeye (17 to 6) and albacore (28 to 3). If combining regression models on residuals with ANOVA and Dunnett's test, the numbers of significant seamounts is similar to the ones mentioned above. It ranged from 176 to 16 for all tuna species, 69 to 16 for yellowfin tuna, 61 to 6 for bigeye and 69 to 4 for albacore.

The number of seamounts that satisfy all criteria defined for all methods varied from 89 (5.4%) to 11 (0.7%) if considering all tuna species, 43 (2.6%) to 7 (0.4%) for yellowfin, 30 (1.8%) to 3 (0.2%) for bigeye and 27 (1.6%) to 2 (0.1%) for albacore.

Seamounts with significantly higher tuna catches were found throughout the study area (Figure 5) with similar spatial patterns for all three tuna species: yellowfin, bigeye, and albacore. The only exception was the area north of 10°N where only two seamounts were selected. The proportion of significant seamounts located within EEZs was larger than 85% for most of the methods with only about 15% or less lying in the high seas (Table 2). Many seamounts were selected around French Polynesia, Fiji, Federal States of Micronesia, Kiribati, or Solomon islands but almost every EEZ had significant seamounts (Table 3).

Overtime trends in seamounts effect. Our analyses of the temporal changes in the average slopes and intercepts of the regressions did not show any clear pattern (Figure 6). On the contrary, no evidences of significant changes in the seamount effects in enhancing fisheries yields were revealed. For all species, the slopes of the regressions were always negative, indicating higher catches close to seamounts summits, and the intercepts were always positive indicating that catches around summits were always higher than predicted by our GLM models (Figure 6). In any case, some patterns can be described, such as weakening of seamount effects with time for yellowfin (smaller slopes in absolute terms and smaller intercepts), enhancement for bigeye (greater slopes in absolute terms and greater intercepts), and an irregular pattern for albacore.

Quantifying tuna longline catch around seamounts. Our methodology has identified that a significant proportion of tuna longline catch is associated with seamounts with these proportions varying over time (Figure 7a). For yellowfin tuna, the proportion of the catch for the total period apportioned to

seamounts varied from 10.1% when considering all selected seamounts, to 6.8% or 7.4% when considering only those seamounts selected by regression models on residuals of the catch or regression models on aggregated residuals at 10km distance bins. The proportions of yellowfin tuna were higher before 1980 where it reached the minimum of about 6%. From this year onwards, the proportions have increased steadily reaching a value of 14% in recent years (Figure 7a, YFT). For bigeye tuna, the proportion of the catch being allocated to seamounts was smaller but more constant over time. For the whole period, the proportion of bigeye catch allocated to seamounts varied from 9.3% for all significant seamounts to 6.6% or 5.9% when considering the other two main methodologies (Figure 7a, BET). These proportions did not change much from 1965 to 2007. The contrary was observed for albacore, with higher proportions of the catch coming from seamounts in recent years (Figure 7a, ALB). When considering the whole period, the proportions of albacore were very similar to bigeye varying from 9.2% for all significant seamounts to 6.9% or 5.9% when considering only those seamounts selected by regression models on residuals of the catch or regression models on aggregated residuals.

From the proportion of the tuna longline catch apportioned to seamounts (Figure 7a), it was possible to estimate annual landings for different species (Figure 7b). Longline fishing around seamounts may be responsible in recent years for about 8000 tons of yellowfin, 6000 tons of bigeye and 10000 tons of albacore. The catches around seamounts have increased over time for bigeye and albacore but have been fairly stable for yellowfin (Figure 7b). Generally, seamounts in the western central Pacific region may be responsible for an annual catch by longline of as much as 25 thousand tons (Figure 8).

Seamounts showing higher catches for the whole period (1965-2007) were located around the 10°S parallel with Phoenix Islands (Kiribati) and Tuvalu having some important seamounts. For bigeye tuna, seamounts with large catches were identified throughout the region with Line Islands (Kiribati), Federal States of Micronesia (FSM) and French Polynesia (FP) having some of the most productive seamounts. For albacore, the most productive seamounts were located south of the parallel 10°S with Fiji, American Samoa and Cook Islands having some important seamounts. These patterns, however, varied with time with individual seamounts showing different catches between decades. Yellowfin tuna showed higher catches during the 1970's from Tuvalu, Phoenix and Line Islands (Kiribati) seamounts, whereas in the 1980's and 1990's the most important seamounts were from FSM and Papua New Guinea and in 2000's from Vanuatu and Fiji. Bigeye seamount catch did not varied significantly between decades and the most productive seamounts were located in FSM, FP and Line Islands. For albacore, seamount tuna catches have increased steadily in the last decades with important seamounts changing over time. In the 1970's the most productive seamounts were located in the high seas south of Cook Islands and in the Cook Islands, whereas in the 1980's and 1990's were mostly in Australia and New Zealand, and in 2000's mostly in Fiji, American Samoa, Cook Islands and Solomon Islands.

