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REDUCING SHARK BYCATCH IN TUNA FISHERIES: ADAPTIVE SPATIO-TEMPORAL MANAGEMENT OPTIONS FOR THE EASTERN PACIFIC OCEAN

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CONTENT

ABSTRACT

Purse-seine tropical tuna fishing in the eastern tropical Pacific Ocean (EPO) results in the bycatch of several sensitive species groups, including elasmobranchs. Effective management of ecosystems balances conservation and resource use, but requires actionable knowledge that accounts for both trade-offs and synergies. Seasonal and adaptive spatial management measures can be effective to reduce the impact of fisheries on non-target species while preserving, or even increasing, target species catch. Exploring the potential distribution and impact of fisheries closures in the open ocean, where highly dynamic environmental conditions drive distributional changes in biological communities throughout the year, requires the identification of persistently high-risk areas, where the likelihood of encountering and catching unwanted bycatch species, relative to the target species, is high. We used fisheries observer data from 1995–2021 to explore the spatio-temporal persistence of areas of high bycatch risk for two species of oceanic sharks, silky shark (*Carcharhinus falciformis*) and oceanic whitetip shark (*Carcharhinus longimanus*), and low tuna catch rate areas—defined as areas of high fishing inefficiency (i.e., poor fishing areas). We found that if areas of high fishing inefficiency were closed throughout the study period, and effort reallocated proportionally to reflect historical effort patterns, yearly tuna catch may have increased by 1–11% while the bycatch of silky and oceanic whitetip sharks could have decreased by 10-19% and 9%, respectively. Prior to fishing effort redistribution, bycatch reductions would have accrued to 21–41% and 14% for silky and oceanic whitetip sharks, respectively. Our analysis builds on past evidence and

demonstrates the high potential for reducing elasmobranch bycatch in the EPO, while not compromising the catch rates of target tuna species. It also highlights the need to consider new dynamic and adaptive management measures to more efficiently fulfill conservation and sustainability objectives for exploited resources in the EPO.

INTRODUCTION

Global populations of several oceanic shark and ray species (i.e., elasmobranchs) have been declining steadily for the past half-century, mainly due to fishing, placing many species at risk of ecological extinction (Pacoureau et al., 2021; Dulvy et al., 2021). Elasmobranch populations generally have low productivity, as a result of slow growth rates, extended longevity, and low reproductive potential. Although targeted in some fisheries, a large fraction of sharks and rays are caught incidentally (i.e. "bycatch") in industrial, semi-industrial, artisanal and recreational wild capture fisheries (Murua et al., 2013; Bonfil, 1994). One of the primary concerns for their long-term sustainability is the general lack of effective conservation and management measures (CMMs) established and enforced by relevant national, regional and international authorities (Camhi et al., 2008; Worm et al., 2013).

Several provisions of the 1995 FAO Code of Conduct for Responsible Fisheries and of the 1995 UN Fish Stocks Agreement stipulate that Regional Fisheries Management Organizations (RFMOs)—in particular those responsible for the management of species with trans-jurisdictional distributions, including tunas—have an explicit mandate to reduce impacts on non-target species or species belonging to the same ecosystem as the target species. These provisions are reflected in the mandates of the five tuna RFMOs, including the Antigua Convention of the Inter-American Tropical Tuna Commission (IATTC) in the eastern Pacific Ocean (EPO), but vary in the degree to which they have been operationalized (Juan-Jordá et al., 2018)RFMOs can implement a range of management measures to reduce the impact of their fisheries on ecosystems and the broader environment. These measures can be broadly classified into two groups: input control (e.g., the amount of fishing effort, type and dimensions of fishing gear, where and how fishing is allowed) and output control (e.g., how much can be caught or landed for any given species) measures (Morison, 2004). Multispecies fisheries pose a unique challenge, as competing objectives and trade-offs must be considered. For example, modifying fishing gear characteristics (e.g., hook type) to reduce the bycatch of a particular species group may unintendedly result in increased catch rates of other non-target species groups (Ward et al., 2009). Therefore, it is important, albeit challenging, to assess the impacts of each proposed management measure across taxonomic groups, some of which often are data-limited. Among other measures, spatial management is a specific type of input control measure that seeks to reduce the extent to which fishing operations overlap with features of ecological interest (e.g., sensitive habitats, non-target species, nursery areas). The identification of areas of potential interest for spatial management in the open ocean is directly dependent on empirical data at high spatial resolution and over extended time periods (Hilborn et al., 2021), which can also be modeled to estimate and predict species' distributions and relative abundance across space and time to inform the design of spatial management measures (Visalli et al., 2020).

The task of disentangling the spatial (where) and temporal (when) overlap of multiple target and non-target species requires an in-depth exploration of risk and trade-offs across scenarios and species groups (Hilborn et al., 2021; Pons et al., 2022). Those spatial management measures can be "static", when, for example, a fixed area is closed to fishing (currently the most common measure used), or "dynamic", when the area can change across space and time (Crespo et al., 2020). Although Hyrenbach et al., (2000) argued for the importance of exploring dynamic spatial management over 20 years ago, there are still few examples of dynamic or adaptive spatial management to reduce bycatch to date (Dunn et al., 2019; Welch et al., 2020). Presently, and over 70 years after the establishment of the first tuna RFMO (IATTC), no spatial management measures have been implemented to specifically reduce the catch of non-target species.

However, a few static spatial closures have been created to reduce the catch of target species during certain times of the year or at particular life-history stages (e.g., the "corralito" in the IATTC Convention Area) (Dunn et al., 2019) or closures for the use of drifting fish aggregating devices (FADs) (WCPFC, 2021; ICCAT, 2021).

However, since the late 1970s, the global catch rates of many bycatch species, particularly pelagic sharks, have increased in both artisanal and industrial tuna fisheries, especially those using longline or purse-seine gears (Pacoureau et al., 2021; Doherty et al., 2014). This trend also characterizes the EPO. For example, bycatch rates of various pelagic shark species increased in the industrial purse-seine fishery in the EPO, primarily due to the expansion of the floating-object fishery (mainly man-made drifting FADs) (SAC-10-INF-K). The identification of potential candidate areas for spatial closure in the highly dynamic pelagic environment has inherent difficulties, particularly in regions where resources, data availability or monitoring technologies are limited (Hilborn et al., 2021). On the other hand, initial global and regional research has demonstrated that it is possible to identify areas of high bycatch risk or areas where bycatch reduction can be minimized while target catch is simultaneously maximized (Hazen et al., 2013; Watson et al., Román-Verdesoto, 2014; 2009, Pons et al. 2022).

Therefore, in this study, we aimed to identify areas of relatively high bycatch rates of vulnerable species that coincide with relatively low tuna catches, which we defined as "high fishing inefficient" areas and that could be considered potential areas for the application of "dynamic" spatial mitigation management measures. We based our empirical data analysis on the long-term full-coverage historic information gathered by scientific observers from the EPO tropical tuna purse-seine fleet. Because of their life histories and ecological significance and current concerns over their conservation status, we focused our analyses on two of the most frequently-caught and potentially vulnerable shark bycatch species in the fishery, the silky shark (*Carcharhinus falciformis*) and the oceanic whitetip shark (*C. longimanus*) (Román-Verdesoto and Orozco-Zoller, 2005; Watson et al., 2009, Griffiths et al 2017). The latest global level assessments by the International Union for Conservation of Nature (IUCN) Species Red List classified these species as 'Vulnerable' and 'Critically Endangered' to extinction, respectively. Although these species were last assessed by the IUCN in 2017 (Rigby et al., 2021) and 2018 (Rigby et al., 2019), respectively, and were both found to have declining population trajectories, the abundance of oceanic whitetip sharks has declined much more significantly, possibly due to their low fecundity and long gestation period (Seki et al., 1998; Young & Carlson, 2020).

The primary goal of our analysis is to provide fishery managers with reliable spatial management options for bycatch mitigation for these two threatened shark species and for these options to be supported by estimates of the potential trade-offs between bycatch reductions and target species catches; thus enabling a practical implementation of "dynamic" spatio-temporal fisheries closures.

METHODS

Study species and fishery

The silky shark, which is one of the most commonly caught shark species in tuna fisheries globally, can grow to about 300 cm in total length, may live for at least 25 years and produces few (2–14) offspring per year (Rigby et al., 2021). Similarly, the oceanic whitetip shark is also commonly caught by tuna fisheries and grows to about 400 cm in total length, is thought to live for up to 22 years and also has a small litter size of 1–14 offspring per year (Bonfil et al. 2008). By contrast, one of the targeted tropical tuna species, yellowfin tuna (*Thunnus albacares*), grows to about 250 cm, lives for about 8 years, and produces several million offspring per year through broadcast spawning (Zudaire et al., 2014; Schaefer & Fuller, 2022).

The fishing activities of the tropical tuna purse-seine fleet in the EPO regulated by the IATTC—defined in the 2003 Antigua Convention as the area between 50°N and 50°S, from 150°W to the coast of the

Americas—are found primarily within the tropical and subtropical latitudes of the Convention Area (20°N–20°S) and are characterized by three fishing set types, depending on the fishing operation: i) “dolphin set” (DEL), where the net is intentionally deployed around a pod of dolphins in an attempt to catch associated tuna (i.e., mostly large yellowfin tuna), ii) “floating object set” (OBJ), where the net is set around a natural (e.g., log) or artificial floating objects (FADs) with tunas and other species associated underneath, and iii) “unassociated or free school set” (NOA), where the net is set around a free-swimming school of tuna that is not associated with dolphins or a floating object.

Although the EPO tropical tuna purse seine fishery targets yellowfin, skipjack (*Katsuwonus pelamis*), and bigeye (*T. obesus*) tunas, it incidentally also catches a range of non-target species across all set types, including sharks, rays, dolphins, sea turtles, and teleosts (Duffy at al. 2019; SAC-13-10), which are generally discarded or released either dead or alive at sea .

Data

Analyses were undertaken using data collected by fisheries scientific observers onboard large purse-seine vessels in the EPO as part of the Agreement on the International Dolphin Conservation Program (AIDCP) observer program. In most cases, the program is composed of 50% national observers and 50% IATTC observers, who collect operational and catch information for target and non-target species from nearly 100% of sets made by class-6 (>363 t) tuna purse-seine vessels (IATTC, 2006). While our focal species of shark are also frequently caught in IATTC’s longline fishery, the coarser spatial resolution of the longline observer data and its spatial and temporal scatteredness due to low observer coverage did not allow for its inclusion in this analysis (Griffiths *et al.,* 2021). The AIDCP program’s data collection protocols have remained fairly consistent since its implementation in 1993. In the context of our investigation, the only change to the raw records consisted of an adaptation of the silky shark unique species codes prior to 2006, to account for their misidentification as blacktip sharks (*C. limbatus*) (Fuller et al. 2022, Watson et al 2009). For our analysis, we aggregated data for all size classes of silky and oceanic whitetip sharks (i.e., small [<90cm], medium [90-150 cm], large [>150 cm]), whereas all size and species data for the three main tropical tuna species—yellowfin tuna, bigeye tuna, and skipjack tuna (i.e., small [<2.5 kg], medium [2.5-15 kg], large [>15 kg])—were aggregated into a single “tuna” category.

The database contained data for 560,278 sets—comprising the three set-types—observed in the EPO between January 1995 and December 2021. We explored the differences in the extent of bycatch of each shark species in the three principal set types by calculating the total bycatch and average bycatch per unit of effort (BPUE, defined in this case as the number of sharks per set). Floating object (OBJ) sets had the highest total catch and BPUE for both silky and oceanic whitetip sharks, accounting for nearly 90% and 95% of the total purse-seine silky and oceanic whitetip catch, respectively (Table 1). Consequently, the study focused on OBJ sets.

As part of the data exploration process, we also assessed the intra-annual patterns of tuna and shark catch by calculating the monthly variability in catch per unit effort (CPUE, for tuna) and BPUE throughout the time series (Supplementary Figure 1). In addition, we explored the spatial variability of tuna and shark catch/bycatch per unit effort and their stability over time to assess if there were broad spatial or temporal windows of higher risk of bycatch or opportunity to increase tuna CPUE.

