Contributed Paper

Trade-Offs in the Design of Fishery Closures: Management of Silky Shark Bycatch in the Eastern Pacific Ocean Tuna Fishery

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Abstract: *Bycatch—the incidental catch of nontarget species—is a principal concern in marine conservation and fisheries management. In the eastern Pacific Ocean tuna fishery, a large fraction of nonmammal bycatch is captured by purse-seine gear when nets are deployed around floating objects. We examined the spatial distribution of a dominant species in this fishery's bycatch, the apex predator silky shark (*Carcharhinus falciformis*), from 1994 to 2005 to determine whether spatial closures, areas where fishing is prohibited, might effectively reduce the bycatch of this species. We then identified candidate locations for fishery closures that specifically considered the trade-off between bycatch reduction and the loss of tuna catch and evaluated ancillary conservation benefits to less commonly captured taxa. Smoothed spatial distributions of silky shark bycatch did not indicate persistent small areas of especially high bycatch for any size class of shark over the 12-year period. Nevertheless, bycatch of small silky sharks (<90 cm total length) was consistently higher north of the equator during all years. On the basis of this distribution, we evaluated nearly 100 candidate closure areas between 5°N and 15°N that could have reduced, by as much as 33%, the total silky shark bycatch while compromising only 12% of the tuna catch. Although silky sharks are the predominant species of elasmobranchs caught as bycatch in this fishery, closures also suggested reductions in the bycatch of other vulnerable taxa, including other shark species and turtles. Our technique provides an effective method with which to balance the costs and benefits of conservation in fisheries management. Spatial closures are a viable management tool, but implementation should be preceded by careful consideration of the consequences of fishing reallocation.*

Keywords: bycatch, *Carcharhinus falciformis*, fisheries management, fishery closures, marine conservation, shark, tuna

Ventajas y Desventajas del Diseño de Cierres de Pesquerías: Manejo de la Captura Incidental de *Carcharhinus falciformis* en la Pesquería de Atún en el Este del Océano Pacífico

Resumen: *La captura incidental de especies que no son objetivo de la pesca—es una preocupación mayor en la conservación marina y el manejo de pesquerías. En la pesquería de atún en el este del Océano Pacífico, una importante fracción de la captura incidental es capturada cuando las redes son desplegadas alrededor de objetos flotantes. Examinamos la distribución espacial de una especie dominante en la captura incidental de esta pesquería,* Carcharhinus falciformis*, de 1994–2005 para determinar sí los cierres espaciales, áreas donde la pesca está prohibida, efectivamente pueden reducir la captura incidental de esta especie. Posteriormente identificamos las localidades candidatas para cierres de pesquería que específicamente consideraron las ventajas y desventajas de la reducción de la captura incidental y la pérdida de captura de atún y evaluamos los beneficios de conservación adicionales para taxa capturados menos comúnmente. Las distribuciones*

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espaciales de la captura incidental de C. falciformis *no indicaron áreas pequeñas con captura incidental especialmente alta para ninguna clase de tamaño de tiburones en todo el período de 12 años. Sin embargo, la captura incidental de tiburones pequeños (<90 cm de longitud total) fue consistentemente mayor al norte del ecuador durante todos los años. Con base en esta distribución, evaluamos casi 100 áreas candidatas a cierre entre los 5°N y 15°N que pudieron haber reducido, hasta en 33%, la captura incidental de tiburones mientras comprendía solo 12% de la captura de atún. Aunque* C. falciformis *es la especie predominante de elasmobranquios capturados incidentalmente por esa pesquería, los cierres también sugirieron reducciones en la captura incidental de otros taxa vulnerables, incluyendo otras especies de tiburón y tortugas. Nuestra técnica proporciona un método efectivo para balancear los costos y beneficios de la conservación en el manejo de pesquerías. Los cierres espaciales son una herramienta de manejo viable, pero su aplicación debe ser precedida por una consideración cuidadosa de las consecuencias de la redistribución de la pesca.*