Discussion

Our analyses suggest that a significant number of seamounts throughout the Pacific Ocean are being targeted by the tuna longline fleets. The numbers of seamounts that appear to have significantly increased catch-per-unit-of-effort, however, varied substantially between methods mostly because more statistically restrictive methods selects fewer seamounts. Adopting somewhat conservative figures, this study concluded that at least 5.3-10% of the seamounts in the Pacific show significant higher CPUE values for at least one tuna species. These estimates are extremely high considering that many seamounts in the region are very deep (Alain et al., 2008) and thus not likely to have an impact on aggregating pelagic visitors (Morato et al., 2008), and that many seamounts were not included in the study due to insufficient fisheries logbook data. It should also be noted that the complexity of the

western Pacific Ocean basin with many islands, atolls and ridges, and the existence of numerous fishing aggregating devices (FAD) in the region (OFP/SPC, confidential data) may also detract tuna from gathering around some specific seamounts.

Our study estimated that seamounts in the western central Pacific region may be responsible for an annual longline catch of as much as 25 thousand tons. The proportion of the catch apportioned to seamounts varied from 6.8% to 10.1% for yellowfin, and 5.9% to 9.3% for bigeye and albacore. These proportions were very similar to those estimated by Watson et al. (2007). When extrapolating these values for the whole longline fisheries in the Pacific, we ended up with tonnages estimates of 8000 tons for yellowfin, 6000 tons for bigeye and about 10000 tons for albacore for recent years. It should be noted that the estimates are very dependent on the method used to select seamounts and also very dependent on the area considered to be under the influence of each seamount. The results presented however are conservative as we only considered those seamounts that showed a significant effect in increasing fishing yields.

Aggregations of yellowfin, bigeye and albacore in the Pacific have been directly observed for only a few seamounts such as the Hawaiian Cross (Holland et al., 1999; Itano and Holland, 2000; Sibert et al., 2000; Beverly et al., 2004; Musyl et al., 2003) and Emperor seamounts (Yasui, 1986), the Espíritu Santo seamount in Baja California, Mexico (Klimley et al., 2003), and the Capricorn seamount in Tonga (Anon., 1994). In contrast, our study identified many seamounts throughout the western Pacific Ocean that may act as important aggregating points for tuna species. It should be noted that this study covered only 1663 of the 7741 seamounts that have been mapped in the region (Allain et al., 2008; Kitchingman and Lai, 2004; Kitchingman et al., 2007), and consequently it is likely that these numbers may be underestimated.

Information on the physical characteristics of most seamounts, such as depth of the summit, elevation and slope are unknown or not accurately measured preventing any detailed analyses on the parameters that may be driving tuna aggregations. The rough estimates of seamount depths in the database used in this study show, however, significant seamounts with summits ranging from a few meters down to over 4000m depth. Nevertheless, it is believed that shallow seamounts with summits below 1000m will potentially have a higher effect on aggregating most tuna species (Morato et al., 2008), which is in agreement with the most common vertical movement patterns of these species (Musyl, 2003; Dagorn et al., 2006; Schaefer et al., 2007; Arrizabalaga et al., 2008; Weng et al., 2009). Albacore is believed to utilize intermediate depths spending most of their time between 150 and 250 m (Domokos et al., 2007).

This study also demonstrated that seamounts enhancing tuna yields were found throughout the study area with a great proportion lying within national EEZs. This aspect may have significant impact in terms of management since it is easier to implement effective fishing regulations on seamounts within national boundaries (Probert et al., 2007; Santos et al., in press). Only about 15% of the seamounts with higher catch were located in the high seas; with the pocket between Solomon Islands and Tuvalu having a few significant seamounts for yellowfin and bigeye tuna and the high seas area south of Cook Islands having significant seamounts for albacore. A more detailed analyses is required to fully evaluate the importance of these high seas areas for the conservation of tuna resources.

This study did not show clear temporal changes on the seamount potential to enhance fisheries yields over the period from 1965 to 2007. The patterns revealed by analyzing the average slopes and intercepts of the regressions may indicate that even in situations of overfishing, such as the present situation of bigeye and yellowfin (Langley et al., 2007; 2008), seamounts will still increase tuna fisheries

yields. Furthermore, our analyses showed increased proportions of the longline catch being taken from seamounts. These aggregations, areas as well as any other aggregation points such as FADs, atolls or islands, may lead to hyperstability of catch rates caused by shoaling behavior and range contraction during stock declines (Hilborn & Walters, 1992; Pitcher 1995, Mackinson et al., 1997) and should be carefully accounted, in the analysis of spatial catch rate data (Walters, 2003).