Data aggregation

The principal aim of the analysis was to identify areas of persistent shark BPUE risk and low tuna CPUE across space and time. We standardized the spatial and temporal units in the database for enabling comparisons among scenarios. OBJ sets were aggregated spatially to 1°x1° cells across the area of operation of the fishery and temporally into months, resulting in 98,622 discrete cells with OBJ sets across all months and years. The tuna catch (combined for the three tropical tuna species) and shark bycatch estimates for both species of interest were also aggregated at 1°x1° resolution and by month. We considered this to be the most appropriate spatial and temporal resolution at which to explore fine-scale patterns of fishing inefficiency which could also be considered for spatial management options.

Spatio-temporal optimization

A series of sequential calculations were conducted to identify areas where the following two conditions were met simultaneously and persisted across years in each given month, in order to identify cells with low target tuna CPUE and high shark BPUE: (i) determine whether shark catch rates are higher than monthly historic average and (ii) determine whether tuna catch rates were lower than the monthly historical average (Figure 1). The spatio-temporal persistence of higher risk cells (PH) with low tuna CPUE and high shark BPUE was calculated by assessing the frequency with which a cell was classified as being inefficient during each historic monthly series (Figure 1).

First, BPUE (Eq. 1, Figure 1) and CPUE (Eq. 2, Figure 1) were calculated within each cell for each of the 312 months of the time series. Second, the monthly cells for which BPUE was higher than the historical monthly average (Eq. 3, Figure 1) and where CPUE of tuna was lower than the historical monthly average were identified (Eq. 4, Figure 1). For example, we compared the BPUE/CPUE value of a cell in the month of January in one year to the mean value for January of that cell considering all years in the time series. Third, these locations in space and time were cross-referenced to identify cells where both conditions were met, thus classifying monthly cells of high bycatch and low catch rates as 'hotspots' of high fishing inefficiency; a lose-lose situation (Eq. 5, Figure 1). Fourth, the temporal persistence of monthly areas of fishing inefficiency was explored to identify potential monthly hotspots that remain between years (Eq. 6). This consisted of a summation of the times a specific monthly cell was classified as low efficiency across years (Supplementary Figure 3 & Figure 4). Different threshold values (e.g., the number of times a cell was identified as inefficient in the month of January) above which a cell would be deemed persistently inefficient for purse-seine fishing on OBJ were also tested (Supplementary Figure 3 & Figure 4).

Finally, a two-fold process was conducted, which consisted of i) computing the total number of sharks and tonnes of tuna that would have not been caught had persistent inefficient fishing hotspots been closed for each of the months in the time series, and ii) recalculating the catch and bycatch based on an even redistribution of OBJ sets across the remaining fished cells in each month based on historical patterns.

Based on the inter-annual persistence of areas of high inefficiency results, we tested two persistence thresholds (i.e., the number of times a cell was identified as a high inefficiency location for a given month) for silky sharks (2 and 3 months) and one for oceanic whitetip sharks (2 months). Each threshold resulted in different sizes of the areas of high inefficiency, as well as a different level of fishing activity that occurred within them (Supplementary Table 1, Supplementary Figure 5–7).

While Watson et al. (2009) identified candidate closure areas as areas "with coincident high bycatch regions across all years" (1994–2005), our use of different temporal thresholds allowed us to identify areas of relatively high monthly persistence of high bycatch and low target catch throughout the time series.

Early data exploration showed how seasonal variability in silky shark and oceanic whitetip shark bycatch and BPUE remained fairly stable throughout the year, with slightly lower BPUE for silky sharks during the months of February–April and March–June for oceanic whitetip sharks (Supplementary Figure 1). These results suggest an absence of a clear temporal window for significant bycatch reduction and justified the need to consider all months in our analysis. The relative similarity of BPUE ranges of silky shark and oceanic whitetip shark across months (Supplementary Figure 1) suggests that using monthly BPUE averages as a threshold for identifying areas of higher risk is appropriate for identifying comparable high-risk areas throughout the time series.

RESULTS

The spatial footprint of the OBJ fishery between 1995–2021 oscillated between a total of 865–1,863 1°x1° cells, with an average of 1,498 cells per year, or 14.9 million km^2 (this excludes 2020 and 2021 given the potential effect of the COVID-19 pandemic on fishing activity). Over time, the effort spatial footprint was stable at around 1,170 cells between 1995–2005 but increased in spatial coverage by about 50% between 2006–2017, to an average of 1,757 cells with OBJ fishing sets. For the majority of years, OBJ sets had a bimodal distribution that was roughly centered around 5°N and 5°S (Figure 2). The spatial distribution of catches of tunas and silky and oceanic whitetip sharks closely followed that of fishing effort, although peak BPUE for both shark species occurred above 5°N, but a notable smaller peak occurred below 5°S for oceanic whitetip sharks (Figure 2). It is also important to note that the low fishing effort, low tonnage of tuna catch and the relatively small number of sharks caught above 15°N make the CPUE and BPUE estimates in these latitudes less reliable. Interestingly, tuna CPUE was higher at latitudes 0° and 10°N away from those of peak fishing effort (~5°N).

The longitudinal differences in patterns of catches of tuna and the two shark species suggest that longitudinal bands could also be candidate areas for high fishing inefficiency. The patterns of tuna CPUE were remarkably stable across the longitudinal cross-section of the IATTC Convention Area (Figure 3). The patterns of shark BPUE were different, however, and resembled almost an inverse distribution to that of fishing effort, as areas of higher fishing intensity (further east) had lower BPUE rates for both shark species, while higher BPUE were at longitudes further west, where historically less fishing took place.

These exploratory results suggest that the region north of 5°N and west of approximately 110° W could be suitable candidates for fishing effort reductions or closures to reduce silky shark bycatch, while the broad areas of opportunity for oceanic whitetip shark could be located west of 110° and north of 10°N or south of 5°S.

Shark bycatch hotspots

The spatio-temporal optimization analysis allowed for the identification of areas of the EPO where the historical below-average tuna CPUE and above-average silky shark and oceanic whitetip shark BPUE co-occur. Of the 98,622 monthly cells containing at least one OBJ set, catches of silky shark and oceanic whitetip shark occurred in 49.0% (n = 48,452) and 7.7% (n = 7,658) of the cells, respectively. The proportion of fished monthly cells with higher than average BPUE rates for silky shark and oceanic whitetip shark was 24.0% (n= 23,618) and 7.2% (n = 7,164), respectively.

Results of the persistence of areas of high monthly inefficiency varied by species and month, although the relatively low persistence between years suggests that areas of high fishing inefficiency may be ephemeral (Supplementary Figure 2–4).

Both thresholds for silky sharks resulted in the identification of a longitudinal band of high fishing inefficiency centered around 5°N (Figure 4), while the two-month threshold accentuated the presence of an area of high inefficiency at around 5°S between 110°W and 140°W. The majority of inefficient fishing areas for oceanic whitetip sharks were found between 5°S–10°S and 110°W–130°W, but also around 5°N and 100°W–110°W (Figure 5). The persistence of areas of high fishing inefficiency for oceanic whitetip sharks was lower than that for silky sharks and fishing cells were not identified for closure for more than 5 months of the year, while some of the cells for silky sharks were identified as highly inefficient for up to 11 months of the year. It is also worth noting how the (2- and 3-month) persistence thresholds were based on a maximum persistence of areas of high fishing inefficiency of 4 months for oceanic whitetip sharks and 8 months for silky sharks (Supplementary Figures 3 & 4).

The information from these areas was used to estimate reductions in the amount of tuna catch (in tonnes) and shark bycatch (in numbers) that may have resulted if monthly closures of persistent high inefficiency cells were in place between 1995–2021 (PH in Figure 6). A marked reduction in the catch of both shark species across thresholds was estimated if the areas of high inefficiency were to be closed. These reductions in bycatch averaged 41% (n = 213,992) and 21% (n = 110,418) for the 2- and 3-month thresholds for silky sharks and 14% (n = 5,588) for the 2-month threshold for oceanic whitetip sharks, while reducing fishing effort by an average of 25%, 11% and 5%, respectively. Prior to fishing effort redistribution, these closures were predicted to result in an average reduction in tuna catches of 20%, 9%, and 3%, respectively (Supplementary Table 1; Figure 6).

After redistributing the fishing effort within the investigated closures, results still showed a net decrease in shark bycatch across all scenarios—ranging from a 28% to 3% of reduction—and a projected increase of tuna catches across all scenarios between 1–11% (Supplementary Table 1; Figure 6).

DISCUSSION

RFMO management strategies must attain a balance between ensuring that fisheries remain biologically and economically sustainable whilst simultaneously ensuring the structure and function of the ecosystems they are part of are not compromised by, among other things, driving the populations of non-target species beyond biologically sustainable thresholds, from which they may never recover. Reaching this important balance becomes increasingly complex in multi-species fisheries that interact with species having vastly different life histories, such as tunas and elasmobranchs. As a first step towards seeking strategies that may provide mutually beneficial outcomes for tunas and bycatch, this study focused on two of the more common and vulnerable shark bycatch species in the EPO and provided convincing evidence that the tuna purse-seine fishery could reduce its impact on silky and oceanic whitetip sharks through the establishment of adaptive management spatio-temporal measures. Apart from the dynamic management applied in Australia's East Coast Tuna and Billfish Fishery to seasonally close certain areas based on sea surface temperature thresholds to avoid the bycatch of southern bluefin tuna by fisheries without a southern bluefin tuna catch quota (Hobday and Hartmann, 2006; Hobday et al., 2010; AFMA, 2021), dynamic closures guided by our approach could become the first example of spatial management measures used in a tuna RFMO to explicitly reduce bycatch of non-target elasmobranch species, while maintaining, or even increasing, the catch rates of target tuna species. Importantly, the spatial management scenarios presented also straddle national and international waters, which is a key factor for the proper management of highly-mobile species.

The conservation and sustainable management of target and non-target species by tuna RFMOs fundamentally hinges on the ability of scientists to accurately characterize the relative abundance, distribution, and maximum biologically sustainable fishing mortality rates across species that can allow managers to develop science-based management measures. Input control measures, such as the adaptive management closures presented here, can then be used as tools to guide managers on where best to focus fishing efforts to meet multiple conservation and sustainable management objectives simultaneously; these, however, should represent only an element of a more comprehensive strategy. It is against this backdrop that we recommend the use of adaptive spatial management in the region to reduce shark bycatch, while emphasizing the need for the continued development of broader management plans for target and non-target taxa that estimate and control the maximum amount of fishing-induced mortality that different species can withstand. The practicality of our results depends on the premise that the management of tropical tunas in the region will limit the fishing mortality to levels that will biologically sustain the population as required by IATTC conservation objectives and Resolution C-16-02 on Harvest Control Rules for tropical tunas, through short-term packages of conservation measures (e.g., Resolution C-21-04), as well as the establishment of comprehensive harvest strategies tested through management strategy evaluation for tropical tunas, an ongoing process in the EPO. This is a critical reflection since directing fisheries (which are often regulated through effort controls) to areas of higher than average CPUE, in conjunction with effort creep and technological development of the fleet, could lead to excessive exploitation of target species. While it is beyond the scope of this study, we underscore the need for a deeper understanding of the impact that improved fishing efficiency, including technology, has on fishing mortality and the efficacy of a unit of fishing effort, from which standardized CPUE and indices of abundance can be derived (Kleiven et al., 2022) to better inform stock assessment and the resulting management advice.

Adaptive spatial management scenarios

Importantly, although we used a different methodology, our results agree with a previous study in the region, which also explored spatial management opportunities for reducing one species of shark bycatch without jeopardizing tuna catches. Watson et al. (2009) demonstrated that small silky shark bycatch in the EPO purse-seine fishery could be reduced by up to 33% through the establishment of seasonal closures between 5°N–15°N, which were predicted to result in a 12% reduction in the tuna catch. This is of particular management interest because demographic studies have shown that silky shark population growth is highly dependent on juvenile survival (Román-Verdesoto 2014). While it was mentioned as an area for future research, Watson *et al*. (2009) did not conduct simulations on potential effort redistribution, an important point to efficiently assess the efficiency of potential closures which can be explored at multiple levels of complexity (Powers & Aberare, 2009). The present work not only identifies areas that, if temporarily closed, could reduce monthly silky and oceanic whitetip shark bycatch by as much as 53% and 20 (in a given month) respectively when the fishing effort is not reallocated, but also showed that, even after reallocating fishing effort, all scenarios predicted a net decrease in monthly shark bycatch as high as 29% and a net increase in monthly tuna catches of up to 11%.

