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THE RELATIONSHIP BETWEEN FISHING MORTALITY AND NUMBER OF FLOATING-OBJECT SETS FOR BIGEYE TUNA IN THE EASTERN PACIFIC OCEAN

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SUMMARY

1. The EPO-wide relationship between the fishing mortality for juvenile (age 2 years and less) bigeye tuna and the number of floating-object sets is positive and statistically significant (p-values <0.05).
2. The area-specific relationships between the fishing mortality for bigeye tuna and the number of floating-object sets are also statistically significant (p-values <0.05). Of the five area-specific relationships for bigeye, one (for the inshore equatorial area (Area 3))) is negative and three are strictly positive, including the one for the offshore equatorial area (Area 2) where 75% of the current bigeye catch is taken.
3. Three hypotheses are presented to explain the negative relationship for the inshore equatorial OBJ fishery, the most plausible being a higher degree of local depletion in this area (Area 3).
4. The positive and statistically significant EPO-wide relationship between the fishing mortality for juvenile (age 2 years and less) bigeye tuna and the number of floating-object sets indicates that fishing mortality increases as the number of floating-object sets increases.

1. INTRODUCTION

The staff recently conducted a new benchmark assessment for bigeye tuna (BET) in the eastern Pacific Ocean (EPO) (SAC-11-06). Different from the previous "best assessment" approach that bases the management on one base case model, the new "risk analysis" approach considers a variety of models to represent alternative hypotheses. The risk analysis (SAC-11-08), based on results from all reference models for BET, suggested that 1) the probability that the target reference points (fishing mortality (*F*) and spawning biomass corresponding to maximum sustainable yield) have been reached is around 50%; 2) the probability that the limit reference points have been exceeded is below the threshold level of 10% specified in Resolution C-16-02. However, the staff recommends precautionary management of maintaining the *status quo*[1] fishing mortality conditions due to the bimodality of assessment results for BET (SAC-11-08). If only the pessimistic group of assessment models is considered, the probability that the limit reference points have been exceeded reaches or even slightly surpasses the 10% threshold level.

The relationship between the F for BET and the number of floating-object (OBJ) sets (N_{OBJ}) needs to be better understood in order to provide management recommendations aiming to maintain the *status quo* F. The new benchmark assessment suggests that juvenile (age 2 years and less) BET, caught predominantly by the OBJ fishery, have been experiencing increased fishing mortality due to the expansion of the OBJ fishery in the EPO since mid-1990 (Figure 14 in SAC-11-06). At the same time, stock status indicators (SAC-11-05) show that N_{OBJ} have continued to increase in the EPO. It is assumed that the increase in N_{OBJ} leads to the increased F for juvenile BET. This paper investigates whether there is a statistically significant relationship between the F for BET and the N_{OBJ} in the EPO, as well as presents several hypothesis, from biological to fisheries or environmental aspects, to explain the different observed relationships by area.

2. DATA AND METHODS

2.1. Fishing mortality for bigeye tuna

Throughout this paper, the F for BET is defined as the weighted F estimates from all forty-four reference models considered in the last benchmark assessment (SAC-11-06). The weights used to compute model-combined F are from the implementation of the risk analysis methodology (see SAC-11 INF-F for technical details regarding how model weights for BET are defined and calculated). The weighted F for BET is computed only from 2000 on because one group of reference models for BET covers a shorter temporal window (2000-2019) than do the rest (1979-2019).

2.2. Number of floating-object sets

At-sea observer and logbook data from IATTC Class 1-6 purse-seine vessels fishing in the EPO is used to compute total and vessel class-specific N_{OBJ}, for the entire EPO and by the geographical areas that are used to define OBJ fisheries in the BET assessment (Figure 3). The dataset covers the period 1975-2019, and includes the date (year, month, day), location (1° latitude and 1° longitude), and vessel class associated with each OBJ set in the data set. To match the weighted F for BET, N_{OBJ} is also computed for 2000-2019.

2.3. Relationship between fishing mortality and number of OBJ sets

The *R* package *mgcv* (version 1.8-24; Wood 2006) is used to estimate the statistical relationship between F and N_{OBJ}. Specifically, a generalized additive model (GAM), with Gaussian error, is used to model annual F as a function of annual N_{OBJ}, where N_{OBJ} is treated in the model as a smooth term (thin plate regression spline with a basis dimension of 3). All the statistical analyses in this paper are conducted in *R* (R Core Team 2020) version 3.5.1. The relationship between F and N_{OBJ} is modelled for the whole EPO by age, as well as for each OBJ fishery defined for BET in the EPO.

[1] Defined as the average fishing mortality during the most recent three-year period (2017-2019).

3. RESULTS

3.1. EPO-wide relationship between fishing mortality and number of OBJ sets

The annual N_{OBJ} in the EPO has strongly increased in the past two decades from less than 5,000 sets in 2000 to over 15,000 sets in 2019 (Figure 1). The five OBJ fisheries defined for BET in the EPO have different selectivity curves, so the EPO-wide F that takes into consideration all five OBJ fisheries should have age-specific variation and trends. Given that the OBJ fisheries in the EPO catch primarily juvenile BET of less than 3 years old, the EPO-wide annual F is computed for two age ranges: 0-1 year and 1-2 years. The two time series show that the F for 0-1 year old BET has a positive trend between 2000-2019, and that the F for 1-2 years old BET increased slightly in 2000-2009 before reaching a relatively stable level (Fig. 1). The comparison of F with N_{OBJ} clearly shows that N_{OBJ} increased at a faster rate than F in the past two decades (Fig. 1).

As mentioned above, separate GAMs were built to evaluate the EPO-wide relationship between annual F and annual N_{OBJ} for 0-1 year and 1-2 year old BET. The two EPO-wide relationships between annual F and annual N_{OBJ} are both estimated to be positive and statistically significant (p-values for the smooth term < 0.05) (Table 1; Fig. 2). Consistent with the differing trends showed in the time series of annual F, the increase in N_{OBJ} leads to a larger proportional increase in F for 0-1 year old than 1-2 year old BET (Figure2).

3.2. Area-specific relationship between fishing mortality and number of OBJ sets

Among the five OBJ fisheries defined for BET in the EPO, the two which operate in the equatorial region (A2-OBJ and A3-OBJ for offshore and inshore, respectively) take the majority of BET catches in the EPO (Figure 3). Total BET catch by the five OBJ fisheries combined remained low in 1975-1993, strongly increased in 1994-2000 with the expansion of the OBJ fishery, and remained at a high level after that. Before 2000, the inshore equatorial OBJ fishery (A3-OBJ) was the most important OBJ fishery for BET in terms of catch amount. As the annual catches taken by the inshore (A3-OBJ) and offshore (A2-OBJ) equatorial OBJ fisheries decreased and increased, respectively, over time, the offshore equatorial OBJ fishery (A2-OBJ) became the dominant OBJ fishery for BET in the last decade. Particularly, the offshore equatorial OBJ fishery (A2-OBJ) contributed to more than half of the total BET catch from the OBJ fisheries in the last decade, and its contribution reached around 75% in 2019.

