Received: 20 February 2023 | Revised: 24 January 2024 | Accepted: 15 February 2024

DOI: 10.1111/cobi.14324

Conservation Biology

CONTRIBUTED PAPER

Adaptive spatiotemporal management to reduce shark bycatch in tuna fisheries

Guillermo Ortuño Crespo[1,2] | **Shane Griffiths**[3] | **Hilario Murua**[4] | **Henrik Österblom**[2] | **Jon Lopez**[3]

[1]IUCN World Commission on Protected Areas High Seas Specialist Group & Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

[2]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

[3]Inter-American Tropical Tuna Commission (IATTC), La Jolla, California, USA

[4]International Seafood Sustainability Foundation, Pittsburgh, Pennsylvania, USA

Correspondence
Guillermo Ortuño Crespo, IUCN World Commission on Protected Areas High Seas Specialist Group & Stockholm Resilience Centre, Stockholm University, Albanovägen 28, 106 91 Stockholm, Sweden.
Email: gortunocrespo@gmail.com

Article impact statement: Adaptive spatiotemporal closures can reduce bycatch without affecting target species catch rates.

Funding information
International Seafood Sustainability Foundation; David and Lucile Packard Foundation, Grant/Award Number: 2020-70299

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 ecosystem management balances conservation and resource use and requires considering trade-offs and synergies. Seasonal and adaptive spatial measures can reduce fisheries impacts on nontarget species while maintaining or increasing target catches. Identifying persistently high-risk areas in the open ocean, where dynamic environmental conditions drive changes in species' distributions, is essential for exploring the impact of fisheries closures. We used fisheries observer data collected from 1995 to 2021 to explore the spatiotemporal persistence of areas of high bycatch risk for 2 species of oceanic sharks, silky shark (*Carcharhinus falciformis*) and oceanic whitetip shark (*Carcharhinus longimanus*), and of low tuna catch rates. We analyzed data collected by fisheries scientific observers onboard approximately 200 large purse-seine vessels operating in the EPO under 10 different flags. Fishing effort, catch, and bycatch data were aggregated spatially and temporally at 1° × 1° cells and monthly, respectively. When areas of high fishing inefficiency were closed the entire study period and effort was reallocated proportionally to reflect historical effort patterns, yearly tuna catch appeared to increase by 1–11%, whereas bycatch of silky and oceanic whitetip sharks decreased by 10–19% and 9%, respectively. Prior to fishing effort redistribution, bycatch reductions accrued to 21–41% and 14% for silky and oceanic whitetip sharks, respectively. Our results are consistent with previous findings and demonstrate the high potential for reducing elasmobranch bycatch in the EPO without compromising catch rates of target tuna species. They also highlight the need to consider new dynamic and adaptive management measures to more efficiently fulfill conservation and sustainability objectives for exploited resources in the EPO.

KEYWORDS
bycatch, closure, eastern tropical pacific, fisheries, shark, spatiotemporal management, tuna

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 (Dulvy et al., 2021; Juan-Jorda et al., 2022; Pacoureau 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., are bycatch) in industrial, semi-industrial, artisanal, and recreational wild capture fisheries (Bonfil, 1994; Murua et al., 2013). One of the primary concerns relative to 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 UN Food and Agriculture Organization 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 nontarget species or species belonging to the same ecosystem as the target species. These provisions are reflected in the mandates of the 5 tuna RFMOs, including the Antigua Convention of the Inter-American Tropical Tuna Commission (IATTC) in the eastern Pacific Ocean (EPO), but they vary in the degree to which they have been operationalized (Juan-Jordá et al., 2018). An RFMO 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 2 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 because competing objectives and trade-offs must be considered. For example, modifying fishing gear characteristics (e.g., hook type) to reduce bycatch of a particular species group may unintendedly result in increased catch rates of other nontarget 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, nontarget species, nursery areas). Identifying areas of interest for spatial management in the open ocean depends on empirical data at high spatial resolution and collected over extended periods (Hilborn et al., 2022). The identification of such areas can also be accomplished through models that 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 nontarget species requires an in-depth exploration of risk and trade-offs across scenarios and species groups (Hilborn et al., 2022; Pons et al., 2022). Those spatial management measures can be static, when, for example, a fixed area is closed to fishing (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 (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 nontarget species. Nevertheless, some static spatial closures have been implemented to mitigate the capture of target species either seasonally or during specific life-history phases (e.g., El Corralito in the IATTC Convention Area) (Dunn et al., 2019) or to regulate the deployment of drifting fish aggregating devices (FADs) (ICCAT, 2021; WCPFC, 2021).

However, since the late 1970s, the global catch rates of many bycatch species, including sharks and rays (which according to data from Sea Around Us [searoundus.org] increased by 51.74% from 1970 to 2020 to 1642 million t), have increased in artisanal and industrial fisheries, especially for gillnets, longlines, and purse seines (Doherty et al., 2014; Pacoureau et al., 2021). 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 human-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., 2022). However, it is possible to identify areas of high bycatch risk and areas where bycatch reduction can be minimized while maximizing target catch (Hazen et al., 2013; Pons et al., 2022; Román-Verdesoto, 2014; Watson et al., 2009).

Therefore, we aimed to identify areas of relatively high bycatch rates of vulnerable species that coincide with relatively low tuna catches and that could be considered potential areas for the application of dynamic spatial mitigation management measures. We based our empirical data analyses 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 on 2 of the most frequently caught and potentially vulnerable shark bycatch species in the fishery: silky shark (*Carcharhinus falciformis*) and oceanic whitetip shark (*Carcharhinus longimanus*) (Griffiths et al., 2017; Román-Verdesoto & Orozco-Zoller, 2005; Watson et al., 2009). The latest global-level assessments by the International Union for Conservation of Nature (IUCN) (Rigby et al., 2019, 2021) classified these species as vulnerable and critically endangered, 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 found to have declining population trajectories, the abundance of oceanic whitetip sharks has declined much more than silky sharks, possibly due to their low fecundity and long gestation period (Seki et al., 1998; Young & Carlson, 2020).

Our primary goal was to provide fishery managers with reliable spatial management options for bycatch mitigation for these 2 threatened shark species and for these options to be supported by estimates of the potential trade-offs between bycatch reductions and target species catches. Presenting multispecies trade-offs across space and time may help managers approach a practical implementation of dynamic spatiotemporal 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, grows to about 400 cm in total length, is thought to live up to 22 years, and has 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 (Schaefer & Fuller, 2022; Zudaire et al., 2014).

The fishing activities of the tropical tuna purse-seine fleet in the EPO are regulated by the IATTC, which defines its boundaries under the 2003 Antigua Convention as the area from 50°N to 50°S and from 150°W to the coast of the Americas. Fishing by the tropical tuna purse-seine fleet occurs primarily in the tropical and subtropical latitudes of the area to which the convention applies (20°N–20°S) and is characterized by 3 fishing set types: 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); floating object set (OBJ), where the net is set around natural (e.g., log) or FADs with tuna and other species associated underneath; and 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 (IATTC, 2022).

Although the EPO tropical tuna purse-seine fishery targets yellowfin, skipjack (*Katsuwonus pelamis*), and bigeye (*T. obesus*) tunas, it incidentally catches nontarget species across all set types, including sharks, rays, dolphins, sea turtles, and teleosts (Duffy et al., 2019; Inter-American Tropical Tuna Commission, 2022), which are generally discarded or released at sea dead or alive.