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Tables

Table 1 – Set of analyses and criteria used to select seamounts with higher tuna catches close to their summits

#	Type	Analyses	Condition
1	Data	Longline sets close to each seamount	≥ 100
2	Data	Longline sets in a range of 10km distance bins	blanks < 5
3	Regression	Simple linear and quadratic models on the residuals of the catch in numbers	$p < 0.05$ and $b < 0$
4	Regression	Simple linear and logarithmic models on mean residuals at 10km distance bins	$p < 0.05$ and $b < 0$
5	ANOVA	ANOVA on mean residuals at 10 km distance bins	$p < 0.05$
6	ANOVA	Dunnett's post hoc multiple comparison to determine distance bins with significantly higher residuals	$Q_n > q'$

Table 2 - Number of selected seamounts using different selection criteria. In parenthesis are the number of seamounts within EEZs.

Method	Condition	n of seamounts			
		ALL	YFT	BET	ALB
0 Any method		640 (533)	310 (259)	246 (201)	219 (189)
1 Regression models on residuals	$p < 0.05, b < 0$	459 (395)	209 (180)	164 (137)	161 (140)
2 Regression models on aggregated residuals at 10km distance bins	$p < 0.05, b < 0$	467 (406)	239 (200)	167 (137)	143 (123)
3 Analyses of variance on aggregated residuals at 10km distance bins, Dunnett's post hoc multiple comparison (with method 2)	$p < 0.05,$ $n(Q_{10-40} > q') \geq 1$	99 (91)	50 (44)	32 (27)	28 (26)
4 Analyses of variance on aggregated residuals at 10km distance bins, Dunnett's post hoc multiple comparison (with method 2)	$p < 0.05,$ $n(Q_{10-40} > q') \geq 2$	29 (28)	17 (17)	9 (8)	6 (6)
5 Analyses of variance on aggregated residuals at 10km distance bins, Dunnett's post hoc multiple comparison (with method 2)	$p < 0.05,$ $n(Q_{10-40} > q') \geq 3$	13 (13)	8 (8)	3 (3)	3 (3)
6 Method 1+ Method 3		176 (157)	69 (60)	61 (52)	69 (63)
7 Method 1+ Method 4		51 (47)	19 (18)	22 (19)	15 (15)
8 Method 1+ Method 5		16 (16)	7 (7)	6 (6)	4 (4)
9 Method 1+ Method 2		277 (243)	138 (121)	85 (74)	85 (73)
10 Method 1+ Method 2+ Method 3		89 (82)	43 (38)	30 (25)	27 (25)
11 Method 1+ Method 2+ Method 4		26 (25)	15 (15)	9 (8)	5 (5)
12 Method 1+ Method 2+ Method 5		11 (11)	7 (7)	3 (3)	2 (2)

Table 3 - Number of selected seamounts at different Exclusive Economic Zones (EEZ) and High Seas using different selection criteria. Res is regression models on residuals, Reg is regression models on aggregated residuals at 10km distance bins, YFT is yellowfin tuna, BET is bigeye and ALB is albacore.

EEZ	All Spp			YFT			BET			ALB		
	Any	Any	Res	Reg	Any	Res	Reg	Any	Res	Reg		
French Polynesia	82	50	39	37	31	23	20	20	18	12		
Fiji	47	19	13	13	19	14	12	23	20	9		
Fed. States of Micronesia	38	16	8	13	15	9	12	13	7	9		
Kiribati (Line Islands)	38	15	8	13	15	10	12	13	9	12		
Solomon Islands	34	15	9	11	9	6	6	14	11	8		
Cook Island	32	14	12	12	9	4	6	16	12	9		
Marshall Island	32	15	8	13	13	9	12	7	5	4		
Papua New Guinea	28	6	5	5	11	9	4	13	10	10		
New Zealand	26	12	7	7	12	8	5	6	4	2		
Tonga	21	16	14	14	10	7	6	4	1	4		
Vanuatu	18	11	8	7	10	8	9	3	2	3		
American Samoa	16	10	7	9	8	7	7	8	6	4		
New Caledonia	16	12	11	8	4	4	3	2	1	2		
Australia	15	4	4	3	5	5	2	9	9	7		
Kiribati (Gilbert Islands)	15	7	4	7	2	1	2	8	4	6		
Kiribati (Phoenix Islands)	15	8	6	7	5		5	6	3	4		
Tokelau	15	5	1	4	6	3	6	8	6	6		
Palau	12	5	5	2	5	1	4	4	2	4		
Tuvalu	12	7	4	5	3	3	1	5	4	2		
Norfolk Island	4	2	1	2				2	2	1		
Wallis and Futuna	4	2	1	2	2	1	1					
Samoa	4	4	2	2	3	3	1	1	1			
Niue	3	3	2	3	2	1	1	1		1		
Indonesia	2							2	1	2		
Pitcairn Islands	2				1	1		1	1	1		
USA (Jarvis)	1				1	1						
USA (Palmyra)	1	1	1	1								
High Seas	107	51	29	39	45	26	30	30	22	21		
Total	640	310	209	239	246	164	167	219	161	143		