The trends in area-specific F and N_{OBJ} are positively related for four of the five OBJ fisheries defined for BET in the EPO (Figure 4). All five OBJ fisheries in the EPO made increasing numbers of OBJ sets over time in 2000-2019, and the increasing trends are steeper in offshore areas (Areas 2 and 4) than in inshore areas (Areas 3, 5, and 6). Accordingly, stock assessment models estimate that the F associated with the two offshore OBJ fisheries have pronounced positive trends. Fishing mortalities associated with the two southern inshore OBJ fisheries (A5-OBJ and A6-OBJ) are estimated to increase as well, but their trends are less clear due to large interannual variations. In contrast with the other four OBJ fisheries, the inshore equatorial OBJ fishery (A3-OBJ) shows a decreasing trend of F over time, even through N_{OBJ} for this fishery continued to increase (Figure 4).

GAMs fitting confirms that the relationship between F and N_{OBJ} is strictly positive for three Areas in the EPO, including the most important one for BET (offshore equatorial area; Area 2) (Figure 5). Moreover, the smooth term for N_{OBJ} for Areas 2, 4, and 5 (see Figure 3 for area definition) are significant (p-values < 0.05) (Table 1). In contrast, GAMs suggest that relationship between F and N_{OBJ} is negative for the inshore equatorial area (Area 3), and the percentage of the deviance explained by N_{OBJ} is the lowest among the five Areas. The relationship between F and N_{OBJ} is estimated to be dome-shaped for Area 6.

However, the pattern at larger values of N_{OBJ} is uncertain, as indicated by the wide confidence interval associated with the estimated relationship (Figure 5).

3.3. Comparing the two equatorial OBJ fisheries by vessel class

Regardless of the area of operation, Class-6 purse-seine vessels are more efficient than Class 1-5 purse-seine vessels with respect to catching BET. In the offshore equatorial area (Area 2), BET catch was predominantly taken by Class-6 purse-seine vessels because they made the majority of OBJ sets (Figure 6, left column). The pronounced positive trend in N_{OBJ} made by Class-6 purse-seine vessels resulted in increased BET catch and consequently increased F estimated for BET.

In the inshore equatorial area (Area 3), the relationship is more dynamic and complex. Before 2005, Class-6 purse-seine vessels made the majority of OBJ sets so BET catch was primarily taken by Class-6 purse-seine vessels. After 2005, while Class 1-5 purse-seine vessels were still inefficient in catching BET, they made an increasingly larger proportion of the OBJ sets that reached about 50% in recent years (Figure 6, right column). Another key difference between the OBJ fisheries in Area 2 and Area 3 is in the trend of the catch rate for BET. Since 2005, the nominal catch rate (BET catch per set) of Class-6 purse-seine vessels dropped noticeably more quickly in Area 3 than in Area 2 (Figure 6). Regarding Class-6 purse-seine vessels in Area 3, the fast drop in the catch rate for BET outpaced the increase in fishing effort (i.e. N_{OBJ}), leading to decreased BET catch since 2005.

In summary, at least two factors seem to be responsible for the decrease in post-2005 BET catch taken by the inshore equatorial OBJ fishery (A3-OBJ), even through N_{OBJ} continued to increase in that period:

1. An increasing proportion of the OBJ sets in Area 3 were made by Class 1-5 purse-seine vessels with much lower efficiency in catching BET in comparison to Class-6 purse-seine vessels.
2. While the number of OBJ sets made by Class-6 purse-seine vessels in Area 3 continued to increase since 2005, the catch rate of Class-6 purse-seine vessels dropped at a faster rate during that time.

4. CONCLUSIONS AND DISCUSSION

In this paper, we use statistical tools (*i.e*. GAMs) to evaluate the sign and significance of the relationship between the F for BET and N_{OBJ} for the whole EPO, as well as within each OBJ area defined in the benchmark assessment. Analyses based on GAMs suggest that:

1. The EPO-wide relationship between the F for juvenile (age 2 years and less) BET and the number of floating-object sets is positive and statistically significant (p-values < 0.05).
2. The area-specific relationships between the F for BET and N_{OBJ} are also statistically significant (p-values < 0.05). Of the five area-specific relationships for BET, one (for the inshore equatorial area) is negative and three are strictly positive, including the one for the offshore equatorial area where 75% of the current BET catch is taken.
3. The positive and statistically significant EPO-wide relationship between the F for juvenile (age 2 years and less) BET and N_{OBJ} indicates F increases as N_{OBJ} increases.

Assuming that N_{OBJ} is a reasonable representation of fishing effort, the relationship between F and N_{OBJ} is expected to be significant and positive. This is not the case for the inshore equatorial area (Area 3), where the relationship is significant but negative. Below we provide several hypotheses to explain the negative relationship estimated for BET in the inshore equatorial OBJ fishery (A3-OBJ).

Hypothesis 1: Higher degree of local depletion. Local depletion can be caused by a variety of factors such as reduced local recruitment, increased local fishing effort, and changed movement patterns (increased emigration or/and decreased immigration). Since the stock assessment model for BET is not spatially structured and uses the "areas-as-fleets" approach, every fishery-specific F is estimated with respect to the whole population in the EPO. As such, a faster depletion of BET in Area 3 than in other Areas in the EPO results in less local catch that could translate into decreased F with respect to the whole population in the EPO.

Trends in longline indices of abundance support this hypothesis. Within the EPO, the standardized longline index of abundance decreased at the highest rate in Area 3, indicating that the abundance of adult BET decreased faster in Area 3 than in other Areas in the EPO. The trend in the mean length of BET caught in the OBJ fishery is another good indicator of local depletion. Given the selectivity of the fishery is constant across time, the mean length of BET caught in the OBJ fishery is expected to be negatively associated with the degree of population depletion. Length composition data used in the recent benchmark assessment suggest that the mean length of BET caught in the inshore equatorial OBJ fishery does not have a noticeable long-term trend since 2000 (Figure 7). Unless there was a notable change in the selectivity of the fishery over time, the trend in mean length does not support this hypothesis.

Hypothesis 2: Deteriorated habitat conditions in local fishing grounds. The equatorial EPO is known for large interannual fluctuations (*e.g.* El Niño and La Niña) in the ocean environment. Consequently, habitat conditions for juvenile BET in the EPO, and in particular for the inshore equatorial area (Area 3), can vary greatly from year to year (SAC-10 INF-D). In addition to environmental conditions, the spatial distribution of the OBJ fishing grounds (*i.e*. location of OBJ sets) also has changed over time (Figure 8). Therefore, the negative relationship estimated for BET in the inshore equatorial OBJ fishery (A3-OBJ) could indicate that habitat conditions in Area 3 have been deteriorating for BET or that the OBJ sets in Area 3 have been made in increasingly poor BET habitat over time.