Data

We analyzed 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 nontarget species from nearly 100% of sets made by class-6 (>363 t) tuna purse-seine vessels. As of September of 2023, the IATTC vessel registry had 292 registered purse-seine vessels flagged to 10 coastal nations (https://www.iattc.org/en-US/Management/Vessel-register). Class-6 purse seiners (>363 t) accounted for 211 of these vessels; however, 7 were listed as inactive and 2 were reported to have sunk, resulting in a fleet of 202 class-6 purse seiners registered in the EPO to 10 flags. Ecuador had the highest vessel count ($n = 70$), followed by Mexico ($n = 45$) and Panama ($n = 20$). Seven nations (Colombia, El Salvador, Spain, Nicaragua, Peru, the United States, and Venezuela) had fleets ranging from 3 to 18 vessels. The size and flag composition of the class-6 purse-seine fleet changed throughout the study period. Although our focal species of shark is also frequently caught in IATTC's longline fishery, the coarser spatial resolution of the longline observer data and its spatially and temporally scattered nature, due to low observer coverage, did not allow for its inclusion in our analyses (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*) (Watson et al., 2009). For our analyses, we aggregated data for all size classes of silky and oceanic whitetip sharks (i.e., small [<90 cm], medium [90–150 cm], large [>150 cm]), whereas all size and species data for the 3 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 3 set types—observed in the EPO from January 1995 to December 2021. We explored the differences in the extent of bycatch of each shark species in the 3 principal set types by calculating the total bycatch and average bycatch per unit effort (BPUE) (i.e., 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 (Appendix S1). Consequently, we focused on OBJ sets.

As part of the data exploration process, we also assessed the intraannual 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 (Appendix S2). In addition, we explored the spatial variability of tuna CPUE and shark CPUE and BPUE and their stability over time to determine whether there were broad spatial or temporal windows of higher risk of bycatch or opportunity to increase tuna CPUE.

Data aggregation

Our principal aim 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 to enable comparisons among scenarios. The OBJ sets were aggregated spatially to 1° × 1° 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 3 tropical tuna species) and shark bycatch estimates for both species of interest were also aggregated at 1° × 1° resolution and by month. We considered this the most appropriate spatial and temporal resolution at which to explore fine-scale patterns of fishing inefficiency that could also be considered for spatial management options. We suspected that conducting the analyses and making recommendations at a finer resolution would not only make it more challenging to identify areas of high fishing inefficiency, but also lead to recommendations that would be more difficult to consider and implement.

Spatiotemporal optimization

To identify cells with low target tuna CPUE and high shark BPUE, we conducted a series of sequential calculations to identify areas where the following 2 conditions were met simultaneously and persisted across years in each given month: shark catch rates were higher than monthly historic average and tuna catch rates were lower than the monthly historical average (Appendix S3). The spatiotemporal persistence of high risk cells (PH) with low tuna CPUE and high shark BPUE was calculated by assessing the frequency with which a cell was classified as inefficient during each historic monthly series.

First, BPUE (equation 1 in Appendix S3) and CPUE (equation 2 in Appendix S3) were calculated for 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 across the region (equation 3 in Appendix S3) and where CPUE of tuna was lower than the historical monthly average across the region were identified (equation 4 in Appendix S3). For example, we compared the BPUE and CPUE values of a cell in the month of January in 1 year to the mean value for January of 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 areas of high fishing inefficiency (equation 5 in Appendix S3). Fourth, the temporal persistence of monthly areas of fishing inefficiency was explored to identify potential monthly areas of high fishing inefficiency that remained among years (equation 6 in Appendix S3). This consisted of a summation of the times a specific monthly cell was classified as low efficiency across years (Appendix S4–S6). Different threshold values (e.g., the number of times a cell was identified as inefficient in January) above which a cell would be deemed persistently inefficient for purse-seine fishing on OBJ were also tested (Appendices S7 & S8).

A 2-fold process was conducted, which consisted of computing the total number of sharks and tons of tuna that would have not been caught had areas of persistently high fishing inefficiency been closed for each of the months in the time series and 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. The bycatch recalculation step was conducted for the shark species not originally targeted by the closure to determine the unintended impact in this species.

Finally, in the spirit of exploring multispecies spatiotemporal trade-offs, areas of low tuna CPUE and simultaneous high BPUE of *C. falciformis* and *C. longimanus* were explored and the expected impact of closing those cells was calculated.

Based on the results of the interannual persistence of high-inefficiency areas, we tested 2 persistence thresholds (i.e., number of times a cell was identified as a high-inefficiency location for a given month across years): 2 and 3 months for silky sharks and 2 months for oceanic whitetip sharks. This enabled the identification of interannual areas of inefficiency that are good candidate locations for fisheries closures due to their persistence. Each threshold resulted in different sizes of high-inefficiency areas and a different level of fishing activity in them (Appendices S7–S9). Additionally, we explored the potential for multispecies closures by applying a 2-month persistence threshold.

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 (Appendix S9). These results suggest an absence of a clear temporal window for significant bycatch reduction and justify the need to consider all months in our analyses. The relative similarity of BPUE ranges of silky shark and oceanic whitetip shark across months (Appendix S2) suggested that using monthly BPUE averages as a threshold for identifying areas of higher risk was appropriate for identifying comparable high-risk areas throughout the time series.

RESULTS

The spatial footprint of the OBJ fishery from 1995 to 2021 ranged from 865 to 1863 1° × 1° cells (average 1498 cells per year), or 14.9 million km^2. Over time (1995–2005), the effort spatial footprint was stable at around 1170 cells, but it increased in spatial coverage by about 50% from 2006 to 2017 to an average of 1757 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 1). 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. A notable smaller peak occurred below 5°S for oceanic whitetip sharks (Figure 1). The low fishing effort, low tonnage of tuna catch, and the relatively small number of sharks caught above 15°N made the CPUE and BPUE estimates in these latitudes less reliable. 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 2 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 2). The patterns of shark BPUE were different, however, and resembled almost an inverse distribution to that of fishing effort. Areas of high fishing intensity (further east) had low BPUE rates for both shark species, whereas high BPUE was at longitudes farther west, where historically less fishing took place.

These results suggest that the region north of 5°N and west of approximately 110°W could be suitable candidates for