The distribution of areas of high fishing inefficiency varied across species and persistence thresholds, but also showed interesting similarities. In the case of oceanic whitetip sharks, the majority of areas of high inefficiency were found between 5°S–10°S and 110°W–130°W, with a few additional locations around 5°N. Areas of fishing inefficiency for silky sharks varied, but also highlighted some areas, across thresholds: the three- and two-month thresholds concurred in the presence of areas of high inefficiency between 5°N–10°N (which resemble those found by Watson et al., (2009) and Román-Verdesoto 2014), while the two-month threshold also delineated areas around 5°S, which overlaps with important areas identified for oceanic whitetip sharks. The core areas of high fishing inefficiency for silky sharks stretched from ~90°W–140°W across both thresholds (Figure 4). Based on the results from the three scenarios, it is likely that areas above and below the latitudinal bands around 5°N and 5°S could be considered to meet these multiple sustainability objectives.

Our results suggest that adaptive spatial management can serve as a tool to reduce the unintended catch of non-target elasmobranchs. Despite in occasions being geographically dispersed, it seems possibly to avoid these closure areas in a verifiable way using available vessel tracking technologies, fisheries observer data or by using spatial information and measures to complement potential catch limit scheme for both sensitive bycatch species and target species.

Enabling conditions and roadblocks for scaling dynamic spatial management

The IATTC's high observer coverage of the purse-seine fleet (100% of vessels with a registered carrying capacity greater than 363 metric tons – more than 508 m³ of wells volume) and availability of operational-level data from that fishery since the early 1990s has been instrumental in our ability to conduct this analysis and exemplifies one of the many benefits of collecting high-quality data across the broad spatio-temporal footprint of the fishery for several taxa. The IATTC has adopted various conservation and management measures to reduce the bycatch mortality of silky and oceanic whitetip sharks by establishing non-retention policies and the application of handling and safe release practices in purse seine and other fisheries (IATTC C-11-10 on oceanic whitetip shark; IATTC C-21-06 for silky shark). Moreover, a fraction of the IATTC purse-seine fishery has made notable improvements in its efforts to reduce unintended impacts on non-target species by adopting a voluntary measure to apply best practices for the handling and safe release of elasmobranchs (ISSF 2020) and has also contributed, in conjunction with IATTC observer program, to the generation of substantial knowledge to underpin an ecosystem-based approach to fisheries management (Gilman et al., 2017). Ensuring that the sustainability efforts of the purse seine fishery are effective in a broader context will also require adequate consideration of activities in the IATTC industrial and semi-industrial longline and multi-species and multi-gear artisanal fisheries, which continue to catch a wide range of elasmobranch species, either incidentally or as a target (Griffiths et al., 2021; Oliveros-Ramos et al. 2020).

Unlike the purse-seine fishery, the longline and artisanal fisheries have notably low or non-existent observer coverage (Ewel et al., 2020; Murua et al., 2020), which not only are insufficient in representing the overall activities of these fisheries, but also result in only partial geographic and historical coverage of the fisheries' footprints, in some cases, even in areas of the highest tuna CPUE (Griffiths et al. 2021). Future studies, including data collected from other underrepresented fisheries (ideally with increased observer coverage and data quality), could investigate the habitat use and distribution of both species and further elucidate areas of multi-species potential overlap areas.

Among the challenges identified by the IATTC for the sustainable management of sharks (Siu and Aires-da-Silva, 2016), the lack of reliable species-specific shark catch data from longline fisheries was identified as one of the primary roadblocks preventing the creation of adequate stock assessments and/or stock status indicators. Silky sharks are among the few shark species for which Pacific-wide population assessments have been conducted and were found to be (in 2016) at or below the biomass for maximum sustainable yield, although its authors raised concerns about the association of CPUE indices with oceanographic conditions and suggested they may not directly reflect the fluctuations in population size (Clarke *et al*., 2018). This phenomenon has also been observed in the EPO for silky sharks, where the environment is believed to affect life-stage-specific silky shark relative abundance indices (Lennert-Cody et al. 2018). Furthermore, shark catch data from coastal artisanal fisheries is still very much lacking for silky sharks and most other elasmobranch species (Doherty et al., 2014). While there is room for improvement in the evaluation of silky shark populations across the Pacific basin, there is simply insufficient information to conduct a comprehensive stock assessment for oceanic whitetip sharks. Here it is important to note that despite the promising IATTC resolution C-11-10 that entered into force in 2012 and prohibits the retention of oceanic whitetip sharks, which might have impacted data collection of the species, a decade after, there are few signs indicating a population recovery. This underlines the need to consider further measures, in addition to non-retention policies, to ensure post-release mortality is minimized but also, more generally, the adoption of other measures to reduce overall bycatch mortality through avoidance and mitigation measures. We, therefore, consider that the implementation of adaptive management closures to reduce silky shark and oceanic whitetip shark bycatch would likely be a significant step towards reducing fishing mortality and enhancing the sustainability of both species.

While the dynamic approaches to pelagic spatial management proposed by Hyrenbach et al., (2000) may have been hard to enforce at the start of the century, the advancement and mainstreaming of modern vessel tracking technologies would allow for an accurate assessment of compliance at high spatial and temporal resolutions. A recent IATTC Resolution (C-21-04) requests Members and Cooperating non-Members (CPCs) to submit vessel monitoring system (VMS) data for all commercial tuna vessels larger than 24 meters starting in 2023, but for science purposes only. If the goals in data use are expanded, this could be a promising development that would allow IATTC and CPCs to monitor the compliance of their vessels with any adopted new and existing management measure based on spatial management. The greater use of vessel tracking technologies also opens the possibility for designing and enforcing near-real-time management measures such as '*move-on rules*' or dynamic ocean management (Welch et al., 2020). Such measures could complement our work by helping predict areas of high fishing inefficiency which are not persistent over time. This could be done through the creation of habitat models capable of capturing the patterns of distribution of target and non-target species under different environmental scenarios, by building, for example, on work by Lennert-Cody et al (2018), Lopez et al. (2019), Lezama-Ochoa et al. (2020) and Lennert-Cody et al. (2021), who suggested that environmental conditions do affect tuna and elasmobranch distribution in the EPO and that trends vary by area and size-class.

CONCLUSIONS, CAVEATS AND FUTURE WORK

While our study provides an in-depth analysis of two frequently encountered and vulnerable shark species within the OBJ fishery, we recognize that this is only one of many fisheries that catch them, and other, non-target species within the IATTC Convention Area. In the case of silky shark, purse-seine fishery bycatch is composed primarily of juveniles while other fisheries, such as the longline fishery, catch a wider size spectrum of individuals, including adults. This is very important to consider in the development of holistic bycatch management measures as the whole ontogeny of the species needs to be considered. Therefore, a holistic bycatch approach that would ideally be considered by the IATTC should address several outstanding topics of importance across all fisheries within its convention area to improve sustainable fisheries management:

- Although our analysis attempts to minimize socioeconomic costs to the fishery by quantifying areas of high fishing inefficiency (instead of areas of high bycatch alone), our study did not consider how the suggested spatial management measures could influence costs and benefits for particular fleets or nations. Additional analysis could therefore explore how different fleets would have benefited or been impacted by the proposed closures.
- While the focus of our study was on two moderately to highly vulnerable shark species in need of bycatch reduction measures, it would be important for future work to assess the relative impacts of proposed closures on the catch and bycatch rates of other species, especially after reallocating the displaced fishing effort.
- The exploration of adaptive management for other non-target species should be conducted together with attempts to consolidate all areas of suggested closure to account for multi-species objectives.
- Our study assumed a proportional redistribution of fishing effort across the remaining range of the fishery outside of the proposed closures based on historical patterns. While we accounted for the temporal dimension by reallocating fishing effort for each month separately, alternative forms of fishing effort redistribution exist and could be explored (Powers and Abeare, 2009).
- Since our analysis was unable to account for ephemeral areas of high fishing inefficiency (i.e., monthly cells which were only classified as inefficient for one year only), further research guided by the principles of dynamic ocean management may be required to determine if these areas are predictable using environmental information.
- Our results are primarily applicable to the class-6 (>363 t carrying capacity) purse seine vessels that operate in the OBJ fishery. Improving bycatch data collection by underrepresented fisheries operating in the coastal or pelagic longline fisheries, to which high elasmobranch mortality rates are attributed, will be crucial for the exploration of adaptive management in a holistic way.

The work that is presently carried out within the IATTC in this area does strengthen the potential to implement a multi-species spatial management strategy and provide spatial management options for silky sharks and oceanic whitetip sharks. Importantly, they are in consonance with, but also expanded on, previous research results that explored spatio-temporal trade-offs to reduce shark bycatch in the region (Watson *et al.,* 2009; Román-Verdesoto 2014), further strengthening the scientific basis for the implementation of spatio-temporal management measures to reduce bycatch in the region.

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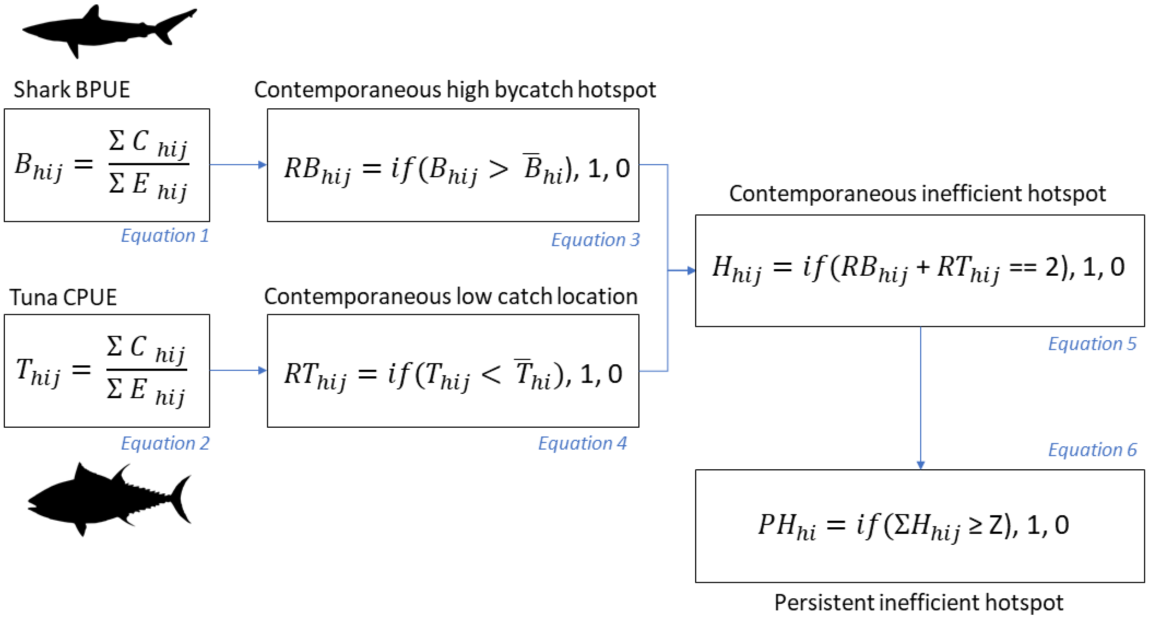


FIGURE 1. Tuna CPUE (C) and shark BPUE (B) rates (Eq. 1 & Eq. 2) were calculated by dividing the total catch (C) of each species group by the total fishing effort (E - number of sets) across every cell (h), month (i) and year (j) combination. Locations with higher than average BPUE (RB) and CPUE (RT) rates (Eq. 3 & Eq. 4) were identified by determining if the rates in a particular cell/month/year location were higher or lower than the monthly historic average for that cell - $\overline{\mathrm{B}}$ & $\overline{\mathrm{T}}$ - respectively. Contemporaneous monthly locations where low CPUE and high BPUE rates converged (H) were identified by combining the estimates for RB and RT (Eq. 5). Finally, the spatio-temporal persistence of inefficient fishing hotspots (PH) was calculated by assessing the frequency against a given threshold (Z) with which a cell was classified as being inefficient during each historic monthly series.