To test this hypothesis, the BET habitat index for every OBJ set recorded in Area 3 was extracted using set information including year, month, latitude, and longitude. The BET habitat index is predicted daily for the EPO between 2002-2017 using a machine learning algorithm developed in SAC-10 INF-D. Then, the set-by-set habitat index for BET was averaged by year and vessel class (1-5 or 6) to obtain a set-weighted habitat index for juvenile BET in Area 3. The lack of a decreasing trend in the set-weighted habitat index (Figure 9) does not seem to support the hypothesis that habitat conditions in Area 3 have deteriorated for BET nor that the OBJ sets in Area 3 have been made in increasingly poor BET habitat over time.

Hypothesis 3: Gear evolution incidentally reduced the catch efficiency for BET. Results from a machine learning algorithm, which was developed to evaluate the catchability for BET in the EPO OBJ fisheries, showed that gear characteristics such as net depth, FAD depth and set time impact the catch rate for BET (SAC-10 INF-D). Given that skipjack (SKJ) rather than BET is the main target species of the OBJ fisheries in the EPO, it is possible that changed gear characteristics, likely aiming to improve the catch efficiency for SKJ, incidentally reduced the catch efficiency for BET in the inshore equatorial area (Area 3). Similarly, the expansion of the OBJ fishery may have happened disproportionally in both the offshore and inshore areas, with greater relative increase in the offshore area (FAD-05-INF-A, FAD-05-INF-C). Indeed, the fleet segment that principally operates on their own FADs, with also deeper FADs and nets, mainly fishes in the offshore area, and their efficiency as well as their use of active FADs seem to be also higher (FAD-05 INF-C).

However, the Productivity and Susceptibility Analysis (PSA; Duffy *et al*. 2019) for the tropical tuna fishery in the EPO suggested that SKJ and BET have about the same susceptibility to purse-seine fishing gear. Therefore, it seems unlikely that the evolution of the OBJ fisheries in the EPO can cause such a large degree of decrease in the catch rate for BET solely in Area 3.

In conclusion, the first hypothesis is considered to provide the most likely explanation for the negative relationship between F and N_{OBJ} for the inshore equatorial OBJ fishery (A3-OBJ). Although longline indices of abundance and OBJ length compositions provide contradictory information regarding the depletion level of BET in the inshore equatorial area (Area 3), indices of abundance are generally more reliable than composition data in terms of informing population trends when data conflict exists (Francis 2011). The evidence currently available does not strongly support the second and third hypotheses, and further research is desirable to more thoroughly investigate those possibilities in the future. It is important to note that the hypotheses mentioned above are not mutually exclusive and several processes could be responsible for the patterns observed. As of now, the negative relationship between the F for BET and N_{OBJ} in the inshore equatorial area (Area 3) likely indicates that BET experienced faster depletion in Area 3 than in rest of the EPO. As such, the management recommendation that *status quo* conditions should be maintained in the management cycle through limiting N_{OBJ} is considered appropriate.

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Table 1. Estimated relationship between the fishing mortality for bigeye tuna and the number of floating-object sets from generalized additive models. The first two columns represent the area where fishing mortality and number of floating-object sets are computed and the age range for which fishing mortality is computed. Area definition can be found in Fig. 3. The other three columns from left to right represent, respectively, estimated degrees of freedom of the smooth term, percentage of deviance explained by the model, and significance of the smooth term.

Tabla 1. Relación estimada entre la mortalidad por pesca del atún patudo y el número de lances sobre objetos flotantes a partir de modelos aditivos generalizados (MAG). Las dos primeras columnas representan el área en la que se calcula la mortalidad por pesca y el número de lances sobre objetos flotantes y el rango de edad para el que se calcula la mortalidad por pesca. La definición de las áreas se encuentra en la Fig. 3. Las otras tres columnas, de izquierda a derecha, representan, respectivamente, los grados de libertad estimados del término suavizado (EstDF), el porcentaje de desviación explicado por el modelo (DevExp) y la significancia del término suavizado.

Region	Age	EstDF	DevExp	p-value
EPO	1-4 quarters	1.00	37.5%	4e-3
EPO	5-8 quarters	1.13	27.0%	2e-2
Area 2	all	1.00	64.3%	1e-5
Area 3	all	1.00	25.7%	3e-2
Area 4	all	1.90	78.8%	2e-7
Area 5	all	1.31	27.4%	5e-2
Area 6	all	1.77	39.3%	2e-2