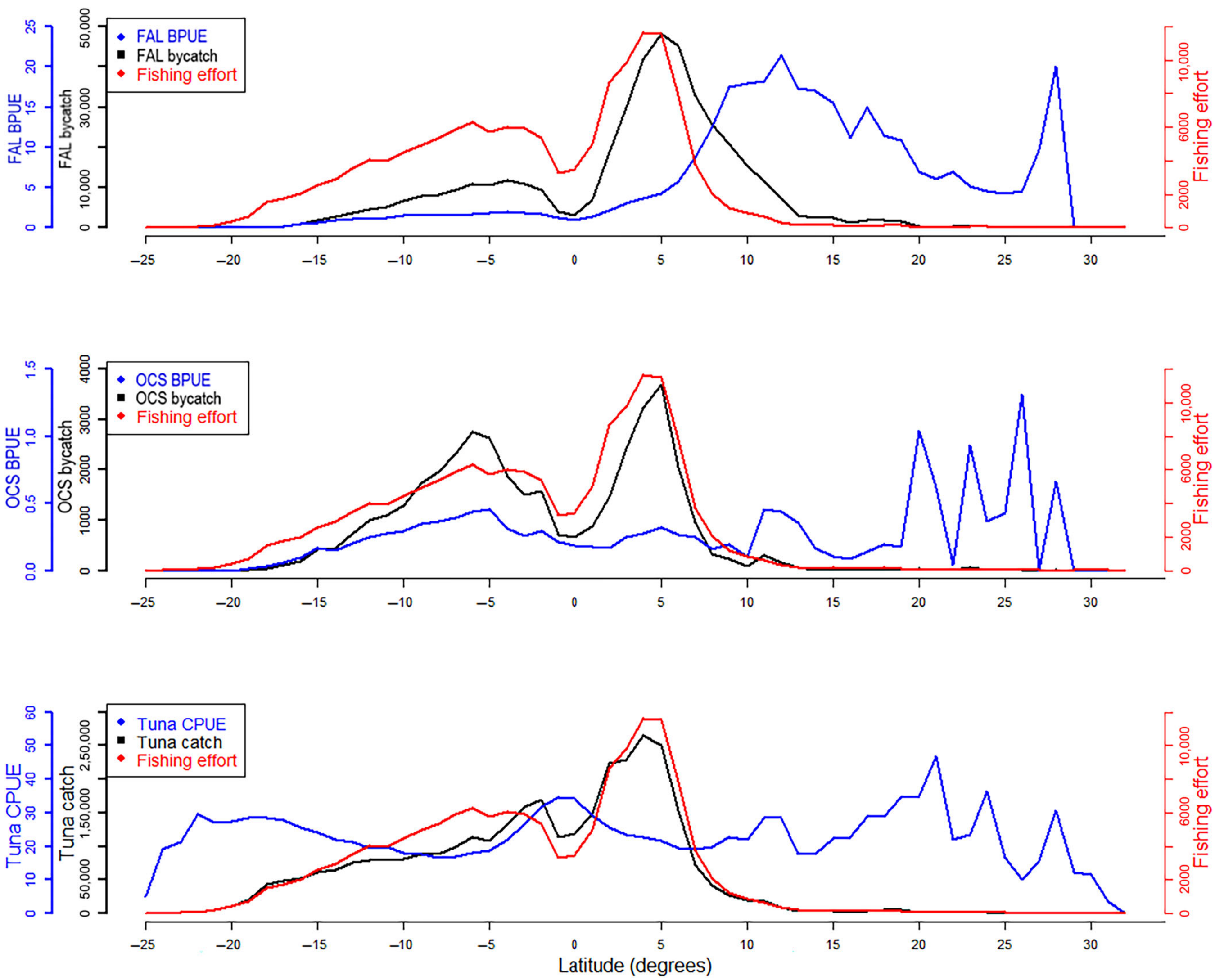

FIGURE 1 Latitudinal distribution of silky shark (FAL), oceanic whitetip shark (OCS), and tuna bycatch per unit effort (BPUE), catch per unit effort (CPUE), and bycatch or catch and fishing effort throughout the time series 1995–2021.

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°W and north of 10°N or south of 5°S.

Areas of high shark bycatch

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% ($n = 7658$) 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% ($n = 7164$), respectively.

Results of the persistence of areas of high monthly inefficiency varied by species and month, although the relatively low persistence between years suggested that areas of high fishing inefficiency may be ephemeral (Appendices S6–S8).

Both thresholds for silky sharks resulted in the identification of a longitudinal band of high fishing inefficiency centered around 5°N (Figure 3), whereas the 2-month threshold accentuated the presence of an area of high inefficiency at around 5°S and from 110°W to 140°W. The majority of inefficient fishing areas for oceanic whitetip sharks were from 5°S to 10°S and from 110°W to 130°W and around 5°N and from 100°W to 110°W (Figure 4). 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 (Figure 4). Some of the cells for silky sharks were identified as highly inefficient for up to 11 months of the year. 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 (Appendices S5 & S6).

The information from these areas was used to estimate reductions in the amount of tuna catch (in tons) and shark bycatch

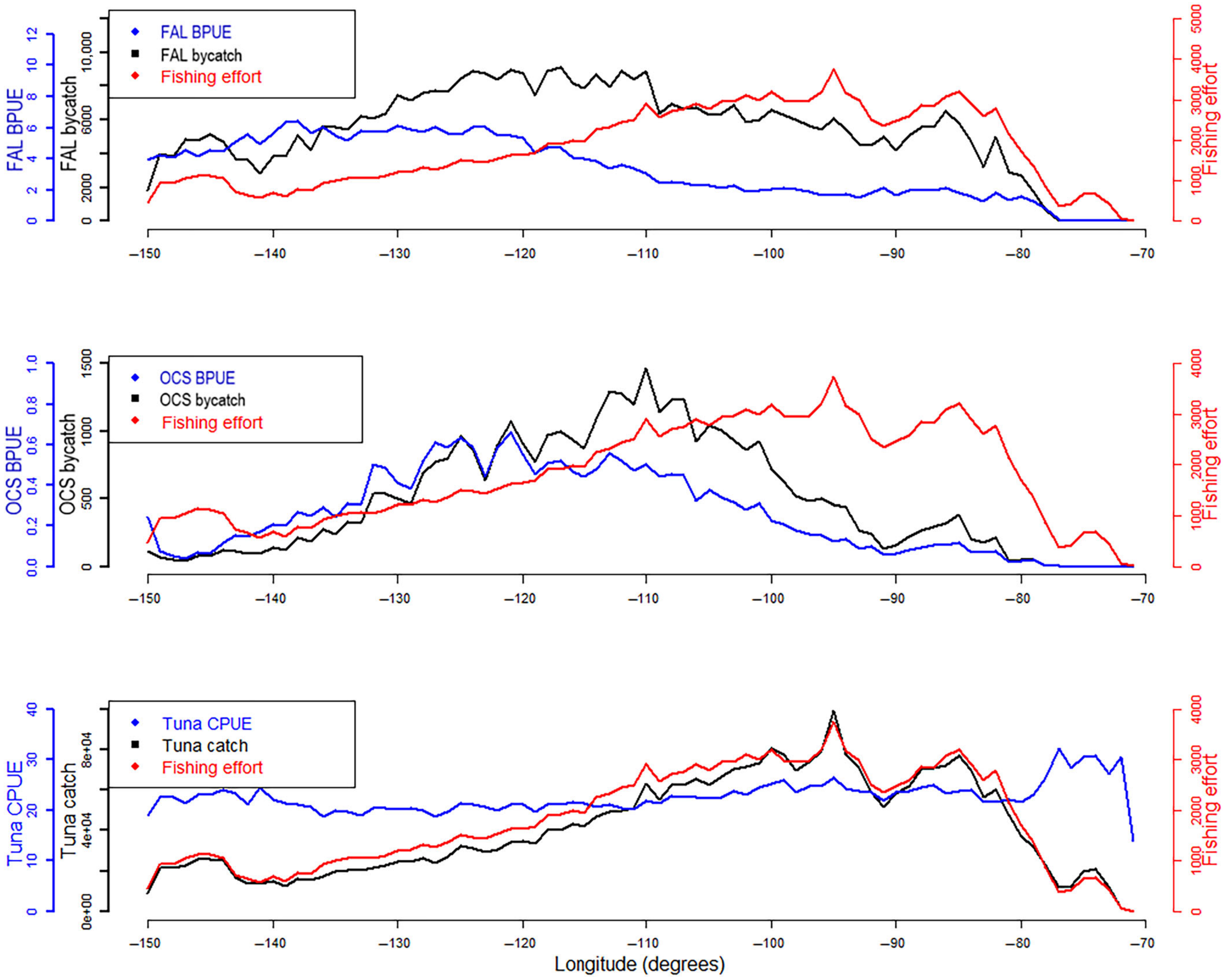

FIGURE 2 Longitudinal distribution of silky shark (top), oceanic whitetip shark (middle), and tuna (bottom) bycatch per unit effort (BPUE), catch per unit effort (CPUE), and bycatch or catch and fishing effort throughout the time series 1995–2021.

(frequency) that may have resulted when monthly closures of persistently high inefficiency cells were in place from 1995 to 2021 (Figure 5). 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 and reduced fishing effort on average by 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 (Figure 5; Appendix S10).

After redistributing the fishing effort in the investigated closures, results still showed a net decrease in shark bycatch across all scenarios (range 28–3% of reduction) and a projected increase of tuna catches across all scenarios of 1–11% (Figure 5; Appendix S10).

Each of the 3 species-specific closure scenarios showed low positive to low negative impacts on the expected bycatch of the other shark species for which the closure was not designed (Table 1) (range: −0.61% to +1.03%).

The identification of high-fishing-inefficiency areas, characterized by above-average BPUE rates for both shark species, resulted in the identification of 84 cells over 12 months. The expected impact of closing these areas to purse-seine fishing and redistributing fishing effort showed low positive effects on expected tuna catch rates. The average increase was 0.27% throughout the year, and average reduction in bycatch rates for *C. falciformis* and *C. longimanus* was −0.07% and −1.85%, respectively.