Figures

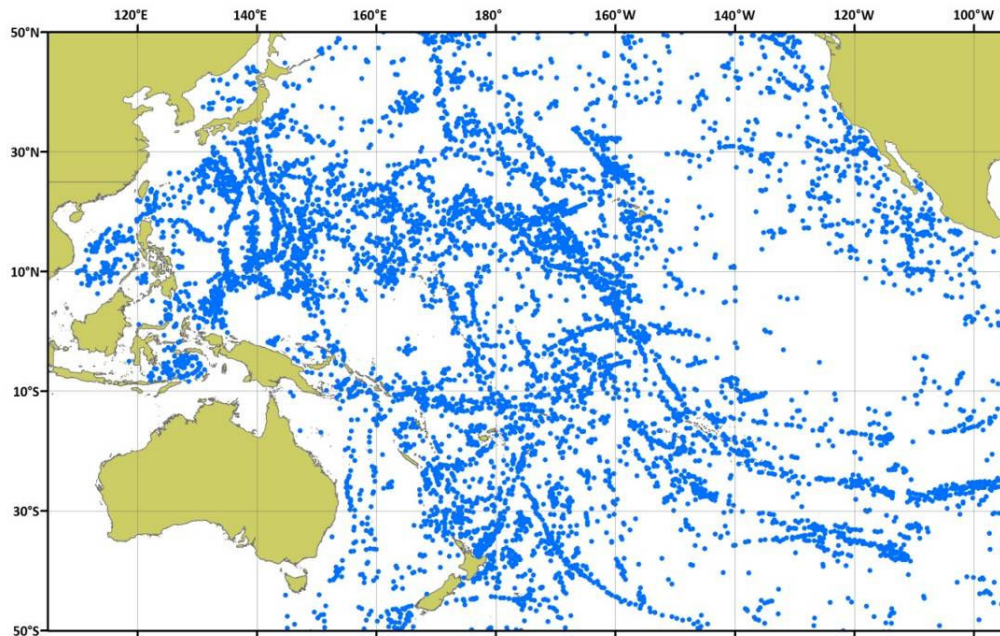


Figure 1 - Final list of seamounts included in the present study. It includes seamounts in the box 50N-50S; 105W-240W ($n=7741$) contained in the SPC dataset ($n=6022$) and the Kitchingman and Lai (2004) dataset ($n=1719$).

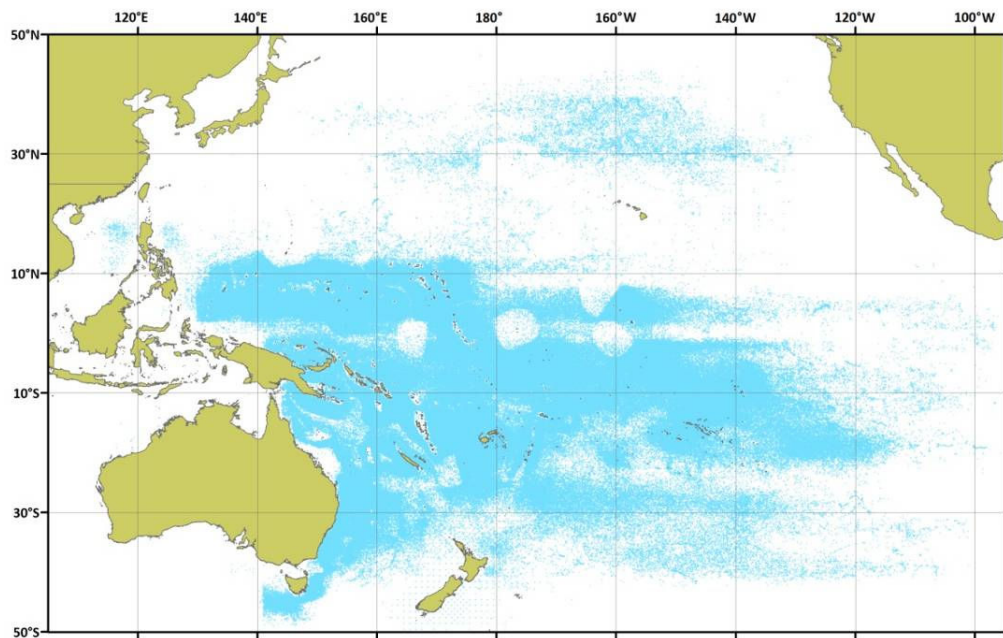


Figure 2 - Location of the 1.8 million longline sets recorded in the SPC's Catch and effort database (1960-2007).