Palabras Clave: atún, captura incidental, *Carcharhinus falciformis* cierre de pesquerías, conservación marina, manejo de pesquerías, tiburón

Introduction

Bycatch—the incidental fishing mortality of nontarget species and small individuals of target species—is a problem of growing concern worldwide (Hall et al. 2000; Fonteneau et al. 2002). In many offshore fisheries, bycatch is discarded at sea to make space for the most valuable target catches. Discarding nontarget species has been criticized as a wasteful practice that might threaten the sustainability of other fisheries that specifically target these species (Hall et al. 2000). Ecologically, bycatch poses additional risks in the form of altered community structure and ecosystem function through the removal of these species (Essington et al. 2002; Fonteneau et al. 2002) and potential loss of biodiversity (Hall et al. 2000).

Among the first bycatch issues that garnered widespread public attention was the accidental catch and mortality of dolphins from the tuna purse-seine fishery in the eastern Pacific Ocean (EPO; Hall 1998). Because per-vessel mammal bycatch limits and "dolphin safe" ecolabeling of tunas were implemented, some fishers shifted purse-seine effort toward tunas associated with natural flotsam and subsequently fish-aggregating devices (FADs; Lennert-Cody & Hall 2000; Inter-American Tropical Tuna Commission (IATTC) 2008). This expansion of the purse-seine fishery on floating objects since the mid-1990s has led to an increase in the volume and diversity of species that are inadvertently captured, raising concerns about the indirect impacts of this fishing method on the ecosystem (Hall 1998).

Bycatch of elasmobranchs—silky sharks (*Carcharhinus falciformis*) in particular—is especially great in these floating object sets (IATTC 2006; Román-Verdesoto & Orozco-Zőller 2006). Sharks are highly susceptible to exploitation as a result of their slow growth, late maturation, and limited fecundity (Musick 1999). Although the magnitude of population depletion by fishing is a source of some debate (Baum & Myers 2004; Burgess et al. 2005), few would argue that shark populations in general have been unaffected by directed fishing and bycatch (Manire & Gruber 1990). Silky shark bycatch per set in this fishery has declined by nearly 50% between 1993 and 2004 (Minami et al. 2007), intensifying concerns about this poorly understood species (Oshitani et al. 2003). Although silky shark bycatch is orders of magnitude greater than the bycatch of other elasmobranch species in the EPO, oceanic whitetip sharks (*C. longimanus*) and hammerhead sharks (*Sphyrna* spp.) are also captured (Román-Verdesoto & Orozco-Zőller 2006). The suite of vulnerable species caught as bycatch in this and other fisheries illustrates global concerns over ecosystem impacts from the exploitation of sharks (Dulvy et al. 2008), a group recognized for their unique roles as apex predators (Stevens et al. 2000; Myers et al. 2007).

One solution to reduce shark bycatch is to prohibit floating object sets in regions with elevated bycatches of these vulnerable species (i.e., implement a spatial fishery closure). We sought to identify candidate fishery closures, evaluate their conservation benefits, and consider their potential impacts on tuna catches. Two considerations are germane in identifying spatial fishery closures to reduce bycatch. First, bycatch must be spatially concentrated and temporally persistent in well-defined regions. Given that spatial distributions of many pelagic marine fishes are closely linked to dynamic oceanic features (Lehodey et al. 1997), it is not clear whether an effective spatial closure can be implemented. Second, it is equally important to consider the co-occurrence of target catch and shark bycatch to identify areas for closure that best maximize bycatch reduction and maximize tuna catches so that the prospects for closure implementation and conservation success are enhanced. Thus, we used data on bycatch and tuna catch from 1994 to 2005 to address the following questions: Are there spatiotemporally persistent hotspots, localized regions (e.g., a 5° latitude–longitude square), in which a substantial amount of bycatch occurs? If no such hotspots exist, are there larger, yet distinct regions—smaller than the entire fishery—that exhibit such persistence of bycatch? and Within regions of persistent bycatch are there optimal areas for fishery closures that produce the smallest reduction in tuna catch and maximize reduction in bycatch?