DISCUSSION

The RFMO management strategies must attain a balance between ensuring that fisheries remain biologically and economically sustainable and ensuring the structure and function of the ecosystems they are part of are not compromised by,

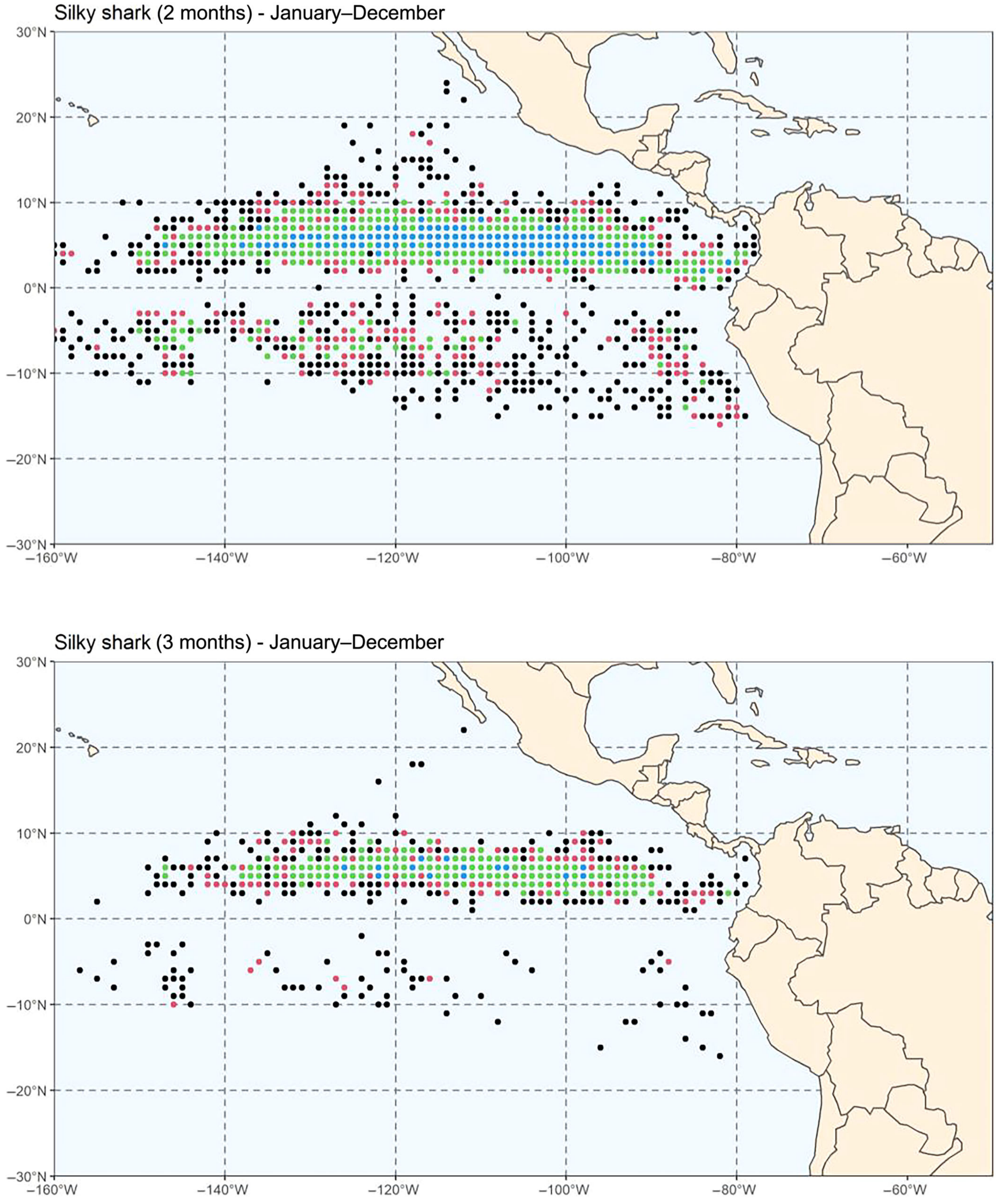

FIGURE 3 Areas of high fishing inefficiency for silky sharks at a 2-month threshold of inefficiency (top) and 3-month threshold (bottom) (black, proposed closure 1 month in the year; red, proposed closure 2 months; green, proposed closure 3–6 months; blue, proposed closure over 6 months).

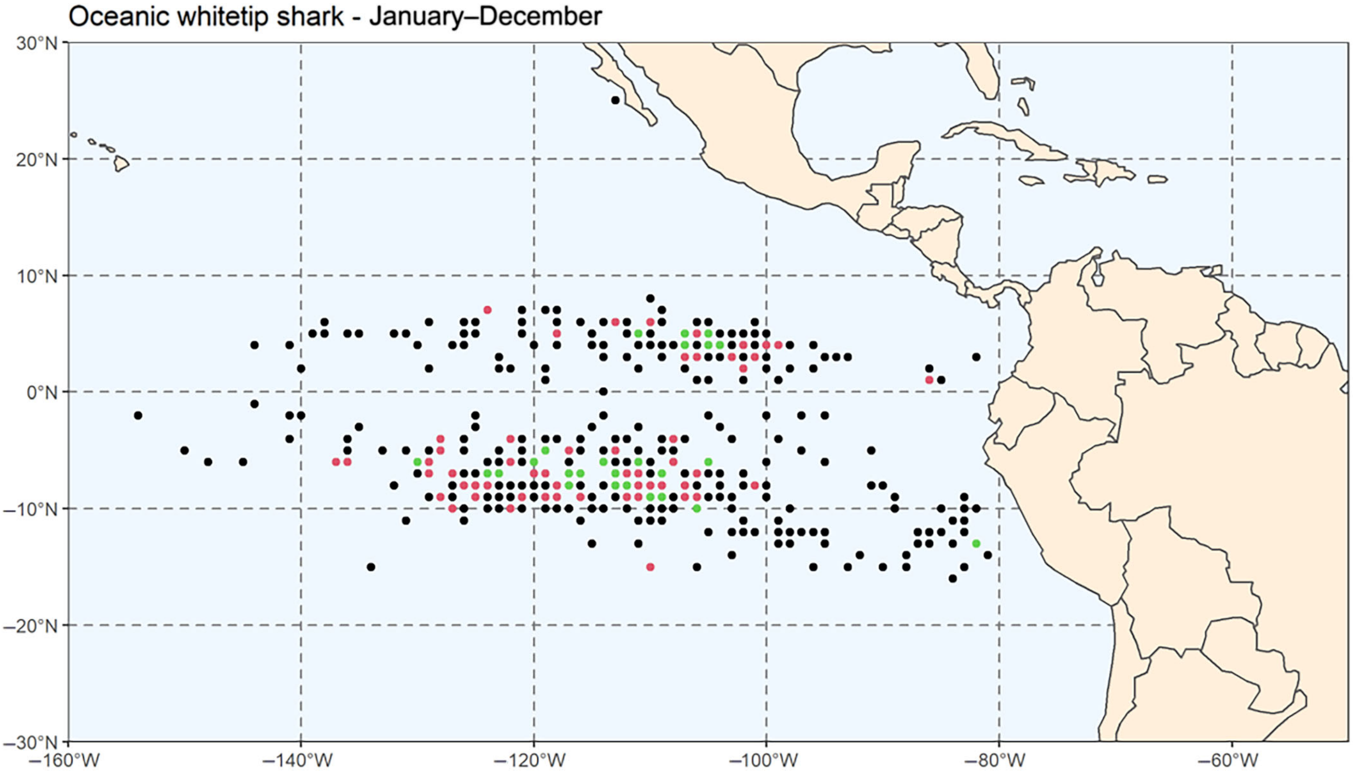

FIGURE 4 Areas of high fishing inefficiency for oceanic whitetip sharks at a 2-month threshold of inefficiency (black, proposed closure 1 month in the year; red, proposed closure 2 months; green, proposed closure 3–5 months).