FIGURA 1. Las tasas de CPUE (C) de atunes y de CIPUE (CI) de tiburones (Ecuación 1 y Ecuación 2) se calcularon dividiendo la captura total (C) de cada grupo de especies por el esfuerzo total de pesca (E - número de lances) en cada combinación de celda (h), mes (i) y año (j). Las ubicaciones con tasas de CIPUE (RB) y CPUE (RT) superiores al promedio (Ecuación 3 y Ecuación 4) se identificaron determinando si las tasas en una ubicación de celda/mes/año en particular eran más altas o más bajas que el promedio histórico mensual para esa celda - $\overline{\mathrm{B}}$ & $\overline{\mathrm{T}}$ - respectivamente. Se identificaron las ubicaciones mensuales contemporáneas en las que convergían (H) las tasas bajas de CPUE y las tasas altas de CIPUE combinando las estimaciones de RB y RT (Ecuación 5). Finalmente, se calculó la persistencia espaciotemporal de los puntos críticos de pesca ineficaz (PH) evaluando la frecuencia frente a un determinado umbral (Z) con el que una celda se clasificaba como ineficaz durante cada serie mensual histórica.

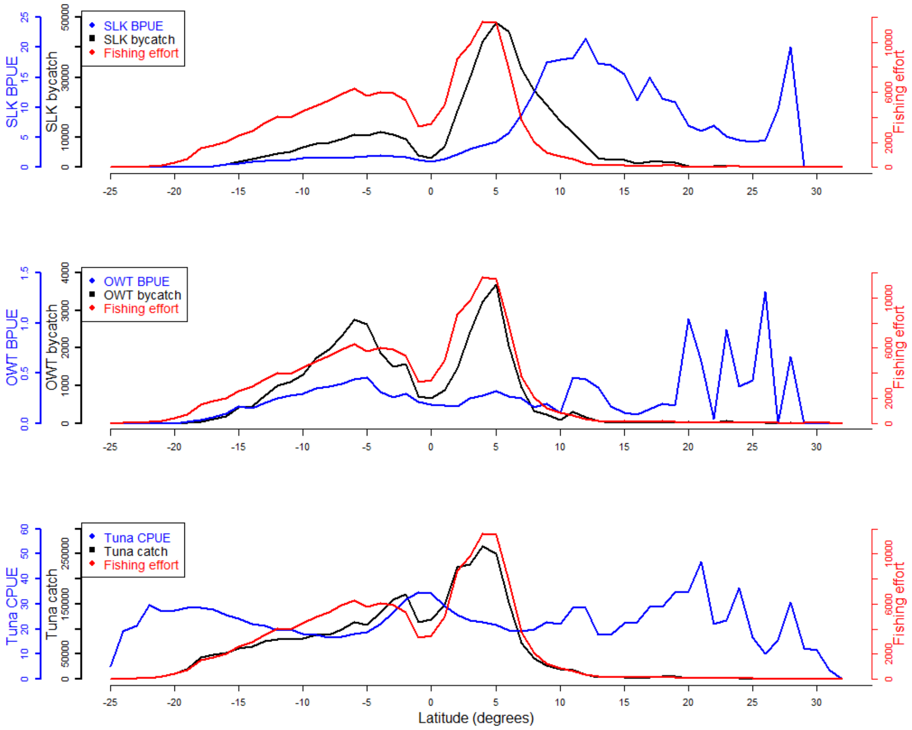


FIGURE 2. Latitudinal distribution of silky shark (top), oceanic whitetip shark (middle) and tuna (bottom) BPUE/CPUE (blue), bycatch/catch (black) and fishing effort (red) throughout the time series 1995–2021.

FIGURA 2. Distribución latitudinal de la CIPUE/CPUE (azul), la captura incidental/captura (negro) y el esfuerzo de pesca (rojo) del tiburón sedoso (arriba), el tiburón punta blanca oceánico (centro) y los atunes (abajo) a lo largo de la serie de tiempo 1995–2021.

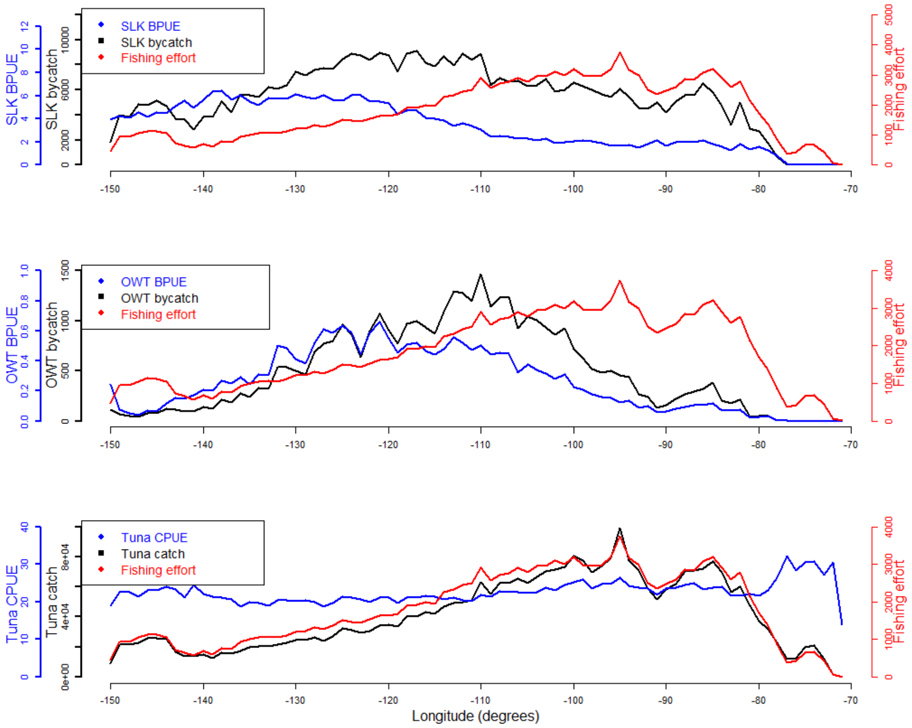


FIGURE 3. Longitudinal distribution of silky shark (top), oceanic whitetip shark (middle) and tuna (bottom) BPUE/CPUE (blue), bycatch/catch (black) and fishing effort (red) throughout the time series 1995–2021.

FIGURA 3. Distribución longitudinal de la CIPUE/CPUE (azul), la captura incidental/captura (negro) y el esfuerzo de pesca (rojo) del tiburón sedoso (arriba), el tiburón punta blanca oceánico (centro) y los atunes (abajo) a lo largo de la serie de tiempo 1995–2021.

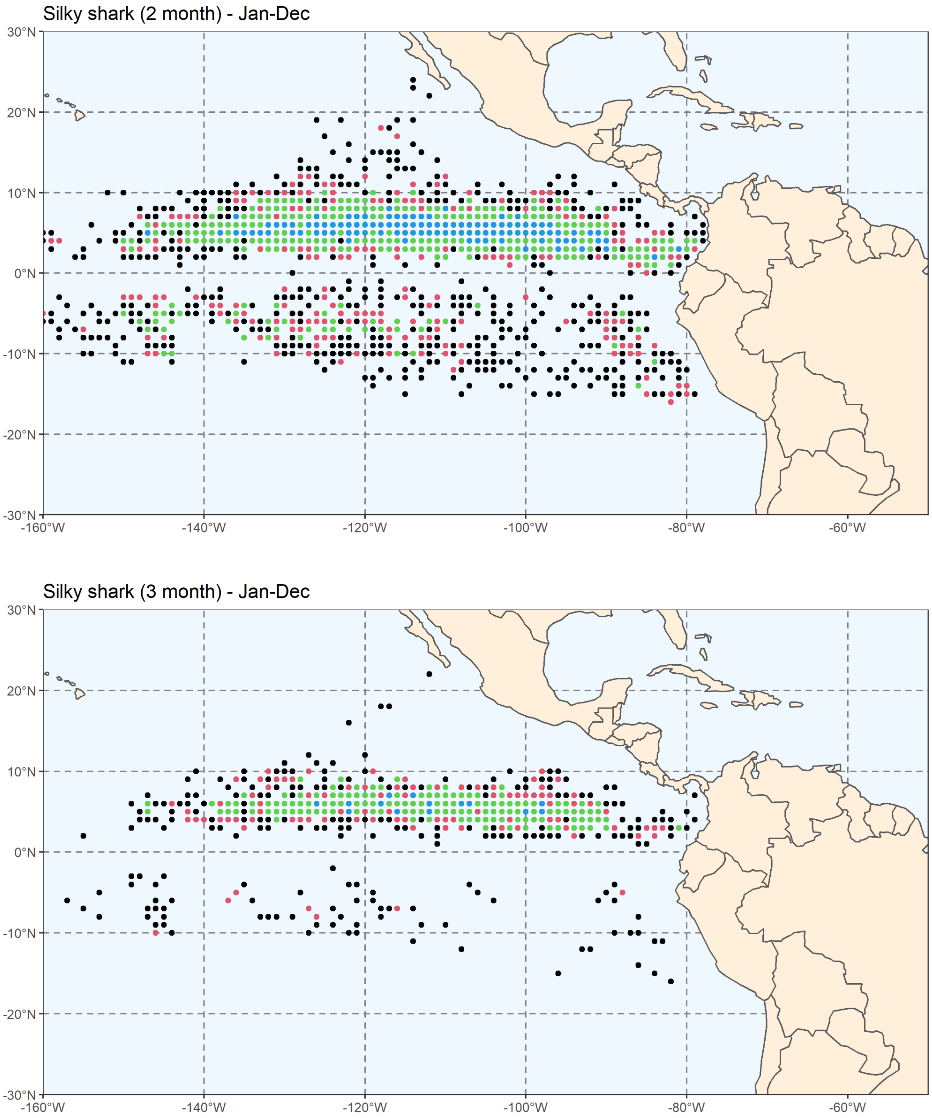


FIGURE 4. Areas of high fishing inefficiency for silky sharks at a two-month threshold (top) and three-month threshold (bottom). The color of the dots reflects the number of months a cell is proposed for closure throughout the year, where black is 1 month, red is 2 months, green is 3-6 months and blue is over 6 months.

FIGURA 4. Áreas de alta ineficacia pesquera para tiburones sedosos en un umbral de dos meses (arriba) y un umbral de tres meses (abajo). El color de los puntos refleja el número de meses que se propone cerrar una celda a lo largo del año, donde el negro es 1 mes, el rojo es 2 meses, el verde es 3-6 meses y el azul es más de 6 meses.

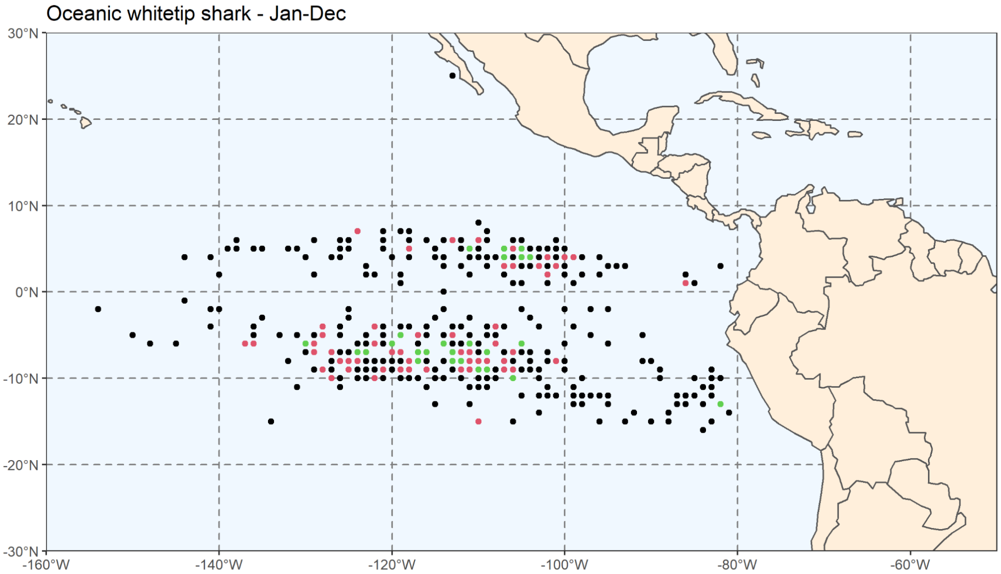


FIGURE 5. Areas of high fishing inefficiency for oceanic whitetip sharks at a two-month threshold. The color of the dots reflects the number of months a cell is proposed for closure throughout the year, where black is 1 month, red is 2 months, green is 3-5 months.

FIGURA 5. Áreas de alta ineficacia pesquera para tiburones punta blanca oceánicos en un umbral de dos meses. El color de los puntos refleja el número de meses que se propone cerrar una celda a lo largo del año, donde el negro es 1 mes, el rojo es 2 meses y el verde es 3-5 meses.