Methods

Data

The IATTC and national programs observe nearly 100% of purse-seine vessels in the EPO with a tuna carrying capacity >363 t (class-6 vessels) (IATTC 2006). Our data were exclusively those from IATTC observers, which accounted for a mean annual sampling coverage of 87% of all observed floating objects sets from class-6 vessels, or 85% of total observed sets. About 1% of our data were from observed sets of smaller vessels, whose trips were also occasionally sampled. *Catch* herein refers to the sum of retained and discarded amounts of the 3 tuna species generally targeted by the purse-seine fishery (yellowfin [*Thunnus albacares*], skipjack [*Katsuwonus pelamis*], bigeye [*T. obesus*]). *Bycatch* refers to incidental mortality of nontarget species, counted as those individuals already dead when brought aboard the vessel (Román-Verdesoto & Orozco-Zőller 2006).

For our purposes silky sharks were those animals labeled at sea by observers as either silky (*C. falciformis*) or blacktip (*C. limbatus*) sharks. *C. limbatus* was unlikely to have been encountered within the area covered by the purse-seine fishery on floating objects because its distribution is restricted primarily to coastal and insular shelves (Compagno 1984). Nevertheless, misidentification of *C. falciformis* as *C. limbatus* occurs because observers may take identification cues from fishers, and the English common name for *C. limbatus* is identical to the Spanish common name for *C. falciformis* (Román-Verdesoto & Orozco-Zőller 2006). Whenever possible (97.8–100% of observed sets each year; 12-year mean = 99.7% of observed sets), sharks were categorized by observers into 1 of 3 size classes: small (<90 cm total length), medium (between 90 and 150 cm), and large (>150 cm), with the majority of animals in the latter size class expected to be reproductively mature (Oshitani et al. 2003). Bycatch of other vulnerable taxa—hammerhead sharks, oceanic whitetip sharks, and turtles—was also considered in evaluating trade-offs. Owing to coarse taxonomic resolution of observer recordings for some species (Román-Verdesoto & Orozco-Zőller 2006), we assessed hammerhead shark species (*Sphyrna* spp.) and sea turtles as pooled categories.

Observers attempted to count all bycatch per set, but bycatch was occasionally estimated in metric tons and later converted to number of sharks (Román-Verdesoto & Orozco-Zőller 2006). These converted bycatch values are associated with an unknown degree of conversion error; therefore, they were systematically removed (288 sets). After processing, our data included 48,417 floating object sets observed from 1994 to 2005 (85% of all estimated sets on floating objects). We randomly divided data from each year into training and test data sets (two-thirds and one-third of the data, respectively). We used the training data to explore spatial patterns for each size class of silky shark and the test data to evaluate catch–bycatch trade-offs within candidate closures.

Spatial Patterns of Bycatch Rates

To identify temporally persistent regions of high bycatch, we used the generalized additive model (GAM) technique to smooth the spatial distributions of silky shark bycatch per set. A range of increasingly complex methods could be used to this end: from simple maps of the average bycatch rate per square area to Bayesian hierarchical spatial models (Sims et al. 2008). Because we were interested in determining the location of high-bycatch areas, not the best estimate of the mean bycatch per set, we chose the GAM approach as a reasonable descriptive tool of intermediate complexity. We implemented the GAM procedure with the negative binomial distribution via the mgcv package (Wood 2006) of the R statistical computing software (R Development Core Team 2008), with default options for smoothing and theta estimation. For each year, the following model was fitted to the training data: $Y_i = \exp[ß_0 + s(\text{lon}_i, \text{lat}_i)]$, where Y_i is the bycatch in the ith set, $ß_0$ is a constant, and $s(\text{lon}_i, \text{lat}_i)$ is a smoothed bivariate term for longitude and latitude (Wood & Augustin 2002). For simplicity, hereafter, we refer to the $s(\text{lon}_i, \text{lat}_i)$ term as the *bycatch surface*.