TABLE 1 Expected effect of each of the 3 species-specific (*Carcharhinus falciformis* [FAL] and *Carcharhinus longimanus* [OCS]) fisheries closure scenarios on the total bycatch of the nontarget shark species after relocating tuna purse-seine fishing effort.

Month	FAL closure 2 OCS bycatch change (%)	FAL closure 3 OCS bycatch change (%)	OCS closure 2 FAL bycatch change (%)
January	−8	−0.56	−0.29
February	4.66	−0.84	2.03
March	5.09	1.02	2.16
April	4.2	1.18	1.78
May	4.86	4.19	1.16
June	−4.16	−0.31	0.56
July	9.15	0.28	1.76
August	3.91	−0.85	2.27
September	5.53	−6.34	0.3
October	1.41	−2.89	0.11
November	−9.35	−2.58	−0.54
December	−4.95	0.44	0.52
Average	1.03	−0.61	0.99

among other things, the health of nontarget species populations. Reaching this important balance becomes increasingly complex in multispecies fisheries that interact with species having vastly different life histories, such as tunas and elasmobranchs. A recent publication that reviewed the effect of global shark management measures identified the need to increase the use and quality of spatial management measures as a means to curtail the increasing global mortality rates of elasmobranch species (Worm et al., 2024). As a first step toward seeking strategies that may provide mutually beneficial outcomes for tunas and

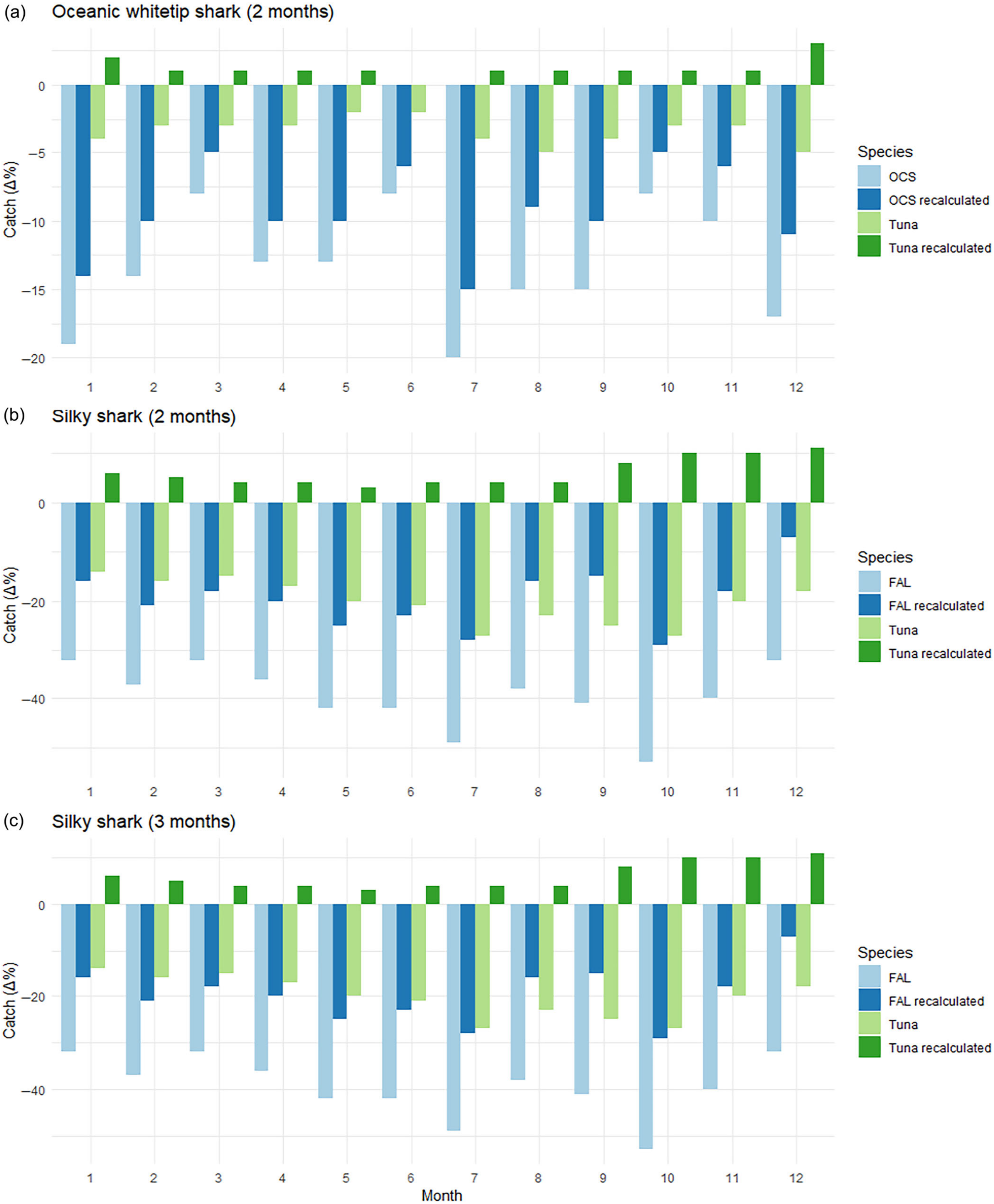

FIGURE 5 Expected reduction in shark bycatch (OCS, oceanic whitetip shark; FAL, silky shark) (blue) and tuna catch (green) under 2 different closure scenarios, without effort redistribution (light shading) and after redistributing fishing effort and recalculating captures (dark shading): (a) closure based on a 2-month threshold of persistence for OCS, (b) closure based on a 2-month persistence threshold for FAL, and (c) closure based on a 3-month persistence threshold for FAL.

bycatch, we focused on 2 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 spatiotemporal measures. Other than the dynamic management applied in Australia's east coast tuna and billfish fishery to reduce the bycatch of southern bluefin tuna by vessels with no quota, there are few examples of adaptive or dynamic spatial fisheries management (Hobday & Hartmann, 2006; Hobday et al., 2010). The dynamic closures we presented could become the first example of spatial management measures used in a tuna RFMO to explicitly reduce bycatch of nontarget elasmobranch species in addition to 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 nontarget species by tuna RFMOs fundamentally hinge on the ability of scientists to accurately characterize the relative abundance, distribution, and maximum biologically sustainable fishing mortality rates across species, which 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 tools, 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 and emphasize the need for the continued development of broader management plans for target and nontarget 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 conservation measures (e.g., Resolution C-21-04). This could be accomplished through the establishment of comprehensive harvest strategies tested through management strategy evaluation for tropical tunas, an ongoing process in the EPO. This is a critical consideration because 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. Although it is beyond the scope of this study, we underscore the need for a deeper understanding of the impact that improved fishing efficiency, including improved technologies, 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

Although we used a different method, our results are consistent 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 from 5°N to 15°N, which were predicted to result in a 12% reduction in the tuna catch. This is of particular management interest because demographic studies show that silky shark population growth is highly dependent on juvenile survival (Román-Verdesoto, 2014). Although 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. Although 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). We identified 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 fishing effort is not reallocated. Our results 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 showed interesting similarities. In the case of oceanic whitetip sharks, the majority of areas of high inefficiency occurred from 5°S to 10°S and from 110°W to 130°W, with a few additional locations around 5°N. Areas of fishing inefficiency for silky sharks varied but highlighted some areas across thresholds. The 3- and 2-month thresholds were the same in the presence of areas of high inefficiency from 5°N to 10°N (which resemble those found by Watson et al. [2009] and Román-Verdesoto [2014]), whereas the 2-month threshold also delineated areas around 5°S, which overlapped with important areas identified for oceanic whitetip sharks. The core areas of high fishing inefficiency for silky sharks stretched from ~90°W to 140°W across both thresholds (Figure 3). Based on the results from the 3 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.