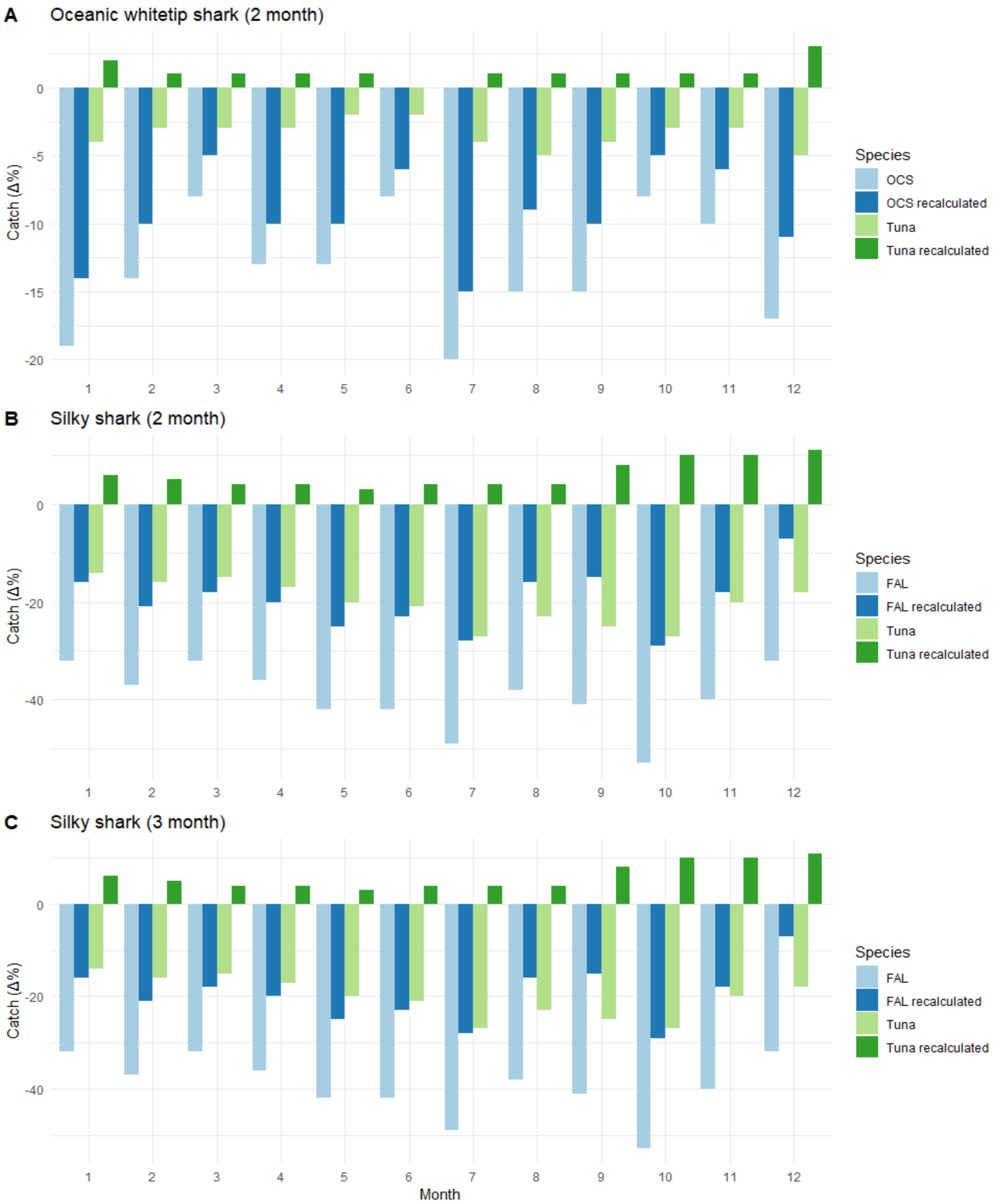


FIGURE 6. Expected reduction in shark bycatch (blue) and tuna catch (green) under two different closure scenarios, without effort redistribution (light) and after redistributing fishing effort and recalculating captures (dark). (A) closure based on a 2-month persistence threshold for oceanic whitetip sharks, (B) closure based on a 2-month persistence threshold for silky sharks, and (C) closure based on a 3-month persistence threshold for silky sharks.

FIGURA 6. Reducción esperada en la captura incidental de tiburones (azul) y la captura de atunes (verde) con dos escenarios de veda, sin redistribución del esfuerzo (claro) y después de redistribuir el esfuerzo de pesca y recalcular las capturas (oscuro). (A) veda basada en un umbral de persistencia de 2 meses para tiburones punta blanca oceánicos, (B) veda basada en un umbral de persistencia de 2 meses para tiburones sedosos, y (C) veda basada en un umbral de persistencia de 3 meses para tiburones sedosos.

TABLE 1. Total bycatch and bycatch per unit effort (BPUE) for silky sharks and oceanic whitetip sharks for three purse-seine set types in the ETP between 1995–2021.

TABLA 1. Captura incidental total y captura incidental por unidad de esfuerzo (CIPUE) para tiburones sedosos y tiburones punta blanca oceánicos para tres tipos de lances cerqueros en el OPO tropical entre 1995 y 2021.

Set type	**Number of sets**	**FAL bycatch (numbers)**	**FAL BPUE (numbers per set)**	**OCS bycatch (numbers)**	**OCS BPUE (numbers per set)**
Floating object	187,431	526,413	2.81	40,863	0.22
Dolphin	222,663	30,240	0.14	912	0.004
Non-associated	94,476	29,484	0.31	1,109	0.01

SUPPLEMENTARY MATERIALS

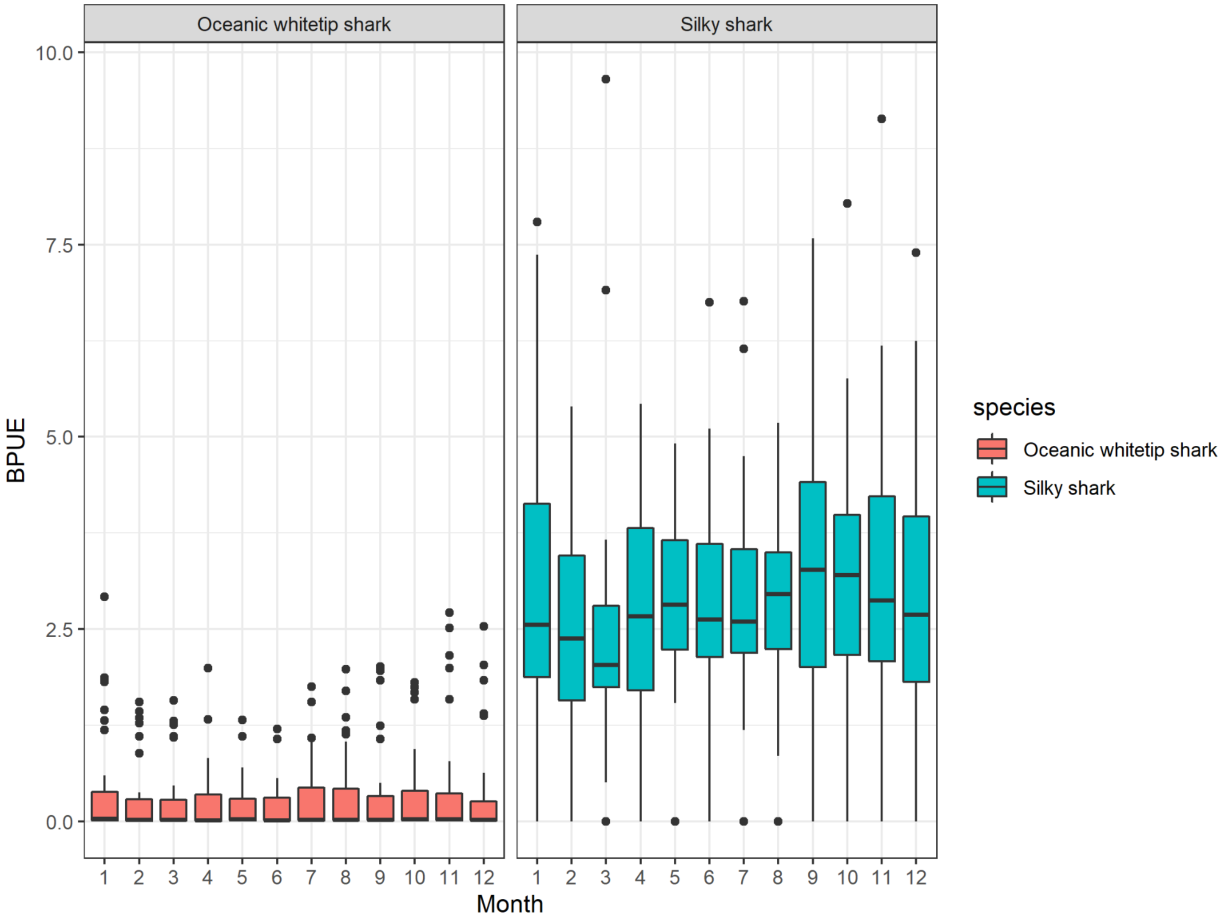


FIGURE 1. Intra-annual distribution of bycatch per unit of effort (BPUE) of oceanic whitetip sharks (left) and silky sharks (right) in the eastern tropical Pacific tropical purse-seine fishery setting on FADs.

FIGURA 1. Distribución intraanual de la captura incidental por unidad de esfuerzo (CIPUE) de tiburones punta blanca oceánicos (izquierda) y tiburones sedosos (derecha) en lances sobre plantados de la pesquería de cerco del Pacífico oriental tropical.

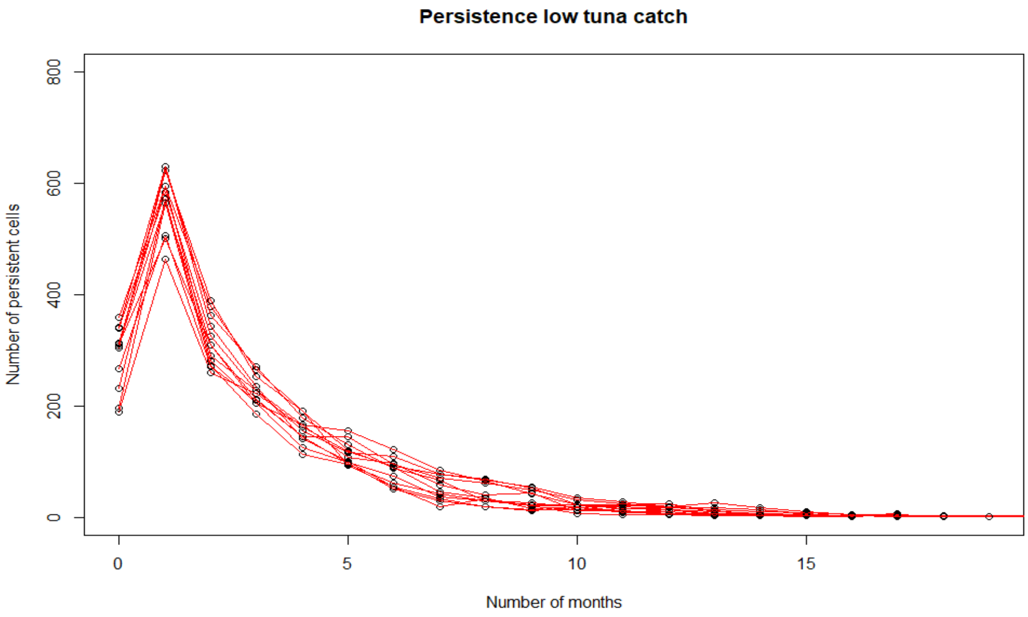


FIGURE 2. Monthly persistence of areas of lower than average tuna CPUE.
FIGURA 2. Persistencia mensual de áreas con una CPUE de atunes inferior al promedio.