We assessed the temporal persistence of regions of high bycatch by comparing annual bycatch surfaces. These annual surfaces were obtained by predicting bycatch surfaces on a fixed 1° latitude–longitude grid of the high-fishing-intensity region from 10°S to 25°N and from the coast to 140°W. Scarce data on silky shark biology prevented us from determining a biologically based definition of high bycatch. Instead we relied on a statistical threshold value. For each year high bycatch was the bycatch surface that exceeded the mean surface value by more than 1 SD. An assessment of the amount of bycatch that could be expected within high-bycatch regions was obtained by summing bycatch in sets of the test data that fell within the region boundaries.

A candidate closure area was defined as any area with coincident high-bycatch regions across all years. Contours of annual high-bycatch regions were overlain onto a single map to highlight interannual variability. Initial efforts included the GAM approach for all size classes of silky sharks (Watson 2007), but small silky sharks were the only size class for which we observed predictable spatial structure. Given these observations, we used only the data on bycatches of small silky sharks to identify candidate closure areas, but we included all size classes in our assessment of closure efficacy.

Evaluating Trade-Offs from Fishery Closures

We evaluated the trade-offs of closures within the candidate closure areas identified in the spatial analysis by summing the annual bycatch that would have been avoided within each of these areas had closures been in place from 1994 to 2005, assuming that effort was not reallocated. We did likewise for tuna catch and for bycatch of oceanic whitetip sharks, hammerhead sharks, and turtles. Results were summarized by the 12-year mean catch retained and bycatch avoided for each closure.

Preliminary analyses suggested that closure efficacy was highly sensitive to the location of the southern and eastern boundaries of a closure. On the basis of the results of the spatial analysis (see later), we emphasized these boundaries in closure simulations, varying southern boundaries by 1° increments from 5°N to 10°N and varying eastern boundaries by 2° increments from 90°W to 120°W. Northern and western boundaries were fixed at 15°N and 140°W, respectively.

Results

Silky sharks were caught in 45% of the sets on floating objects, yielding a mean bycatch per set of 3.8 sharks (median = 0). Of the observed bycatch, 36.8, 41.3, and 21.9% of animals were classified as large, medium, and small silky sharks, respectively. Only 24.4% of sets had bycatch of total silky sharks that exceeded the mean and only 5.7% of sets exceeded the mean by more than 1 SD. Although these high-bycatch sets were rare, collectively they accounted for 90% and 54% of the total bycatch of silky sharks, respectively.

Spatial Pattern

There was more similarity between the spatial distributions of target species catch and fishing effort than between those of bycatch and fishing effort. Integrating over all years, fishing effort was distributed throughout the EPO but with pronounced peaks at latitudes approximately 7°S and 4°N (Fig. 1a). Longitudinally, effort was distributed consistently from 90°W to about 120°W and declined relatively sharply west of about 130°W (not shown). Latitudinally, the spatial distribution of target species catch closely mirrored that of fishing effort (Fig. 1b). For example, about 50% of both the total effort and the catch of tunas occurred south of the equator, 33% and 34% respectively, occurred between the equator and 5°N, and 17% and 16%, respectively, occurred north of 5°N. In contrast, about one-third of the total bycatch of silky sharks was observed south of the equator, about one-third was observed between the equator and 5°N, and slightly more than one-third of the total bycatch of silky sharks was observed north of 5°N (Fig. 1c).