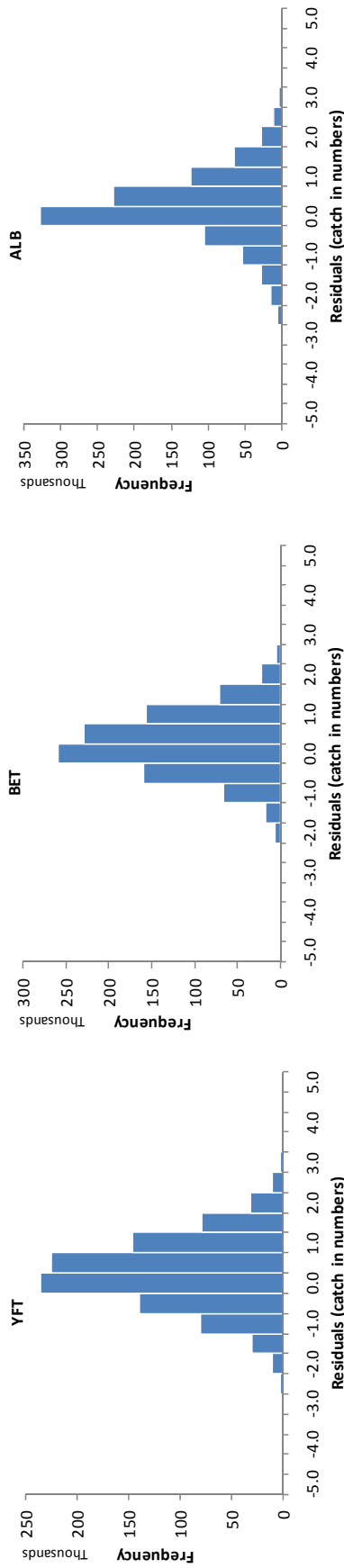


Figure 3 - Frequency distribution of the GLM residuals for (a) Yellowfin tuna, (b) bigeye tuna, and (c) albacore. Note residuals are Log(catch in numbers)

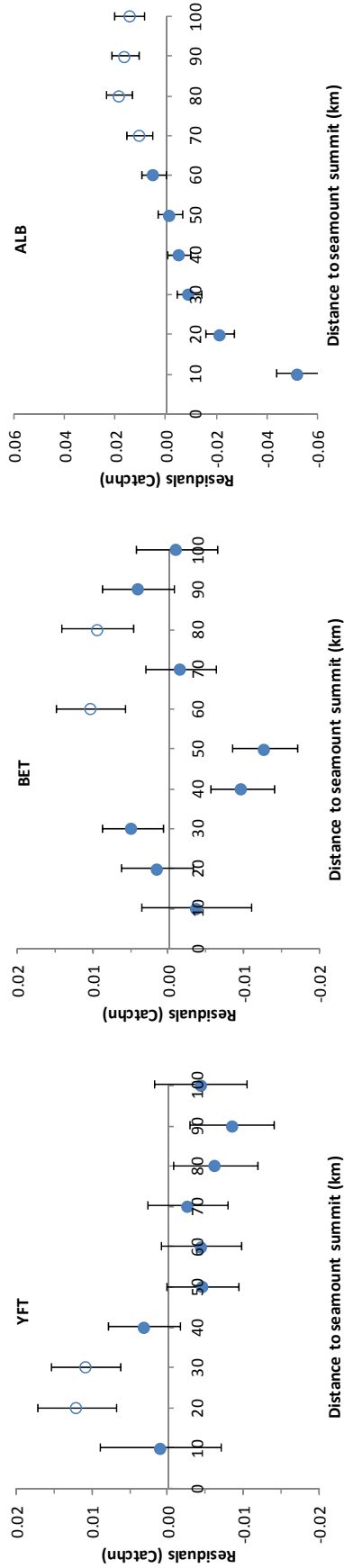


Figure 4- Mean residuals (raw data) as Log(Catch in numbers + 1) \pm 95% confidence limits in relation to the distance to the nearest seamount summit for (a) Yellowfin tuna, (b) bigeye tuna, (c) albacore. Bin size is 10 km and sample sizes are n_{10} = 42437, n_{20} = 101537, n_{30} = 135994, n_{40} = 133493, n_{50} = 130189, n_{60} = 115045, n_{70} = 109165, n_{80} = 100529, n_{90} = 98867, n_{100} = 84207. Open circles are significantly higher (Dunnett test) than the overall mean (light grey dashed line).