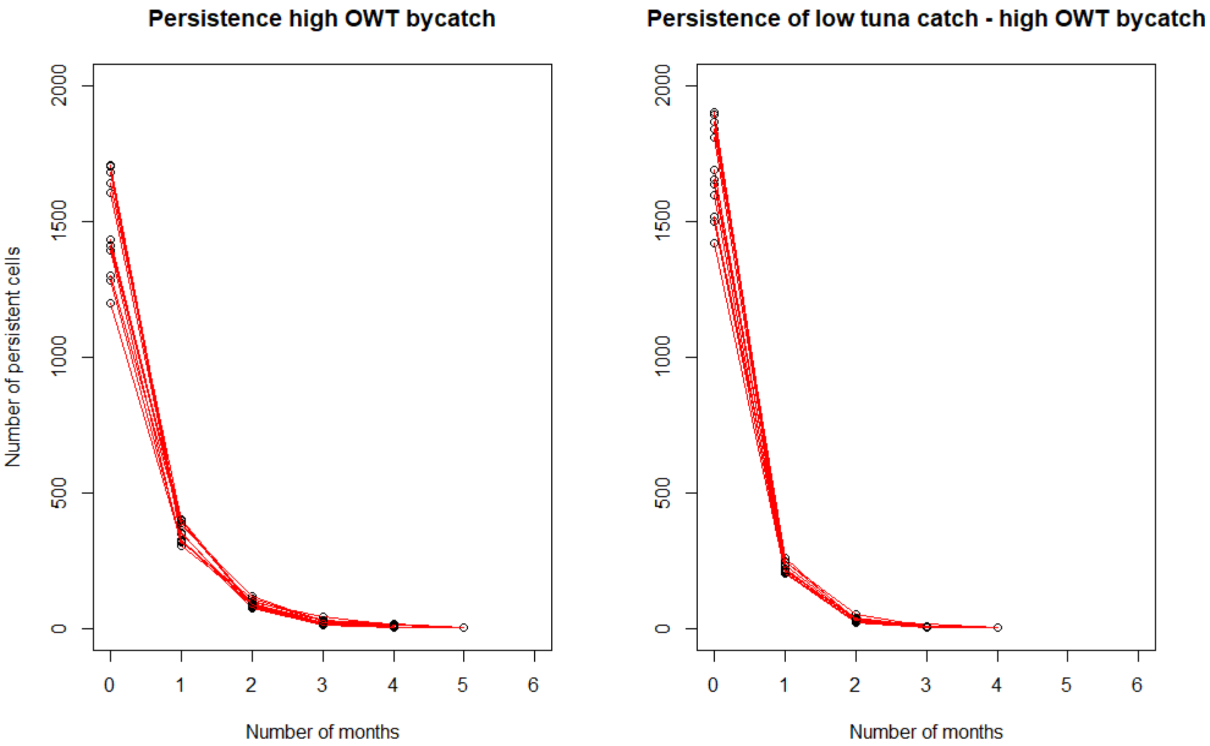


FIGURE 3. Monthly persistence of areas of lower than average oceanic whitetip shark BPUE (right) and monthly persistence of areas where there is a simultaneous high shark BPUE and low tuna CPUE (left).
FIGURA 3. Persistencia mensual de áreas de CIPUE de tiburón punta blanca oceánico por debajo del promedio (derecha) y persistencia mensual de áreas donde existe simultáneamente una alta CIPUE de tiburones y una baja CPUE de atunes (izquierda).

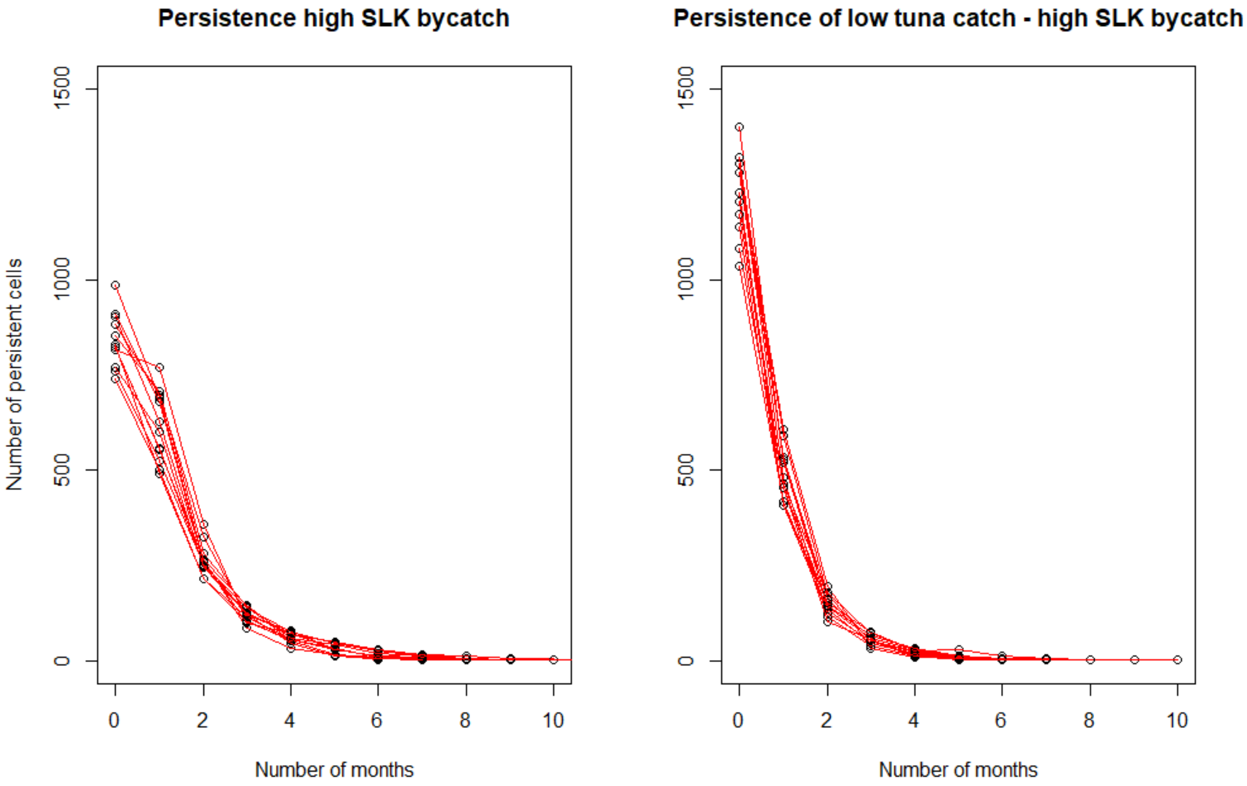
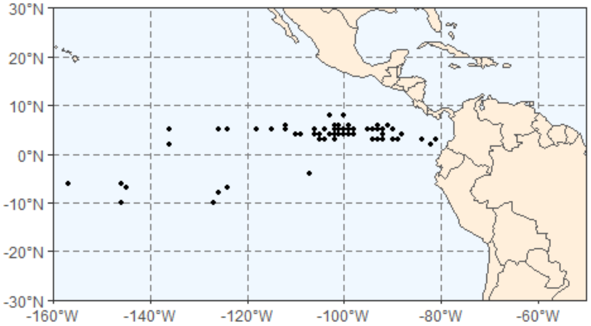
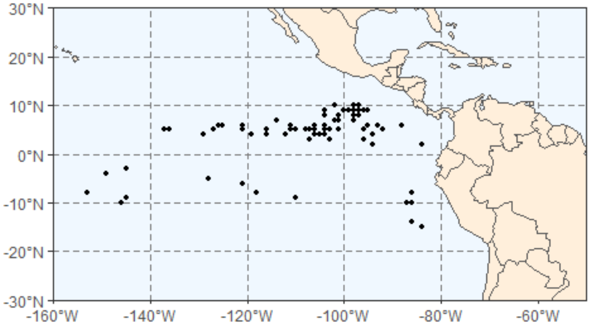


FIGURE 4. Monthly persistence of areas of lower than average silky shark BPUE (right) and monthly persistence of areas where there is a simultaneous high shark BPUE and low tuna CPUE (left).

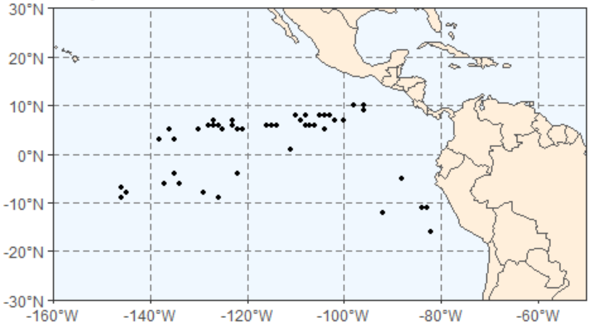
FIGURA 4. Persistencia mensual de áreas de CIPUE de tiburón sedoso por debajo del promedio (derecha) y persistencia mensual de áreas donde existe simultáneamente una alta CIPUE de tiburones y una baja CPUE de atunes (izquierda).