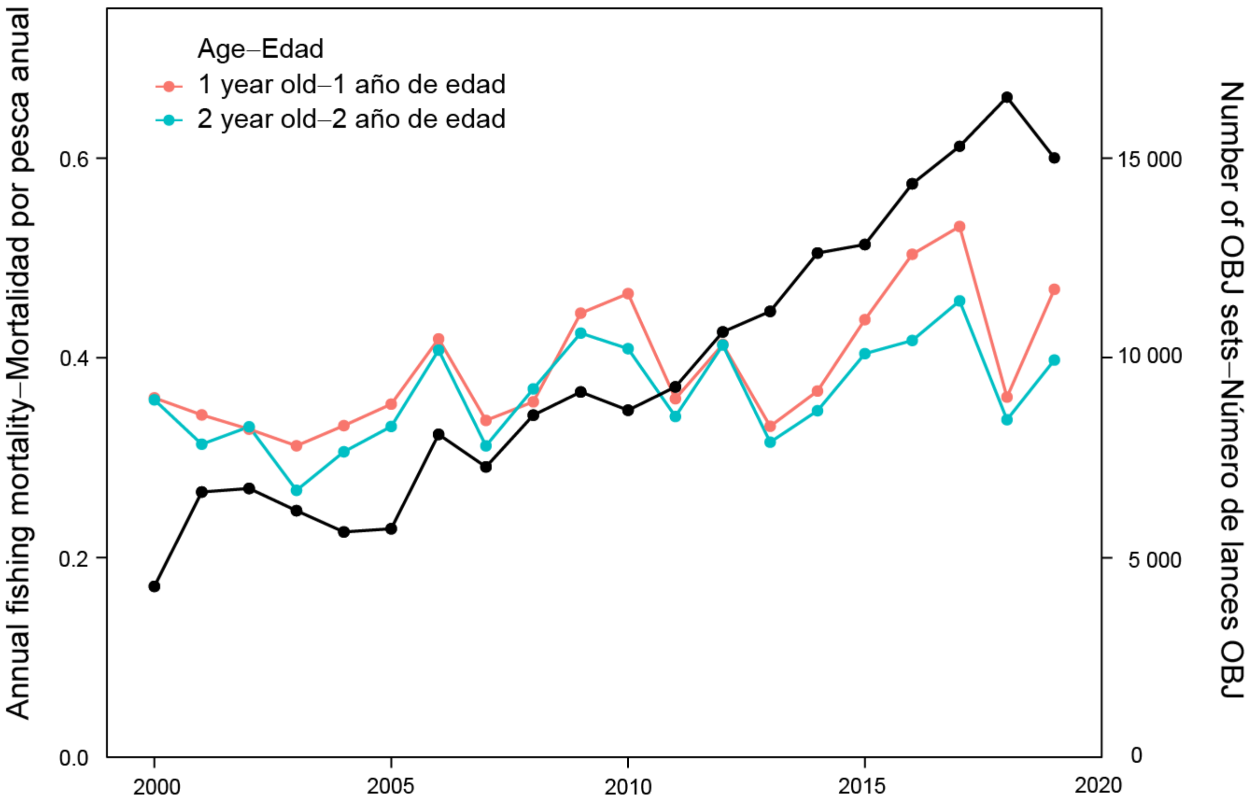

Figure 1. Comparison of age-specific annual fishing mortality for BET (colored lines) and the annual number of OBJ sets in the EPO (black line).

Figura 1. Comparación de la mortalidad por pesca anual por edad para BET (líneas de colores) y el número anual de lances OBJ en el OPO (línea negra).

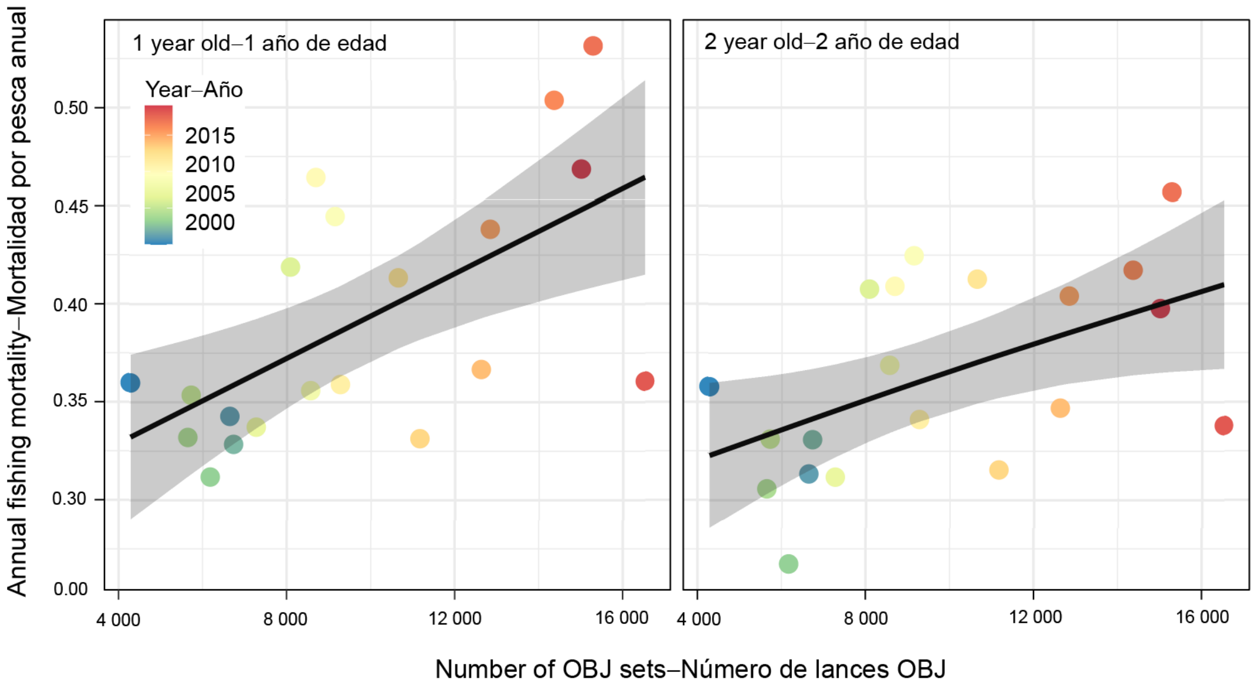

Figure 2. Scatterplot of age-specific annual fishing mortality for BET against annual number of OBJ sets in the EPO. The black line represents the predicted relationship from the GAM and the gray band shows the approximate 95% confidence interval.

Figura 2. Gráfica de dispersión de la mortalidad por pesca anual por edad para BET contra el número anual de lances OBJ en el OPO. La línea negra representa la relación predicha del MAG y la banda gris muestra el intervalo de confianza aproximado de 95%.