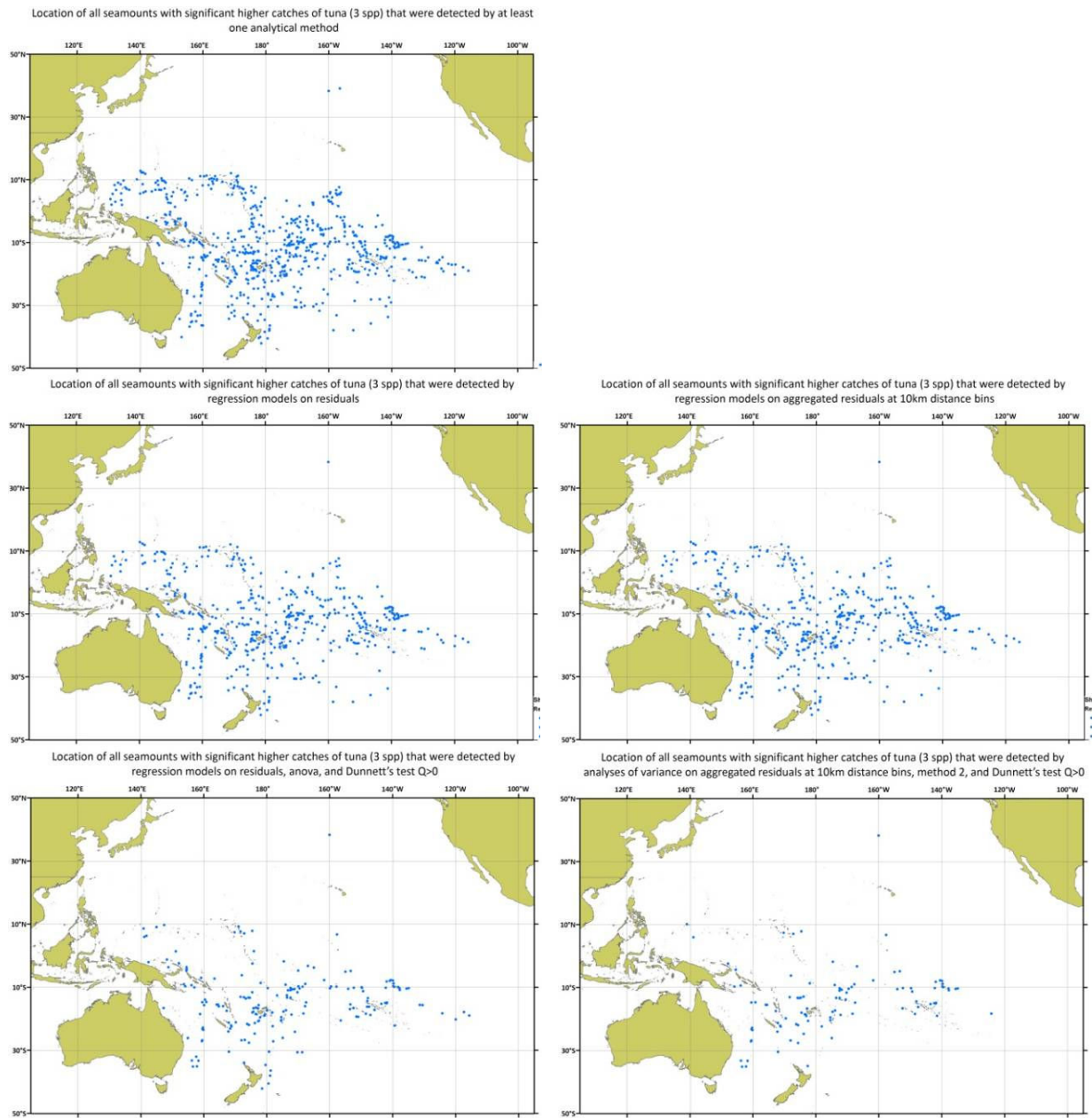


Figure 5 - Location of seamounts with higher catches of any tuna species that were selected by different analytical methods. a) any methods; b) regression models on residuals; c) regression models on aggregated residuals at 10km distance bins; d) regression models on residuals with ANOVA and Dunnett's test; e) regression models on aggregated residuals at 10km distance with ANOVA and Dunnett's test.