The proposed closures overlapped in space and time with IATTC's seasonal tuna fisheries closure for large purse seiners, known as *El Corralito*, which extends from 96° to 110°W and from 4°N to 3°S and is primarily closed for 30 days in October. The most significant overlap, 6–12% of the proposed closure areas, occurred in November across the 3 species-specific scenarios. In October, the proposed closures overlapped 1–7% with El Corralito. In terms of tuna catch and shark bycatch, the overlapping areas accounted for 27–34% of the tuna in the proposed closures for October and November and 1–3% of the shark bycatch in the proposed closure areas. These results suggest that El Corralito plays a limited role in reducing silky shark and oceanic whitetip shark bycatch in the EPO. Although further dedicated studies are needed to better understand the effect of El Corralito on nontarget species, the closure does set an important precedent in the region for the spatiotemporal management of purse-seine vessels and could be used to advance similar closure scenarios for nontarget species, albeit at a more granular spatial and temporal resolution.

Our results suggest that adaptive spatial management can serve as a tool to reduce the unintended catch of nontarget elasmobranchs. Our results showed that species-specific closures resulted in low negative impacts on the shark species for which the closure was not originally designed (Table 1). Although they showed that designing these closures based on more than one bycatch species yielded positive results, these results were not as positive as those from species-specific bycatch closures (Appendix S11). Despite the large geographic dispersion of up to 1863 1° × 1° cells per year, it seems possible for vessels to avoid these closed areas in a verifiable way with vessel tracking technologies, fisheries observer data, and use of spatial information and measures to complement schemes to limit catch of sensitive bycatch 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 m^3 of wells volume) and the availability of operational-level data from that fishery since the early 1990s were instrumental in our ability to conduct this analysis and exemplify one of the many benefits of collecting high-quality data across the broad spatiotemporal footprint of the fishery for several taxa. The IATTC has adopted various CMMs to reduce the bycatch mortality of silky and oceanic whitetip sharks by establishing nonretention 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 nontarget species by adopting a voluntary measure to apply best practices for the handling and safe release of elasmobranchs (Murua, Moreno, et al., 2020). In addition to these best practices, IATTC's purse-seine observer program has proven fundamental 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 multispecies and multigear 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., 2019, Ovando et al., 2023).

Unlike the purse-seine fishery, the longline and artisanal fisheries have notably low or nonexistent observer coverage (Ewel et al., 2020; Murua, Fiorellato, et al., 2020), which means that monitoring of overall activities of these fisheries is insufficient and that there is 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 multispecies potential overlap areas.

Among the challenges identified by the IATTC for the sustainable management of sharks (Siu & 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 stock status indicators. Silky sharks are among the few shark species for which Pacific-wide population assessments have been conducted. In 2016, Clarke et al. (2018) estimated that silky sharks were at or below the biomass for maximum sustainable yield, although they raised concerns about the association of CPUE indices with oceanographic conditions and suggested they may not directly reflect the fluctuations in population size. 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., 2019). Furthermore, shark catch data from coastal artisanal fisheries are still very much lacking for silky sharks and most other elasmobranch species (Doherty et al., 2014).

Although 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. 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 affected 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 nonretention policies, to ensure postrelease 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 toward reducing fishing mortality and enhancing the sustainability of both species.

Although 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 allow for an accurate assessment of compliance at high spatial and temporal resolutions. A recent IATTC Resolution (C-21-04) requests members and cooperating nonmembers (CPCs) to submit vessel monitoring system (VMS) data for all commercial tuna vessels larger than 24 m 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 dynamic ocean management and "move-on rules," which are event-triggered temporary closures in a fishery when a certain bycatch threshold is reached (Dunn et al., 2014; Welch et al., 2020). Such measures could complement our work by helping predict areas of high fishing inefficiency that 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 nontarget species under different environmental scenarios by building, for example, on work by Lennert-Cody et al. (2019), Lezama-Ochoa et al. (2020), and Lennert-Cody et al. (2021), who suggest that environmental conditions affect tuna and elasmobranch distribution in the EPO and that trends vary by area and size class.

Caveats and future work

Although we provided an in-depth analysis of 2 frequently encountered and vulnerable shark species in the OBJ fishery, this is only one of many fisheries that catch them and other nontarget species in the IATTC Convention Area. In the case of silky shark, purse-seine fishery bycatch is composed primarily of juveniles (e.g., Lopez et al., 2020), whereas 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 because 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 in 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), we 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.

Although our focus was on 2 moderately to highly vulnerable shark species in need of bycatch reduction measures, it is 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 nontarget species should be conducted together with attempts to consolidate all areas of suggested closure to account for multispecies objectives and encourage IATTC's contracting parties to explore the best arrangement for reducing shark bycatch rates and mortality across species.

We assumed a proportional redistribution of fishing effort across the remaining range of the fishery outside the proposed closures based on historical patterns. Although 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 & Abeare, 2009).

We were unable to account for ephemeral areas of high fishing inefficiency (i.e., monthly cells that were classified as inefficient for 1 year only). Further research guided by the principles of dynamic ocean management may be required to determine whether these areas are predictable based on environmental information.

Our results are primarily applicable to 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 being carried out in the IATTC in this area strengthens the potential to implement a multispecies spatial management strategy and provides spatial management options for silky sharks and oceanic whitetip sharks. Importantly, it is in consonance with, but also expands on, previous research results that explored spatiotemporal trade-offs to reduce shark bycatch in the region (Román-Verdesoto, 2014; Watson et al., 2009), further strengthening the scientific basis for the implementation of spatiotemporal management measures to reduce bycatch in the region.

ACKNOWLEDGMENTS

The technical and scientific expertise of members of the Inter-American Tropical Tuna Commission (S.G. & J.L.) and the International Seafood Sustainability Foundation (H.M.) were critical for the completion of this study and for conveying its relevance to the pertinent fisheries management authorities. The Inter-American Tropical Tuna Commission and its members, through the work of the Scientific Advisory Council, and the fisheries observers over the past 3 decades are acknowledged for their commitment to improving and sharing fisheries operational information, which remains critical and enables the completion of studies such as this one. We thank the International Seafood Sustainability Foundation, which supported and facilitated this research, and the David and Lucile Packard Foundation (grant 2020–70299).

ORCID

Guillermo Ortuño Crespo https://orcid.org/0000-0001-8029-5387
Shane Griffiths https://orcid.org/0000-0002-4418-6666
Hilario Murua https://orcid.org/0000-0001-8577-5291
Henrik Österblom https://orcid.org/0000-0002-1913-5197
Jon Lopez https://orcid.org/0000-0002-4172-4094

REFERENCES

Bonfil, R. (1994). *Overview of world elasmobranch fisheries* (Fisheries technical paper 341). Food and Agriculture Organization.

Bonfil, R., Clarke, S., & Nakano, H. (2008). The biology and ecology of the oceanic whitetip shark, Carcharhinus longimanus. *Sharks of the open ocean: Biology, fisheries and conservation*, pp. 128–139.

Camhi, M. D., Pikitch, E. K., & Babcock, E. A. (Eds.). (2008). *Sharks of the open ocean: Biology, fisheries and conservation*. Blackwell Science.

Clarke, S., Langley, A., Lennert-Cody, C., Aires-da-Silva, A., & Maunder, M. (2018). *Pacific-wide silky shark (Carcharhinus falciformis) stock status assessment*. Proceedings of the WCPFC Scientific Committee 14th Regular Session, Busan, Korea, 8–16 August 2018; p. 137.

Compagno, L. J. V., & Niem, V. H. (1998). Carcharhinidae. Requiem sharks. In K. E. Carpenter & V. H. Niem (Eds.), *FAO identification guide for fishery purposes. The living marine resources of the Western Central Pacific* (pp. 1312–1360). UN Food and Agriculture Organisation.