Closer inspection of the latitudinal pattern of bycatch by shark size classes revealed that the differences between effort and shark bycatch was mostly due to spatial aggregation of small-sized silky sharks (Figs. 1d–f). Specifically, only 6% of the bycatch of small silky sharks was observed south of the equator, about one-third was observed between the equator and 5°N, and 57% were

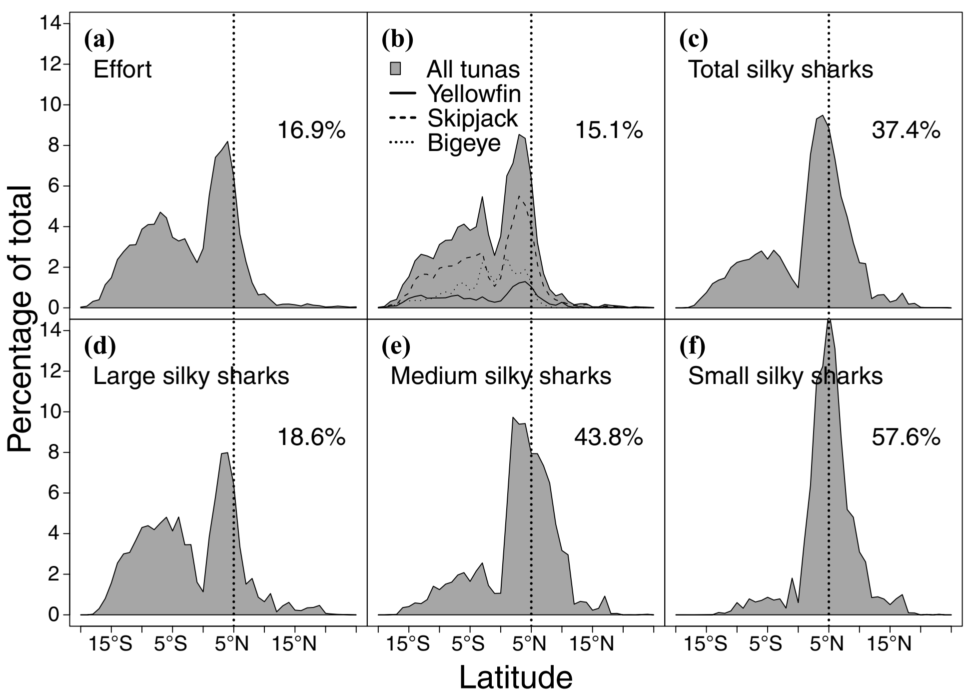

Figure 1. Percentages of total observed (a) floating object sets, (b) tuna catch (including species of tunas), and bycatch of (c) all (total) silky sharks, (d) large silky sharks, (e) medium silky sharks, and (f) small silky sharks as functions of latitude. The number in each plot window represents the percentage of each total that occurred north of 5°N (e.g., 37.4% of the total silky sharks occurred north of 5°N, but only 15.1% of the tuna catch and 16.9% of the fishing effort [number of sets] occurred in this region).