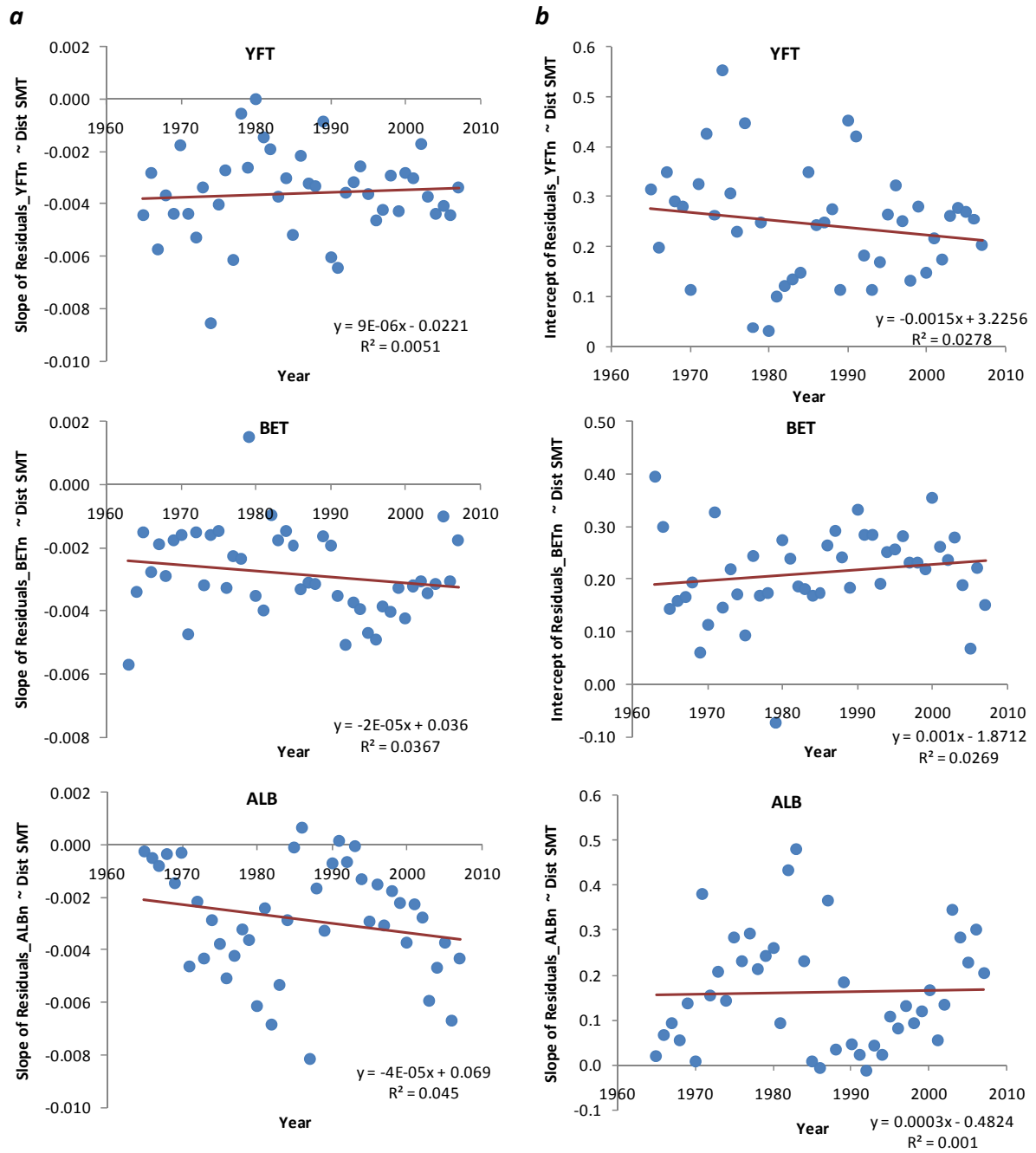


Figure 6 – Temporal patterns on the yearly average (a) slopes and (b) intercepts of the regressions (residuals of the GLMs against the distance of each longline set to the nearest seamount) for the period 1965 to 2007. YFT is yellowfin tuna, BET is bigeye and ALB is albacore.