Crespo, G. O., Mossop, J., Dunn, D., Gjerde, K., Hazen, E., Reygondeau, G., Warner, R., Tittensor, D., & Halpin, P. (2020). Beyond static spatial management: Scientific and legal considerations for dynamic management in the high seas. *Marine Policy*, *122*, 104102.

Doherty, P. D., Alfaro-Shigueto, J., Hodgson, D. J., Mangel, J. C., Witt, M. J., & Godley, B. J. (2014). Big catch, little sharks: Insight into Peruvian small-scale longline fisheries. *Ecology and Evolution*, *4*(12), 2375–2383.

Duffy, L. M., Lennert-Cody, C. E., Olson, R. J., Minte-Vera, C. V., & Griffiths, S. P. (2019). Assessing vulnerability of bycatch species in the tuna purse-seine fisheries of the eastern Pacific Ocean. *Fisheries Research*, *219*, p. 105316.

Dulvy, N. K., Pacoureau, N., Rigby, C. L., Pollom, R. A., Jabado, R. W., Ebert, D. A., Finucci, B., Pollock, C. M., Cheok, J., Derrick, D. H., Herman, K. B., Sherman, C. S., VanderWright, W. J., Lawson, J. M., Walls, R. H. L., Carlson, J. K., Charvet, P., Bineesh, K. K., Fernando, D., … Simpfendorfer, C. A. (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. *Current Biology*, *31*, 4773.e8–4787.e8. https://doi.org/10.1016/j.cub.2021.08.062

Dunn, D. C., Crespo, G. O., & Caddell, R. (2019). *Area-based fisheries management. Strengthening international fisheries law in an era of changing oceans*. Bloomsbury Publishing.

Dunn, D. C., Boustany, A. M., Roberts, J. J., Brazer, E., Sanderson, M., Gardner, B., & Halpin, P. N. (2014). Empirical move-on rules to inform fishing strategies: A New England case study. *Fish and Fisheries*, *15*(3), 359–375.

Ewell, C., Hocevar, J., Mitchell, E., Snowden, S., & Jacquet, J. (2020). An evaluation of regional fisheries management organization at-sea compliance monitoring and observer programs. *Marine Policy*, *115*, 103842.

Gilman, E., Weijerman, M., & Suuronen, P. (2017). Ecological data from observer programmes underpin ecosystem-based fisheries management. *ICES Journal of Marine Science*, *74*(6), pp. 1481–1495.

Griffiths, S., Duffy, L., & Aires-da-Silva, A. (2017). *A preliminary ecological risk assessment of the large-scale tuna longline fishery in the eastern pacific ocean using productivity-susceptibility analysis* (Document SAC-08-07d). 8th Meeting of the Scientific Advisory Committee of the Inter-American Tropical Tuna Commission, La Jolla, California, USA.

Griffiths, S., Lennert-Cody, C., Wiley, B., & Fuller, L. (2021). *Update on operational longline observer data required under resolution C-19-08 and a preliminary assessment of data reliability for estimating total catch for bycatch species in the eastern Pacific Ocean (Draft)* (Document IATTC BYC-10 INF-D). 10th Meeting of the IATTC Working Group on Bycatch, 5 May 2021, La Jolla, California, USA.

Hall, M., & Roman, M. (2013). *Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. Fisheries and aquaculture technical paper I*. United Nations Food and Agriculture Organization.

Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., Jonsen, I. D., Shaffer, S. A., Dunne, J. P., Costa, D. P., Crowder, L. B., & Block, B. A. (2013). Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Climate Change*, *3*, 234–238.

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H., Benson, S. R., Eguchi, T., Dewar, H., & Kohin, S. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, *4*(5), eaar3001.

Hilborn, R., Agostini, V. N., Chaloupka, M., Garcia, S. M., Gerber, L. R., Gilman, E., Hanich, Q., Himes-Cornell, A., Hobday, A. J., Itano, D., & Kaiser, M. J. (2022). Area-based management of blue water fisheries: Current knowledge and research needs. *Fish and Fisheries*, *23*(2), 492–518.

Hobday, A., & Hartmann, K. (2006). Near real- time spatial management based on habitat predictions for a longline bycatch species. *Fisheries Management and Ecology*, *13*, 365–380.

Hobday, A. J., Hartog, J. R., Timmiss, T., & Fielding, J. (2010). Dynamic spatial zoning to manage southern bluefin tuna (*Thunnus maccoyii*) capture in a multi-species longline fishery. *Fisheries Oceanography*, *19*, 243–253.

Hyrenbach, K. D., Forney, K. A., & Dayton, P. K. (2000). Marine protected areas and ocean basin management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *10*(6), 437–458.

Inter-American Tropical Tuna Commission (IATTC). (2022). *The tuna fishery in the Eastern Pacific Ocean in 2022* (Document SAC-14-03). Inter-American Tropical Tuna Commission.

Inter-American Tropical Tuna Commission. (2022). *Ecosystem considerations* (Document SAC-13-10 Corr.). https://www.iattc.org/getattachment/4b63e5bd-bc41-4c71-9ad6-f9b3d50b6e39/SAC-13-10_Ecosystem-considerations.pdf

International Commission for the Conservation of Atlantic Tunas (ICCAT). (2021). *ICCAT recommendation 21-04 on a multi-annual conservation*. Author.

Juan-Jordá, M. J., Murua, H., Arrizabalaga, H., Dulvy, N. K., & Restrepo, V. (2018). Report card on ecosystem-based fisheries management in tuna regional fisheries management organizations. *Fish and Fisheries*, *19*(2), 321–339.

Juan-Jordá, M. J., Murua, H., Arrizabalaga, H., Merino, G., Pacoureau, N., & Dulvy, N. K. (2022). Seventy years of tunas, billfishes, and sharks as sentinels of global ocean health. *Science*, *378*, eabj0211.

Kleiven, A. R., Espeland, S. H., Stiansen, S., Ono, K., Zimmermann, F., & Olsen, E. M. (2022). Technological creep masks continued decline in a lobster (*Homarus gammarus*) fishery over a century. *Scientific Reports*, *12*, 3318.

Lennert-Cody, C., Aires-Da-Silva, A., Maunder, M., & Altamirano, E. (2021). *Updated stock status indicators for silky sharks in the eastern Pacific Ocean, 1994–2019* (Document IATTC BYC-10 INF-A). 10th Meeting of the Working Group on Bycatch, San Diego, California, USA.

Lennert-Cody, C. E., Clarke, S. C., Aires-da-Silva, A., Maunder, M. N., Franks, P. J., Román, M., Miller, A. J., & Minami, M. (2019). The importance of environment and life stage on interpretation of silky shark relative abundance indices for the equatorial Pacific Ocean. *Fisheries Oceanography*, *28*(1), 43–53.

Lezama-Ochoa, N., Hall, M., Román, M., & Vogel, N. (2019). Spatial and temporal distribution of mobulid ray species in the eastern Pacific Ocean ascertained from observer data from the tropical tuna purse-seine fishery. *Environmental Biology of Fishes*, *102*, 1–17.

Lezama-Ochoa, N., Pennino, M. G., Hall, M. A., Lopez, J., & Murua, H. (2020). Using a Bayesian modelling approach (INLA-SPDE) to predict the occurrence of the Spinetail Devil Ray (*Mobular mobular*). *Scientific Reports*, *10*(1), 18822.

Lopez, J., Alvarez-Berastegui, D., & Soto, M. (2020). Using fisheries data to model the oceanic habitats of juvenile silky shark (*Carcharhinus falciformis*) in the tropical eastern Atlantic Ocean. *Biodiversity and Conservation*, *29*, 2377–2397.