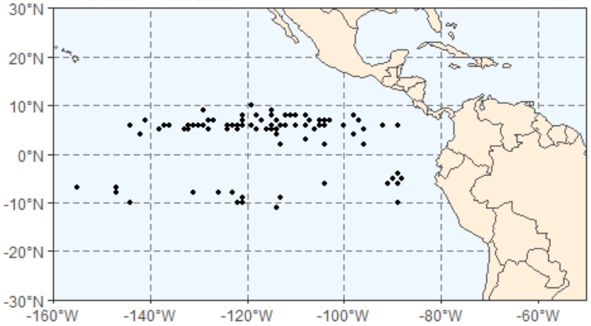
Silky shark - January



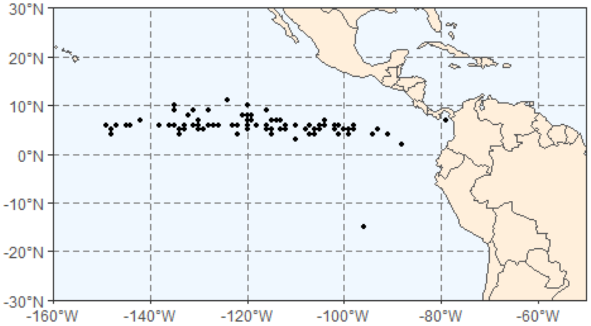
Silky shark - Feburary



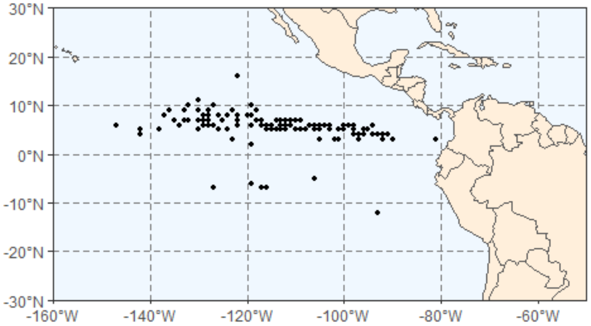
Silky shark - March



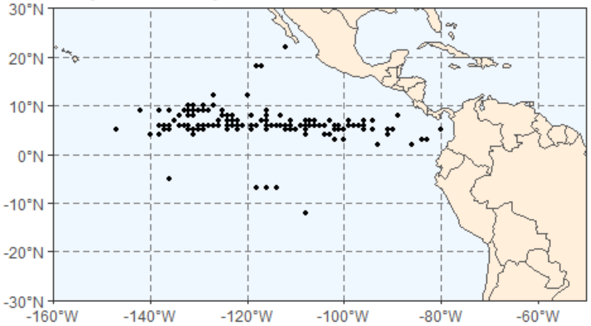
Silky shark - April



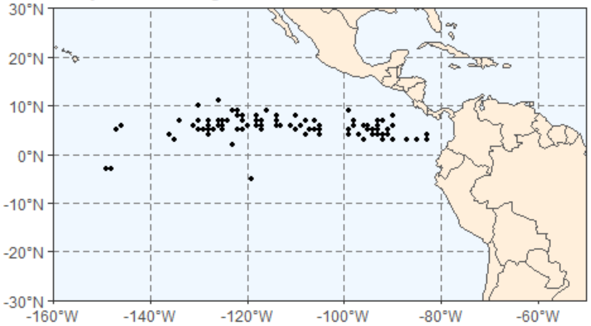
Silky shark - May



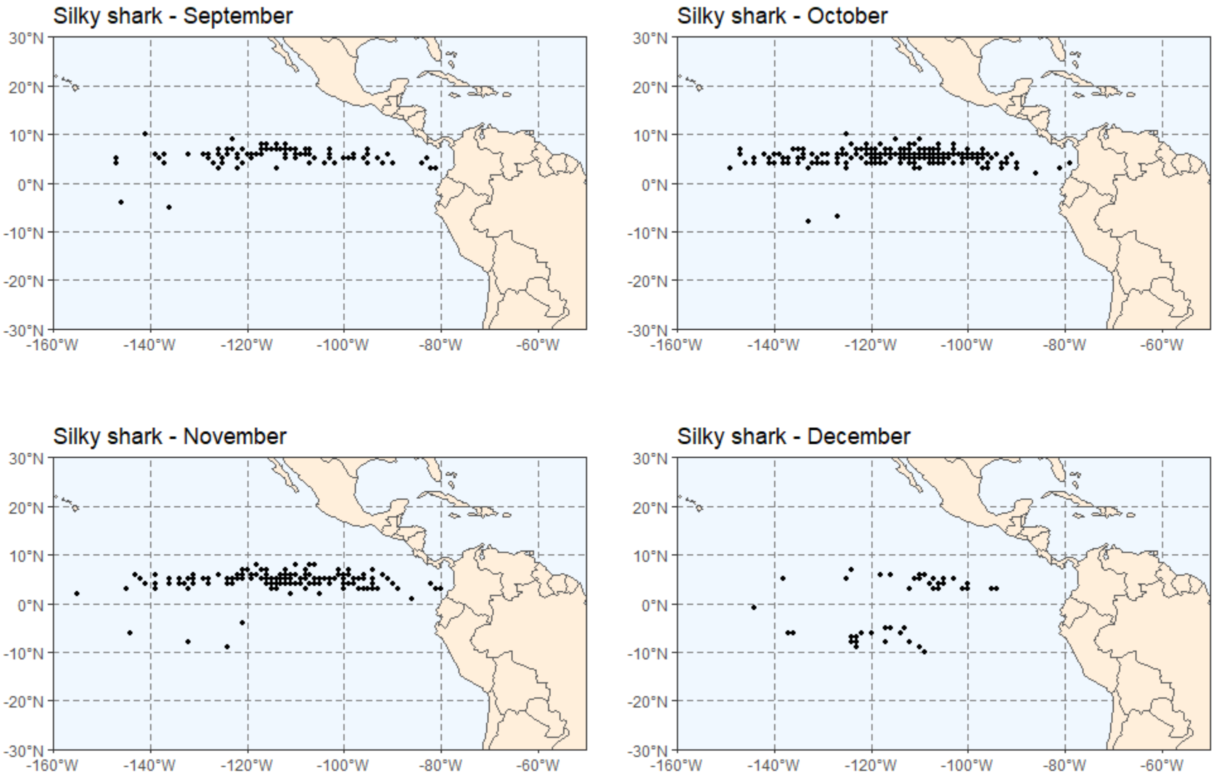
Silky shark - June



Silky shark - July



Silky shark - August



Silky shark - September

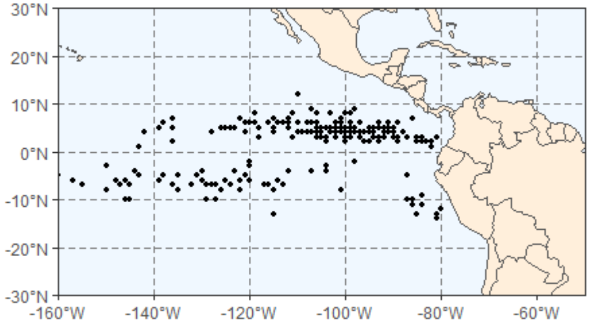
Silky shark - October

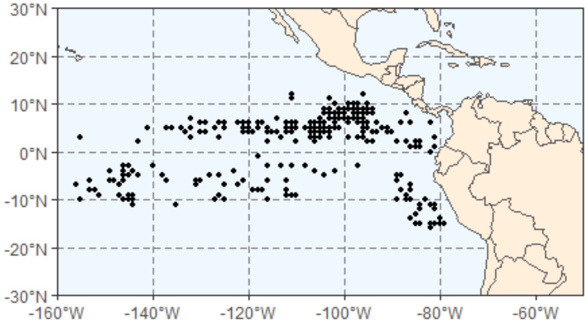
Silky shark - November

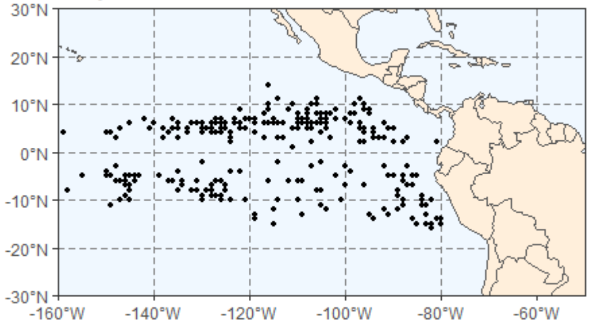
Silky shark - December

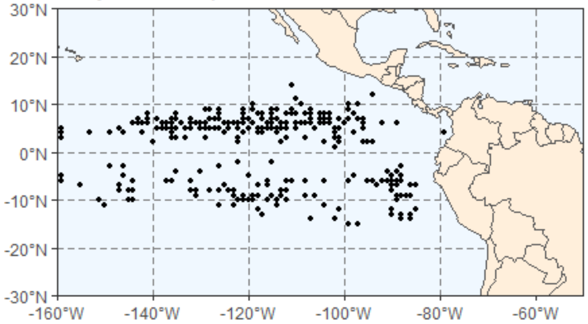
FIGURE 5. Monthly distribution of areas of high fishing inefficiency for silky sharks in the EPO using a 3-month threshold.

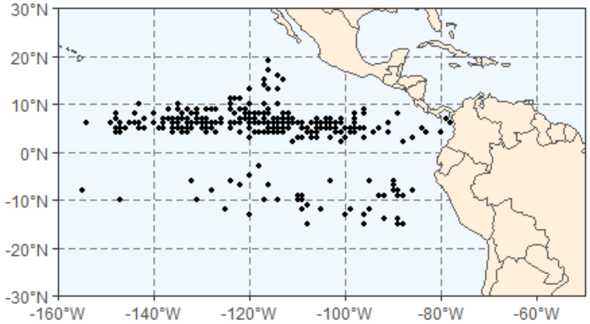
FIGURA 5. Distribución mensual de áreas de alta ineficacia pesquera para tiburones sedosos en el OPO utilizando un umbral de 3 meses.

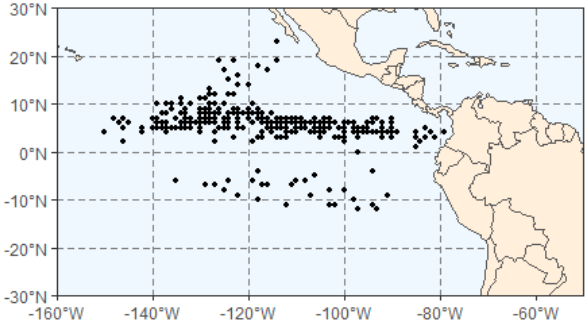

Silky shark - January

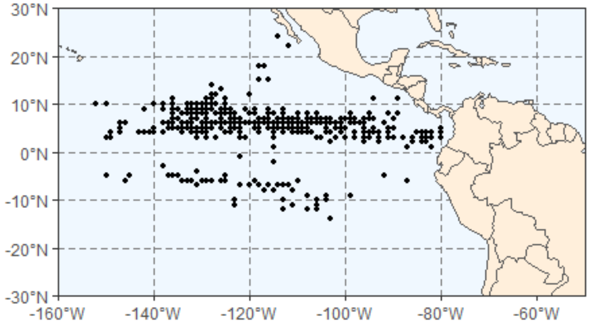

Silky shark - Feburary

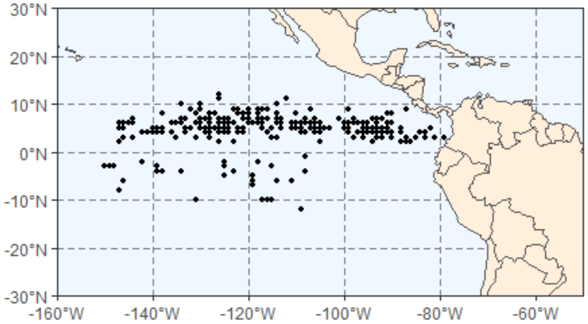

Silky shark - March


Silky shark - April


Silky shark - May


Silky shark - June


Silky shark - July


Silky shark - August

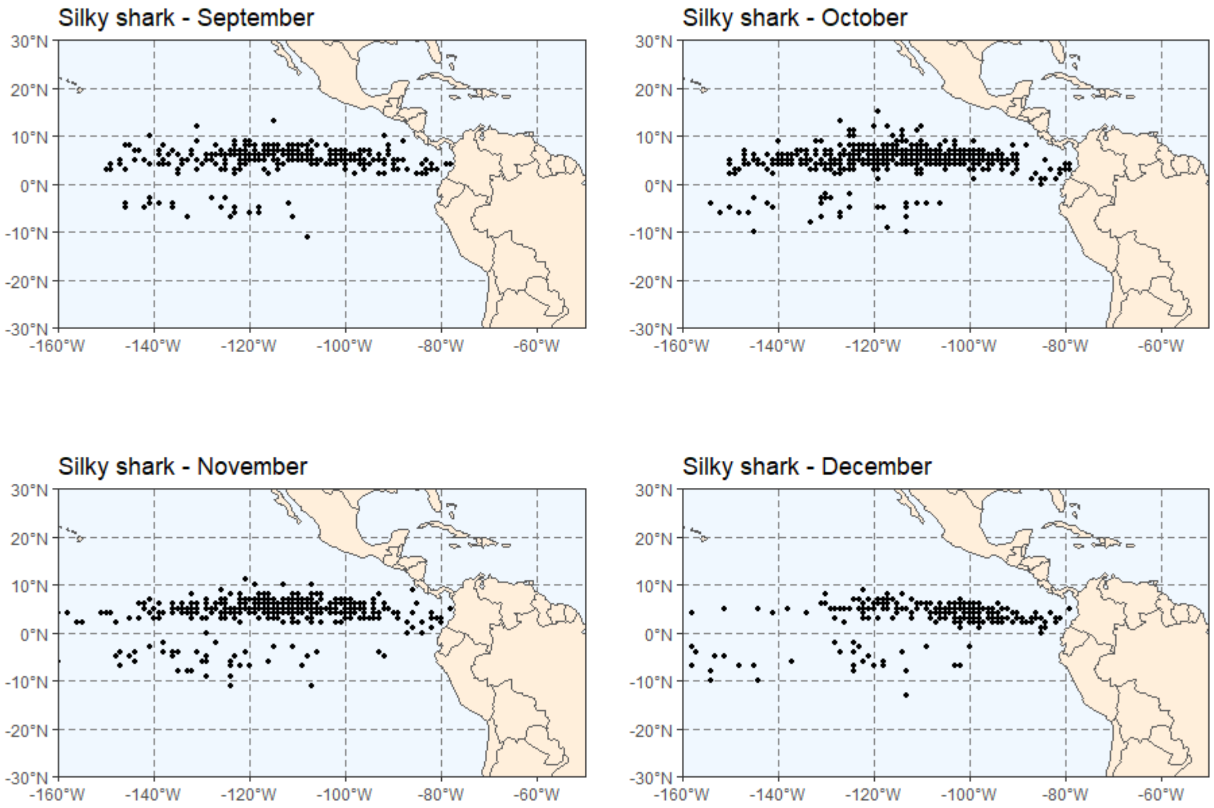
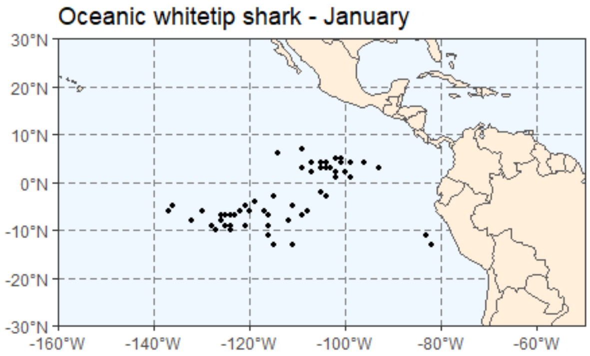
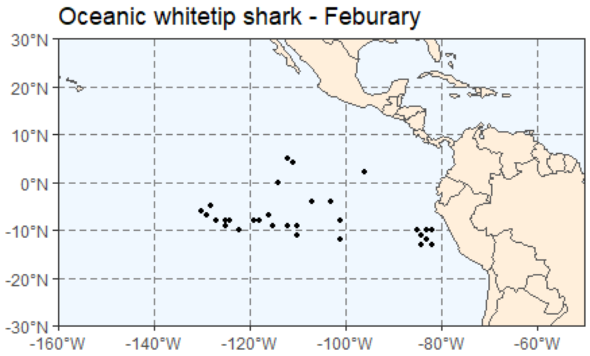
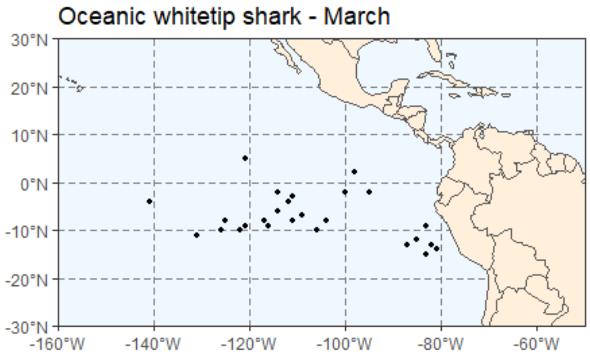


FIGURE 6. Monthly distribution of areas of high fishing inefficiency for silky sharks in the EPO using a 2-month threshold.