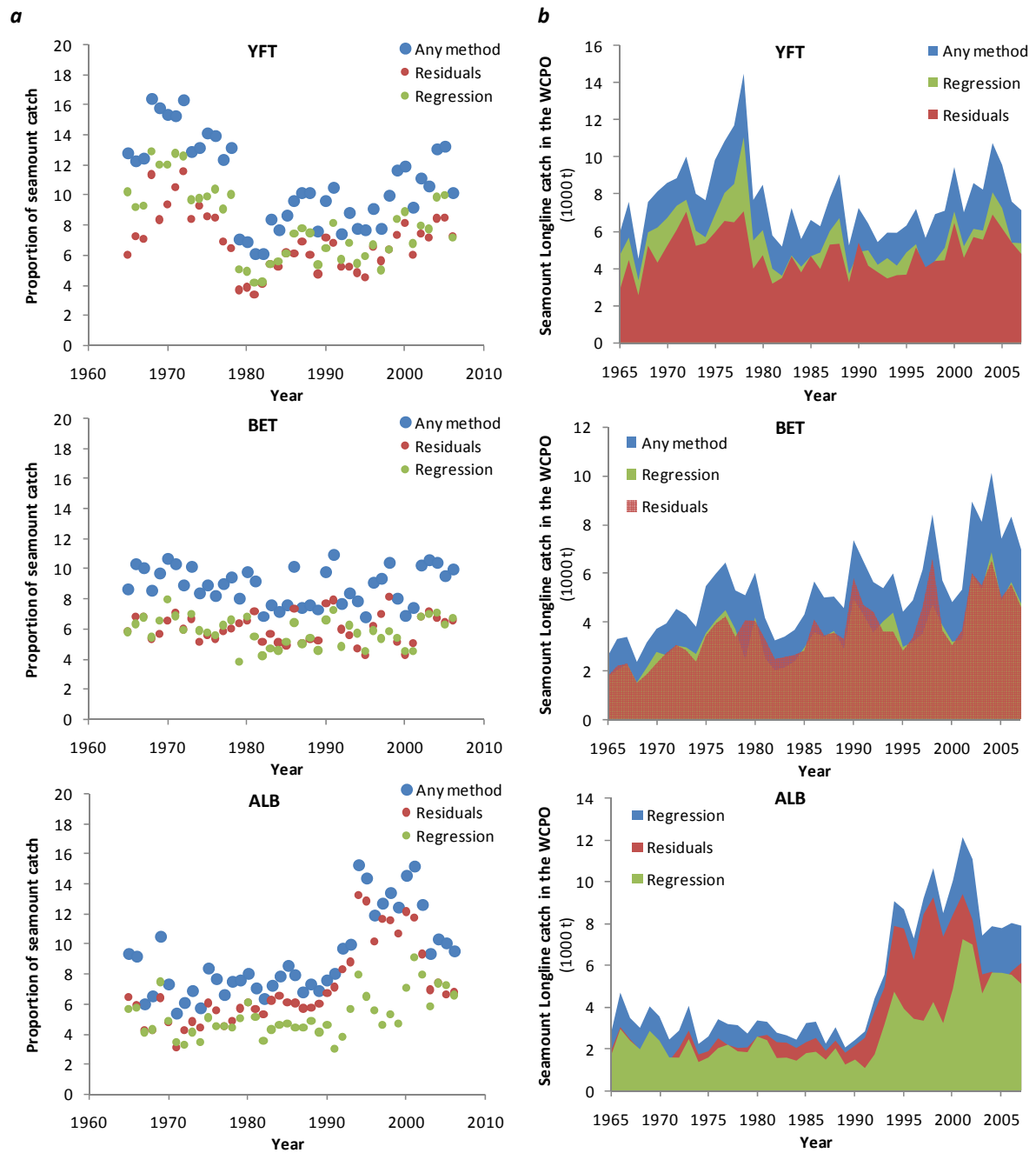


Figure 7 - Longline tuna catch in Western Central Pacific Ocean (WCPO) seamounts in terms of (a- left) proportion of the regions catch and (b- right) estimated values in thousands of metric tons (not cumulative), for three different significant seamount lists. YFT is yellowfin tuna, BET is bigeye and ALB is albacore.

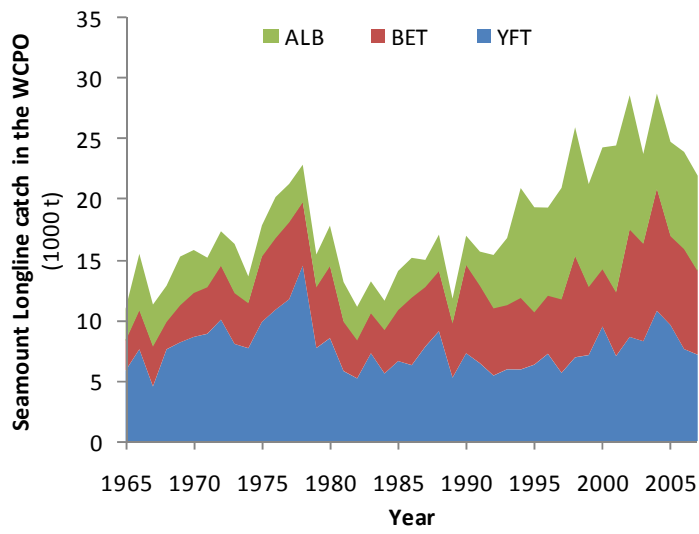


Figure 8 - Cumulative longline tuna catch in Western Central Pacific Ocean (WCPO) seamounts in thousands of metric tons. YFT is yellowfin tuna, BET is bigeye and ALB is albacore.