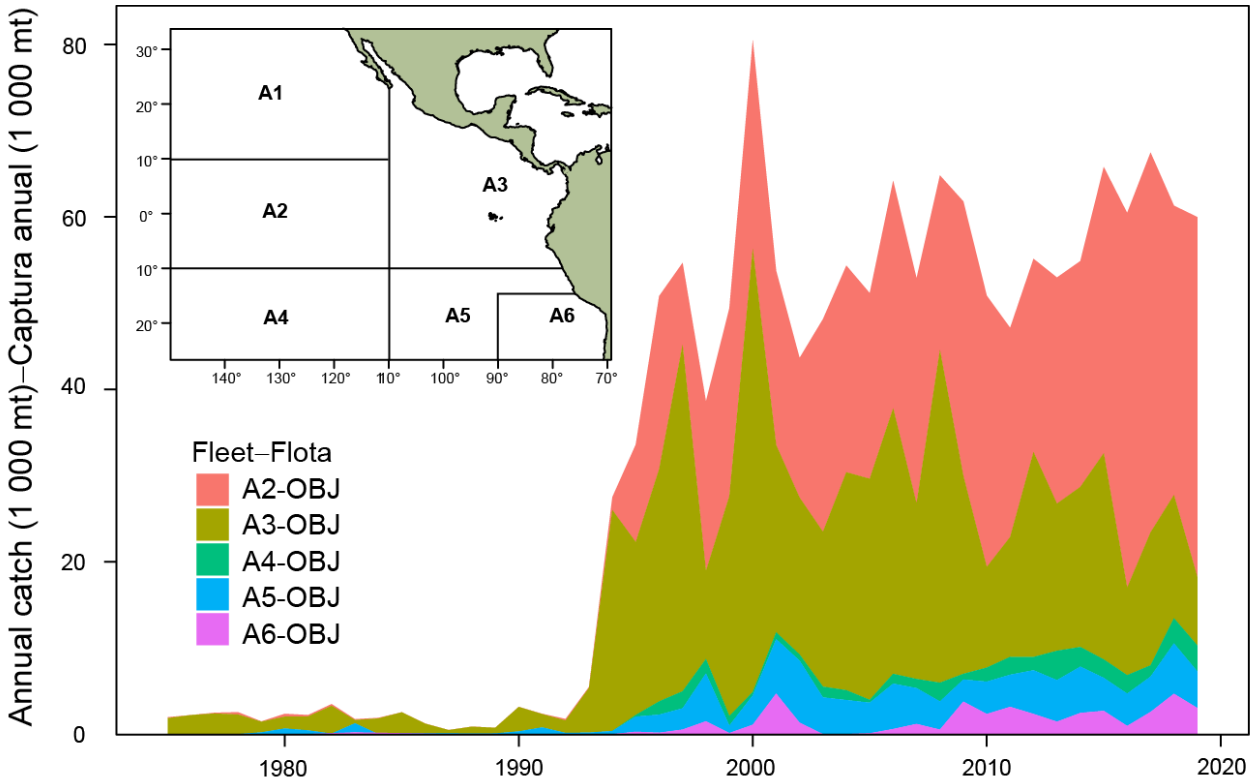

Figure 3. Annual BET catches taken by the five OBJ fisheries in the EPO. At-sea observer and logbook data from IATTC Class 1-6 purse-seine vessels fishing in the EPO is used to compute the area-specific catches.
Figura 3. Capturas anuales de BET realizadas por las cinco pesquerías OBJ en el OPO. Se usan los datos de los observadores en el mar y de las bitácoras de los buques cerqueros de clases 1-6 de la CIAT que pescan en el OPO para calcular las capturas por área.

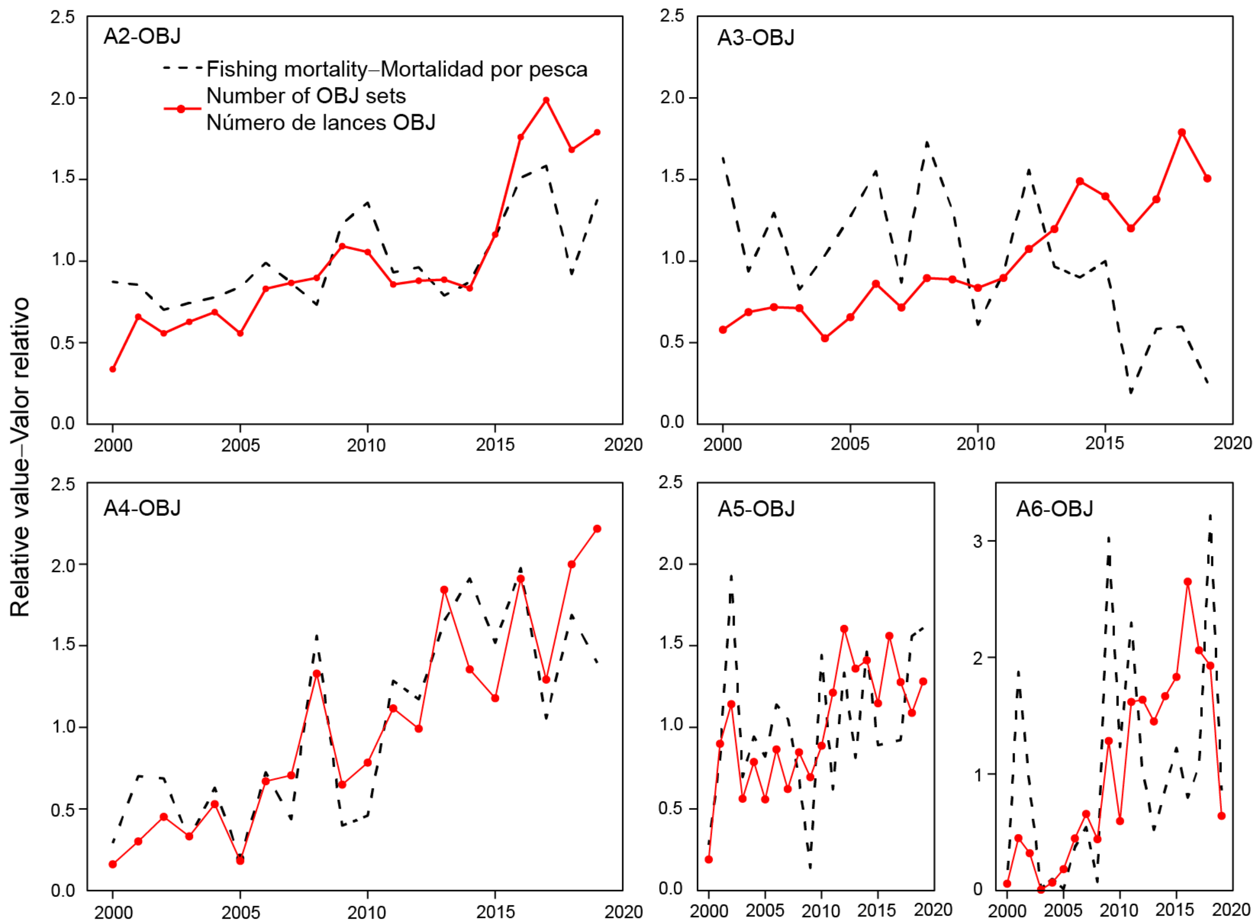

Figure 4. Comparison of annual fishing mortality for BET (black line) and annual number of OBJ sets (red line) for each floating-object fishery. For easier comparison, both fishing mortality and number of OBJ sets for each area are scaled to have a mean of 1. See Fig. 3 for area definition.

Figura 4. Comparación de la mortalidad por pesca anual para BET (línea negra) y el número anual de lances OBJ (línea roja) para cada pesquería sobre objetos flotantes. Para facilitar la comparación, se ajustó la escala de la mortalidad por pesca y el número de lances OBJ para cada área para que tengan un promedio de 1. Ver la Fig. 3 para la definición de las áreas.