Oliveros-Ramos, R., Siu, S., Salaverria, S., Lennert-Cody, C. E., Aires-Dasilva, A., & Maunder, M. N. (2019). *Pilot study for a shark fishery sampling program in Central America* (Document SAC-10). 10th Meeting of the Scientific Advisory Committee of the IATTC, San Diego, California, USA.

Morison, A. K. (2004). Input and output controls in fisheries management: A plea for more consistency in terminology. *Fisheries Management and Ecology*, *11*, 411–413.

Murua, H., Abascal, F. J., Amande, J., Ariz, J., Bach, P., Chavance, P., Coelho, R., Korta, M., Poisson, F., Santos, M. N., & Seret, B. (2013). *Provision of scientific advice for the purpose of the implementation of the EUPOA sharks. Final report (MARE/2010/11 - LOT 2). Studies for carrying out the Common Fisheries Policy*. European Commission.

Murua, H., Fiorellato, F., Ruiz, J., Chassot, E., & Restrepo, V. (2020). *Minimum standards for designing and implementing Electronic Monitoring systems in Indian Ocean tuna fisheries*. https://www.iotc.org/documents/SC/23E,12

Murua, J., Moreno, G., Itano, D., Hall, M., Dagorn, L., & Restrepo, V. (2020). *ISSF skippers workshops round 9* (ISSF Technical Report 2020-01). International Seafood Sustainability Foundation.

Oliver, S. P., Hussey, N. E., Turner, J. R., & Beckett, A. J. (2011). Oceanic sharks clean at coastal seamount. *PLoS ONE*, *6*(3), e14755.

Ovando, D., Siu, S., Lennert-Cody, C., Maunder, M., Lopez, J., Griffiths, S., Santana, O., & Aires-da-Silva, A. (2023). *Silky and hammerhead shark catches in Central American coastal artisanal fisheries* (Document SAC-14 INF-L). Inter-American Tropical Tuna Commission.

Pacoureau, N., Rigby, C. L., Kyne, P. M., Sherley, R. B., Winker, H., Carlson, J. K., Fordham, S. V., Barreto, R., Fernando, D., Francis, M. P., Jabado, R. W., Herman, K. B., Liu, K. M., Marshall, A. D., Pollom, R. A., Romanov, E. V., Simpfendorfer, C. A., Yin, J. S., Kindsvater, H. K., & Dulvy, N. K. (2021). Half a century of global decline in oceanic sharks and rays. *Nature*, *589*, 567–571.

Pons, M., Watson, J. T., Ovando, D., Andraka, S., Brodie, S., Domingo, A., Fitchett, M., Forselledo, R., Hall, M., Hazen, E. L., Jannot, J. E., Herrera, M., Jiménez, S., Kaplan, D. M., Kerwath, S., Lopez, J., McVeigh, J., Pacheco, L., Rendon, L., … Hilborn, R. (2022). Trade-offs between bycatch and target catches in static versus dynamic fishery closures. *Proceedings of the National Academy of Sciences of the United States of America*, *119*, e2114508119.

Powers, J. E., & Abeare, S. M. (2009). Fishing effort redistribution in response to area closures. *Fisheries Research*, *99*(3), 216–225.

Rigby, C. L., Barreto, R., Carlson, J., Fernando, D., Fordham, S., Francis, M. P., Herman, K., Jabado, R. W., Liu, K. M., Marshall, A., Pacoureau, N., Romanov, E., Sherley, R. B., & Winker, H. (2019). *Carcharhinus longimanus*. The IUCN Red List of Threatened Species. https://doi.org/10.2305/IUCN.UK.2019-3.RLTS.T39374A2911619.en

Rigby, C. L., Sherman, C. S., Chin, A., & Simpfendorfer, C. (2021). *Carcharhinus falciformis* (amended version of 2017 assessment). The IUCN Red List of Threatened Species. https://doi.org/10.2305/IUCN.UK.2021-3.RLTS.T39370A205782570.en

Román-Verdesoto, M., & Orozco-Zoller, M. (2005). *Bycatches of sharks in the tuna purse-seine fishery of the eastern Pacific Ocean reported by observers of the Inter-American Tropical Tuna Commission, 1993–2004*. Inter-American Tropical Tuna Commission.

Román-Verdesoto, M. H. (2014). *Potential effects of spatial closures on the demography of silky shark Carcharhinus falciformis in the eastern Pacific Ocean* (MS thesis). Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE).

Schaefer, K. M., & Fuller, D. W. (2022). Spatiotemporal variability in the reproductive biology of yellowfin tuna (*Thunnus albacares*) in the eastern Pacific Ocean. *Fisheries Research*, *248*, 106225.

Seki, T., Taniuchi, T., Nakano, H., & Shimizu, M. (1998). Age, growth and reproduction of the oceanic whitetip shark from the Pacific Ocean. *Fisheries Science*, *64*(1), 14–20.

Siu, S., & Aires-da-Silva, A. (2016). *An inventory of sources of data in Central America on shark fisheries operating in the eastern Pacific Ocean Metadata report* (Technical report SAC-07-06b(ii)). 7th Meeting of the Scientific Advisory Committee of the IATTC, San Diego, California, USA.

Visalli, M. E., Best, B. D., Cabral, R. B., Cheung, W. W., Clark, N. A., Garilao, C., Kaschner, K., Kesner-Reyes, K., Lam, V. W., & Maxwell, S. M. (2020). Data-driven approach for highlighting priority areas for protection in marine areas beyond national jurisdiction. *Marine Policy*, *122*, 103927.

Ward, P., Epe, S., Kreutz, D., Lawrence, E., Robins, C., & Sands, A. (2009). The effects of circle hooks on bycatch and target catches in Australia's pelagic longline fishery. *Fisheries Research*, *97*(3), 253–262.

Watson, J. T., Essington, T. E., Lennert-Cody, C. E., & Hall, M. A. (2009). Trade-offs in the design of fishery closures: Management of silky shark bycatch in the eastern Pacific Ocean tuna fishery. *Conservation Biology*, *23*, 626–635.

Welch, H., Brodie, S., Jacox, M. G., Bograd, S. J., & Hazen, E. L. (2020). Decision-support tools for dynamic management. *Conservation Biology*, *34*(3), 589–599.

Western and Central Pacific Fisheries Commission (WCPFC). (2021). *Conservation Measures CMM 2021-01 for bigeye, yellowfin and skipjack tuna in the Western and Central Pacific Ocean*. Federated States of Micronesia, Western and Central Pacific Fisheries Commission. https://www.wcpfc.int/doc/cmm-2021-01/conservation-and-management-measure-bigeye-yellowfin-and-skipjack-tuna-western-and

Worm, B., Davis, B., Kettemer, L., Ward-Paige, C. A., Chapman, D., Heithaus, M. R., Kessel, S. T., & Gruber, S. H. (2013). Global catches, exploitation rates, and rebuilding options for sharks. *Marine Policy*, *40*, 194–204.

Worm, B., Orofino, S., Burns, E. S., D'Costa, N. G., Manir Feitosa, L., Palomares, M. L., Schiller, L., & Bradley, D. (2024). Global shark fishing mortality still rising despite widespread regulatory change. *Science*, *383*(6679), 225–230.

Young, C. N., & Carlson, J. K. (2020). The biology and conservation status of the oceanic whitetip shark (*Carcharhinus longimanus*) and future directions for recovery. *Reviews in Fish Biology and Fisheries*, *30*(2), 293–312.

Zudaire, I., Murua, H., Grande, M., Pernet, F., & Bodin, N. (2014). Accumulation and mobilization of lipids in relation to reproduction of yellowfin tuna (*Thunnus albacares*) in the Western Indian Ocean. *Fisheries Research*, *160*, 50–59.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Crespo, G. O., Griffiths, S., Murua, H., Österblom, H., & Lopez, J. (2024). Adaptive spatiotemporal management to reduce shark bycatch in tuna fisheries. *Conservation Biology*, e14324. https://doi.org/10.1111/cobi.14324