FIGURA 6. Distribución mensual de áreas de alta ineficacia pesquera para tiburones sedosos en el OPO utilizando un umbral de 2 meses.


Oceanic whitetip shark - January
30°N
20°N
10°N
0°N
-10°N
-20°N
-30°N
-160°W
-140°W
-120°W
-100°W
-80°W
-60°W


Oceanic whitetip shark - Feburary
30°N
20°N
10°N
0°N
-10°N
-20°N
-30°N
-160°W
-140°W
-120°W
-100°W
-80°W
-60°W


Oceanic whitetip shark - March
30°N
20°N
10°N
0°N
-10°N
-20°N
-30°N
-160°W
-140°W
-120°W
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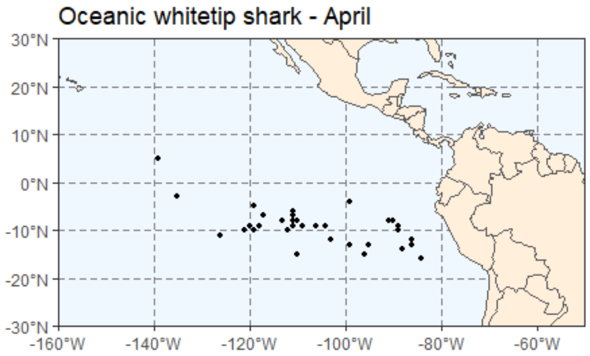
-80°W
-60°W


Oceanic whitetip shark - April
30°N
20°N
10°N
0°N
-10°N
-20°N
-30°N
-160°W
-140°W
-120°W
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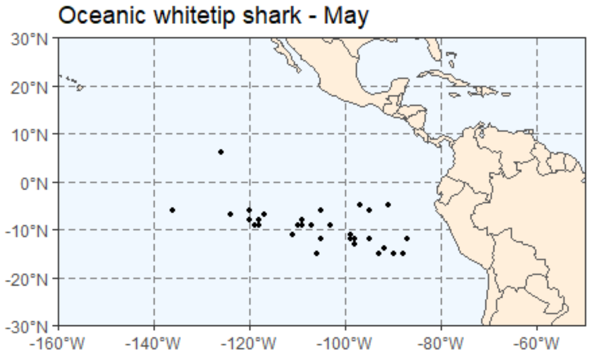
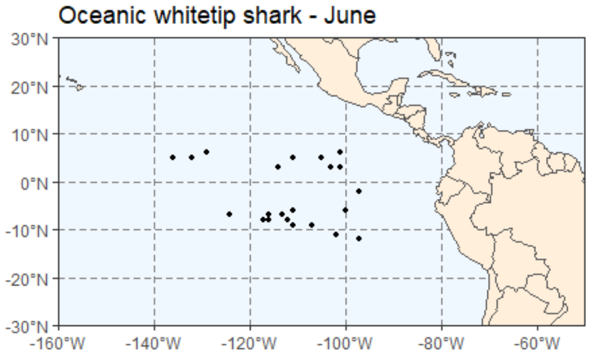
-80°W
-60°W


Oceanic whitetip shark - May
30°N
20°N
10°N
0°N
-10°N
-20°N
-30°N
-160°W
-140°W
-120°W
-100°W
-80°W
-60°W


Oceanic whitetip shark - June
30°N
20°N
10°N
0°N
-10°N
-20°N
-30°N
-160°W
-140°W
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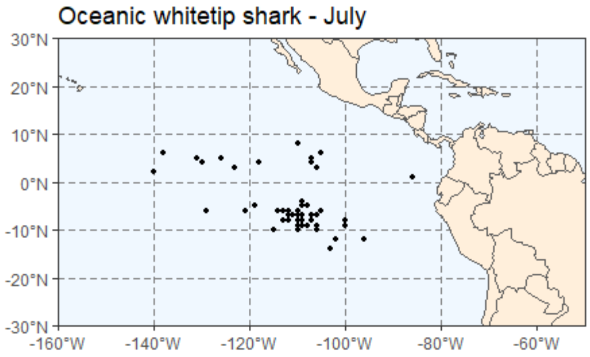
-80°W
-60°W


Oceanic whitetip shark - July
30°N
20°N
10°N
0°N
-10°N
-20°N
-30°N
-160°W
-140°W
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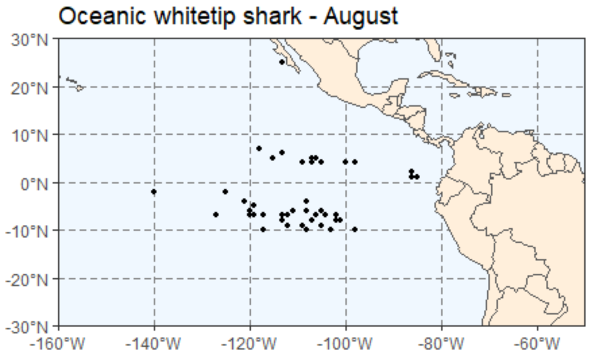
-100°W
-80°W
-60°W


Oceanic whitetip shark - August
30°N
20°N
10°N
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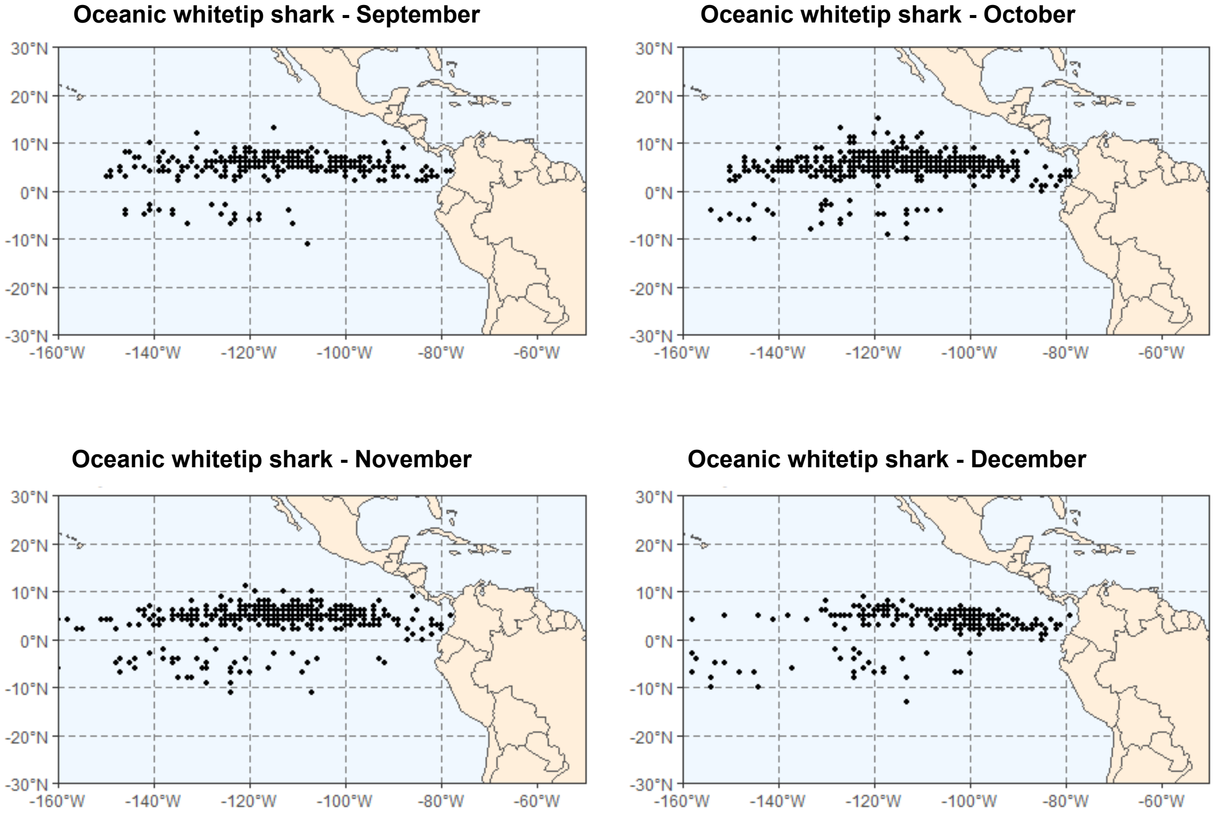

FIGURE 7. Monthly distribution of areas of high fishing inefficiency for oceanic whitetip sharks in the EPO using a 2-month threshold.

FIGURA 7. Distribución mensual de áreas de alta ineficacia pesquera para tiburones punta blanca oceánicos en el OPO utilizando un umbral de 2 meses.

TABLE 1. Expected impact of closing areas of high fishing inefficiency for silky sharks and oceanic whitetip sharks expressed as the change in catch, bycatch and effort, as well as the reconstructed bycatch and catch estimates of each closure based on a proportional redistribution of fishing effort.

TABLA 1. Impacto esperado de cerrar áreas de alta ineficacia pesquera para el tiburón sedoso y el tiburón punta blanca oceánico expresado como el cambio en la captura, la captura incidental y el esfuerzo, así como las estimaciones reconstruidas de captura incidental y de captura de cada veda con base en una redistribución proporcional del esfuerzo de pesca.

Species code	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
FAL - 2 month	Fishing effort (%)	-19	-20	-18	-20	-22	-25	-30	-26	-30	-34	-27	-27
FAL - 2 month	Δ tuna catch (%)	-14	-16	-15	-17	-20	-21	-27	-23	-25	-27	-20	-18
FAL - 2 month	Δ bycatch (%)	-32	-37	-32	-36	-42	-42	-49	-38	-41	-53	-40	-32
FAL - 2 month	Δ recalculated catch (%)	6	5	4	4	3	4	4	4	8	10	10	11
FAL - 2 month	Δ recalculated bycatch (%)	-16	-21	-18	-20	-25	-23	-28	-16	-15	-29	-18	-7
FAL - 3 month	Fishing effort (%)	-7	-5	-4	-7	-9	-13	-14	-13	-12	-22	-15	-14
FAL - 3 month	Δ tuna catch (%)	-5	-3	-3	-6	-8	-11	-12	-11	-9	-17	-10	-9
FAL - 3 month	Δ bycatch (%)	-14	-15	-9	-18	-19	-22	-26	-19	-20	-36	-23	-17
FAL - 3 month	Δ recalculated catch (%)	2	1	1	1	1	3	2	2	3	7	6	6
FAL - 3 month	Δ recalculated bycatch (%)	-7	-11	-6	-12	-10	-10	-15	-8	-9	-17	-9	-3
OCS - 2 month	Fishing effort (%)	-6	-4	-4	-3	-3	-2	-5	-6	-5	-4	-4	-7
OCS - 2 month	Δ tuna catch (%)	-4	-3	-3	-3	-2	-2	-4	-5	-4	-3	-3	-5
OCS - 2 month	Δ bycatch (%)	-19	-14	-8	-13	-13	-8	-20	-15	-15	-8	-10	-17
OCS - 2 month	Δ recalculated catch (%)	2	1	1	1	1	0	1	1	1	1	1	3
OCS - 2 month	Δ recalculated bycatch (%)	-14	-10	-5	-10	-10	-6	-15	-9	-10	-5	-6	-11