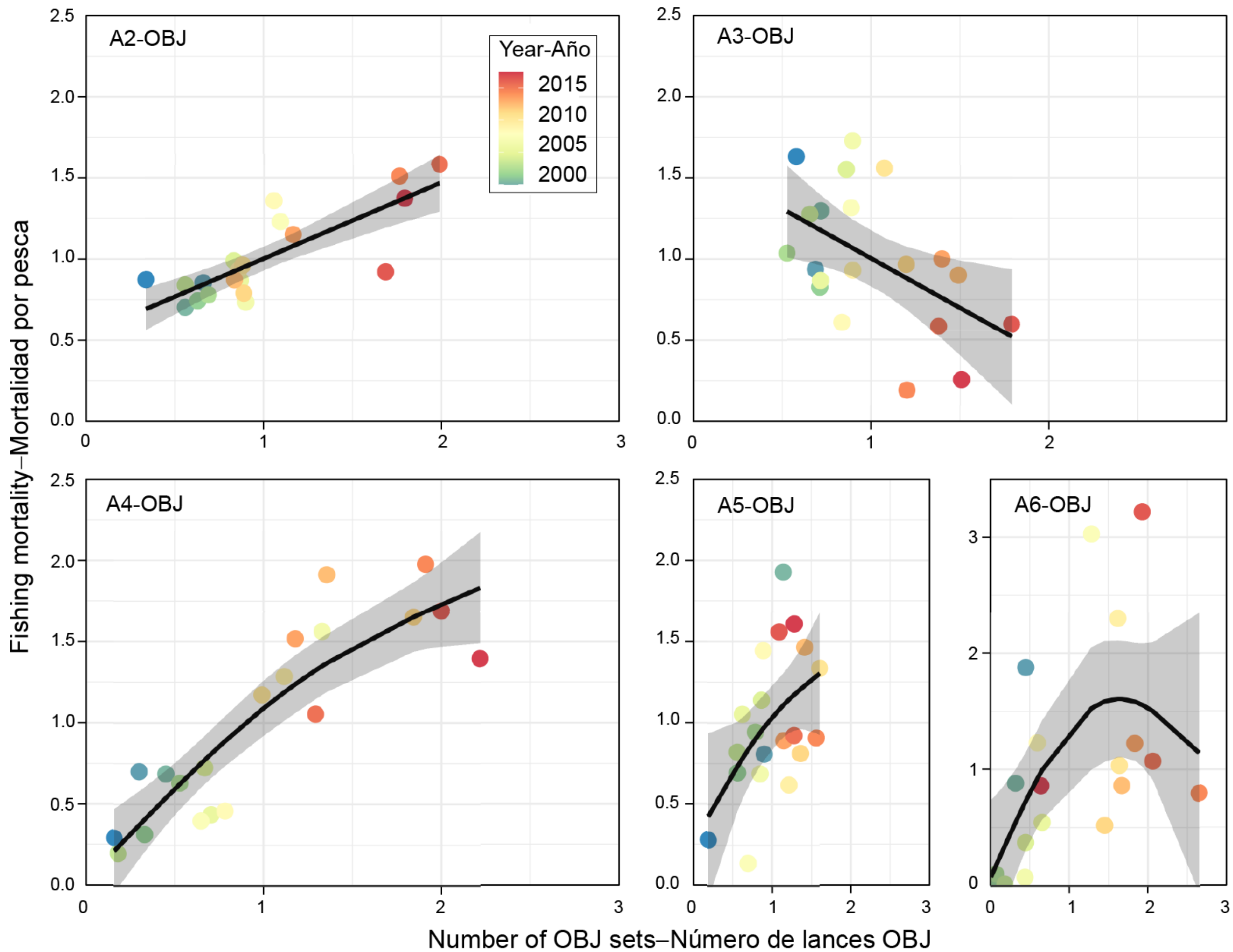

Figure 5. Scatterplot of annual fishing mortality for BET against annual number of OBJ sets for each OBJ fishery in the benchmark assessment. The black lines represents the predicted relationship from the GAMs and the gray band shows the approximate 95% confidence interval. See Fig. 3 for area definition.

Figura 5. Gráfica de dispersión de la mortalidad por pesca anual para BET contra el número anual de lances OBJ para cada pesquería OBJ en la evaluación de referencia. La línea negra representa la relación predicha de los MAG y la banda gris muestra el intervalo de confianza aproximado de 95%. Ver la Fig. 3 para la definición de las áreas.

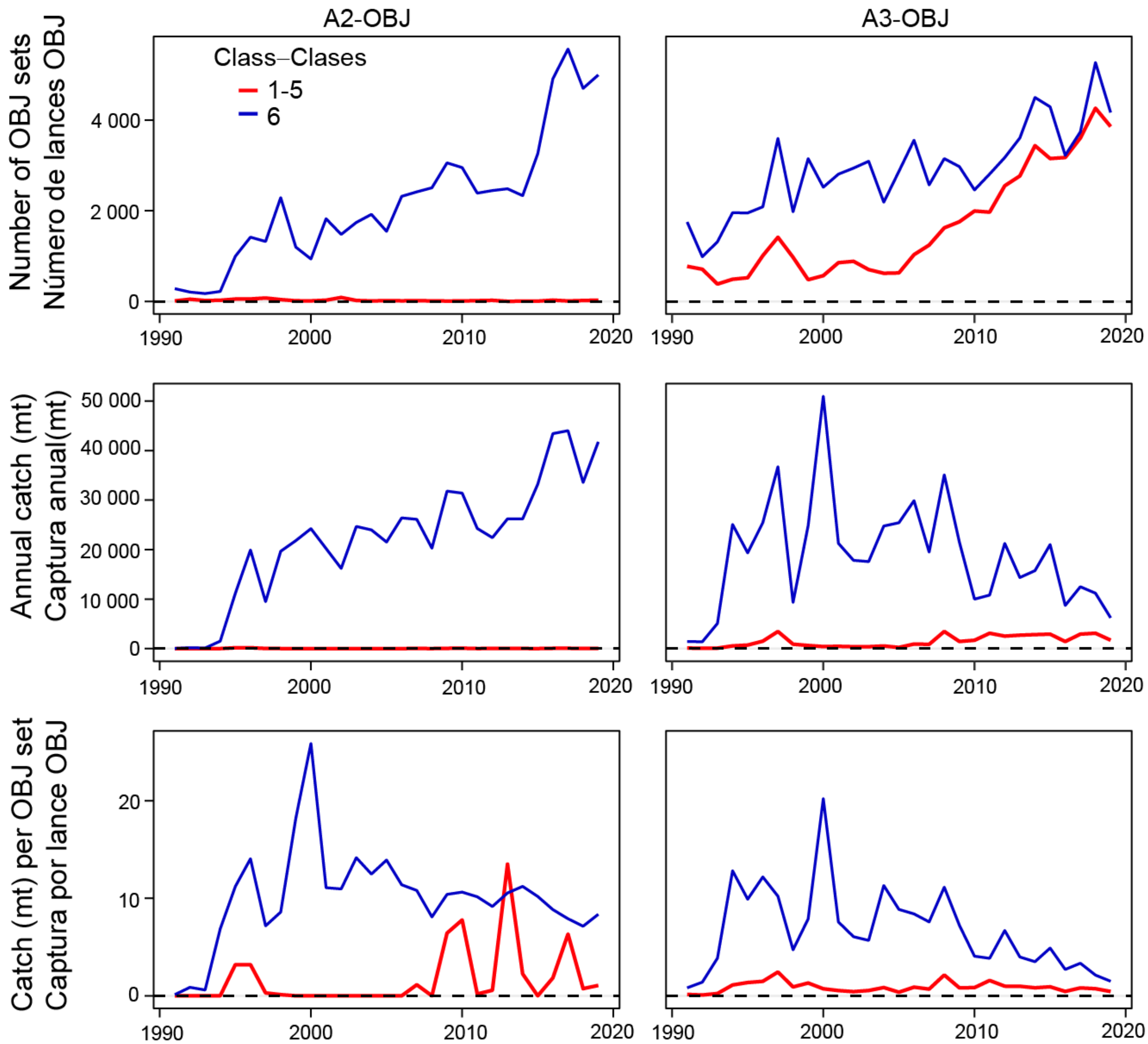

Figure 6. Vessel class-specific fishery indicators for the two equatorial OBJ fisheries for BET in the EPO. At-sea observer and logbook data from IATTC Class 1-6 purse-seine vessels fishing in the EPO is used to compute the vessel class-specific fishery indicators. See Fig. 3 for area definition.

Figura 6. Indicadores pesqueros por clase de buque para las dos pesquerías OBJ ecuatoriales de BET en el OPO. Se usan los datos de los observadores en el mar y de las bitácoras de los buques cerqueros de clases 1-6 de la CIAT que pescan en el OPO para calcular los indicadores pesqueros por clase de buque. Ver la Fig. 3 para la definición de las áreas.

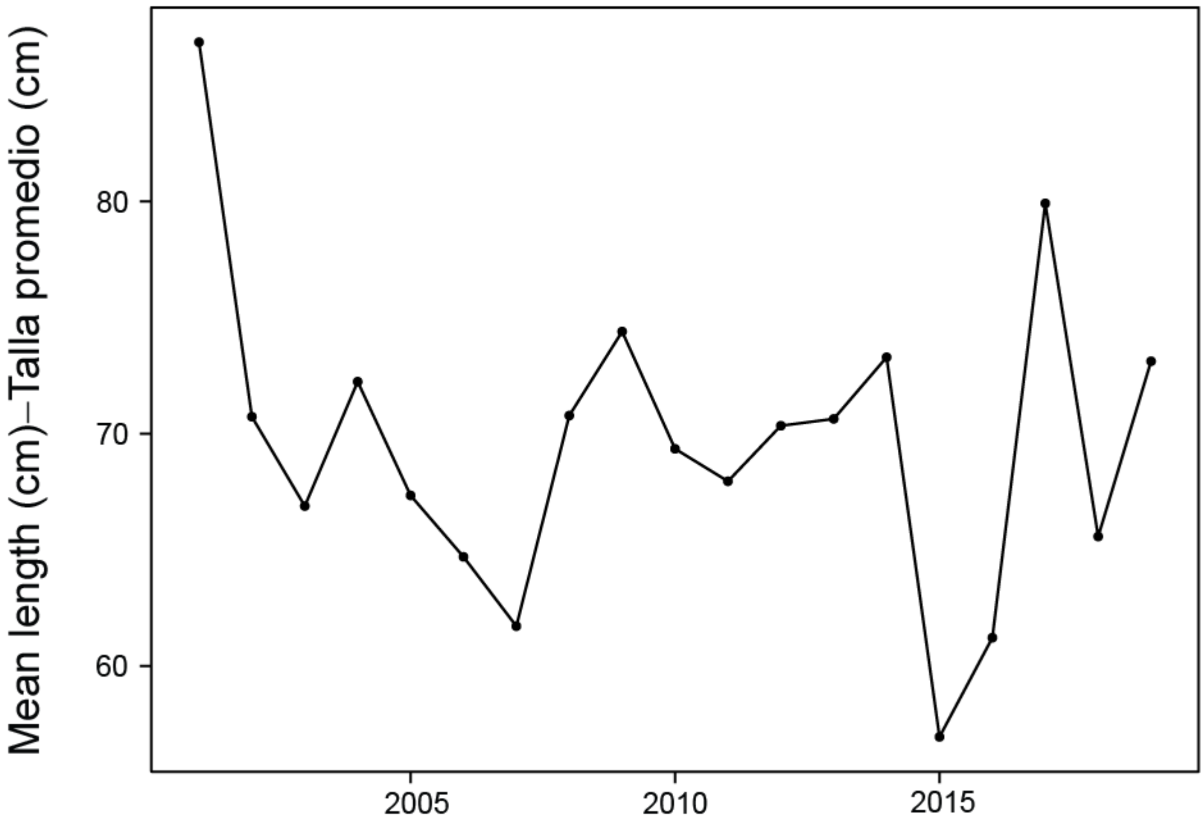

Figure 7. Annual mean length of BET caught by the inshore equatorial OBJ fishery (A3-OBJ).
Figura 7. Talla promedio anual de BET capturado por la pesquería OBJ ecuatorial costera (A3-OBJ).

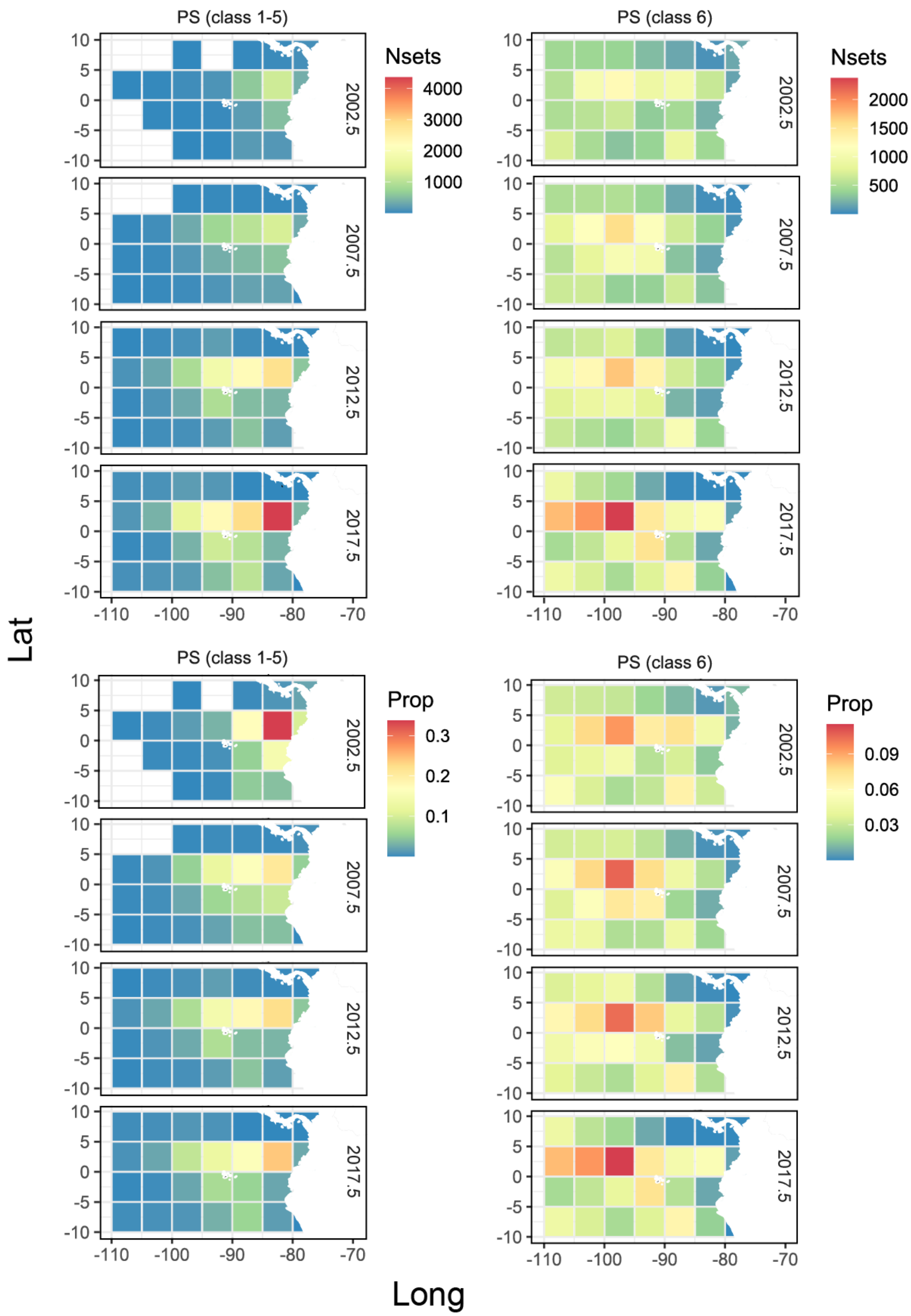

Figure 8. Spatial pattern of annual number (top) and proportion (bottom) of OBJ sets by Class 1-5 (left) and Class-6 (right) purse-seine vessels over time. The time represents the middle of the five-year period over which the values are computed.

Figura 8. Patrón espacial del número anual (arriba) y la proporción (abajo) de lances OBJ por buques cerqueros de clases 1-5 (izquierda) y clase 6 (derecha) a lo largo del tiempo. El tiempo representa la mitad del periodo de cinco años sobre el que se calculan los valores.

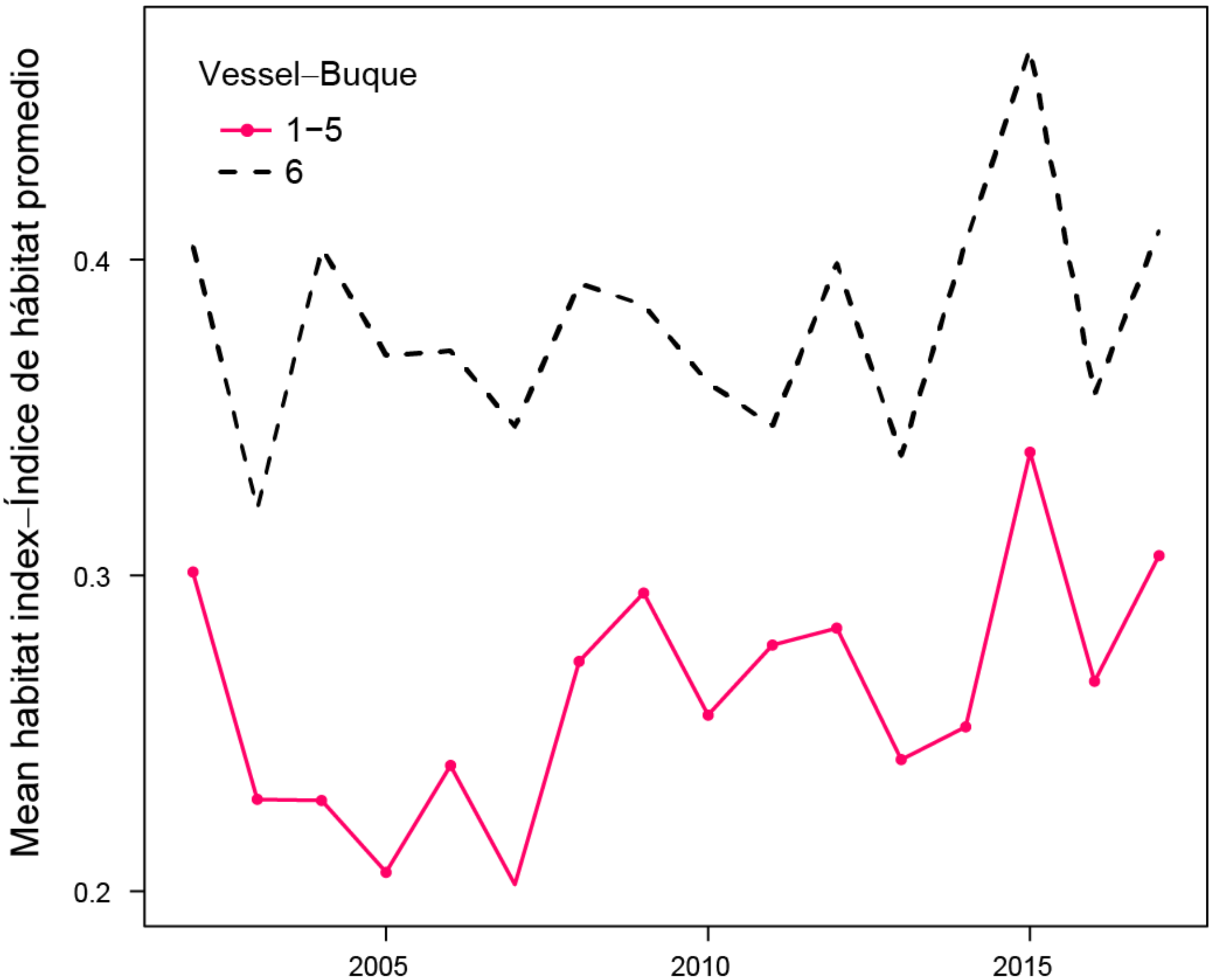

Figure 9. Annual mean habitat index for BET based on the location and date of OBJ sets made by purse-seine vessels that operated in the inshore equatorial area (Area 3).

Figura 9. Índice de hábitat promedio anual para BET basado en la ubicación y fecha de los lances OBJ realizados por buques cerqueros que operaron en el área ecuatorial costera (Área 3).