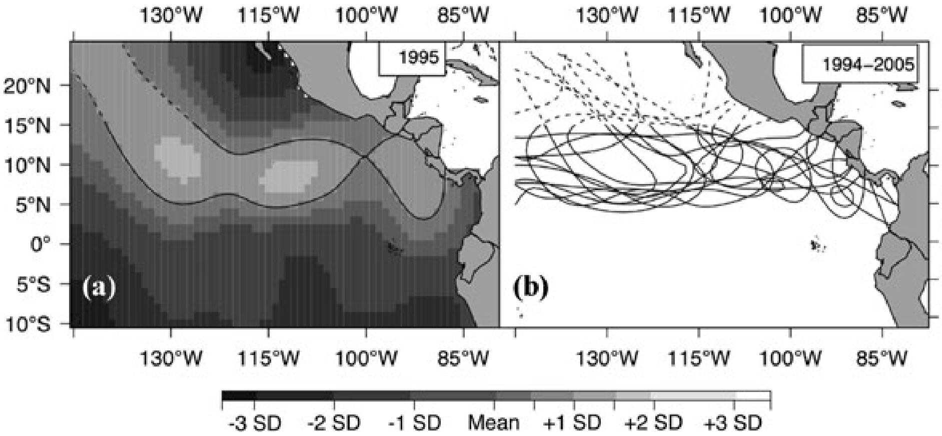

Figure 2. Surface plot (a) of predictions for the spatial term of modeled bycatch of small silky sharks from a single year (1995). Magnitudes of predictions are shown in the figure key (below plot). The black contour line (solid/dashed) overlain on the surface plot defines the boundary of the areas predicted to have high (mean +SD) bycatch; north of 15°N the data fit to models were scarce (dashed contour line). The process that yielded the boundary line in (a) was repeated for all years and the corresponding boundary lines for each year are shown in (b) to reveal the regions persistently predicted to have high bycatch.

observed north of 5°N. In contrast, bycatch of large silky sharks (Fig. 1d) was spatially dispersed throughout the fishery, closely mirroring the distribution of fishing effort (Fig. 1a). The distribution of medium silky sharks appears to be intermediate to those of large and small silky sharks (Fig. 1e), suggesting that this group may include overlap in the classification of individuals in this group with those in the large and small groups.

Comparison of the annual bycatch surfaces of small silky sharks obtained from the GAM smoothing indicated considerable interannual variability in the longitudinal boundaries of high-bycatch regions over the 12-year period, but spatial consistency of the southern latitudinal boundary (e.g., Fig. 2). In 2 small, localized areas, bycatch exceeded the mean by 2 SD (hotspots). Both locations were at approximately 7°N–10°N and positioned longitudinally at 130°W and 112°W. The broader area where the bycatch surface values exceeded the mean by at least 1 SD, our definition of a high-bycatch region, encompassed a band between 6°N and 12°N. In terms of their longitudinal boundaries, not only were such hotspots not consistently located through time (not shown) but neither were within the annual high-bycatch regions (Fig. 2). In contrast, the southern boundary of the annual high-bycatch regions was spatially consistent. Specifically, the southern boundaries of annual high-bycatch regions were tightly clustered at approximately 5°N–6°N, in keeping with the 1-dimensional overall summary shown in Fig. 1. We could not put much emphasis on the locations of the northern boundaries (north of 15°N), however, because these were at the margins of the data.

Based on the test data set, these high-bycatch regions accounted for an annual average 39% (median = 46%; range = 0–79.8%) of the bycatch of small silky sharks and 27% (median = 36%; range = 0–53.4%) of the total silky bycatch. On average, 38.0% (median = 43%; range = 0–78.5%) of test data sets that had high rates of bycatch for small silky sharks fell within the annual high-bycatch regions. Meanwhile, an average of 6.6% (median = 4.5%; range = 0–20.5%) of total silky sharks high-bycatch sets occurred within these annual high-bycatch regions.

Trade-Offs

Because the spatial modeling suggested northern areas as viable candidates for fishery closures to reduce silky shark bycatch, we focused our analysis of trade-offs on candidate closed areas with a southern boundary of 7°N and a northern boundary of 15°N. Within this latitudinal range, we considered several possible closures corresponding to alternative positions of the eastern boundary (with the western boundary fixed at 140°N because relatively few sets occurred farther west of this meridian). Over 12 years, there was substantial variability in the amounts of tuna catch that would have been retained and the amounts of bycatch that would have been conserved if fishing effort had been eliminated within candidate areas (Fig. 3). Despite this variability, the percentage of the tuna catches that occurred in these regions was consistently an order of magnitude less than the percentage of the silky shark bycatches. This order of magnitude difference remained when the longitudinal boundaries of closures changed; the amounts of total bycatch of silky sharks conserved from a closure increased by as much as 20%, and the amounts of tuna catch retained decreased by about 2% from the smallest to the largest-sized closure. Most of the change in bycatch reduction occurred when

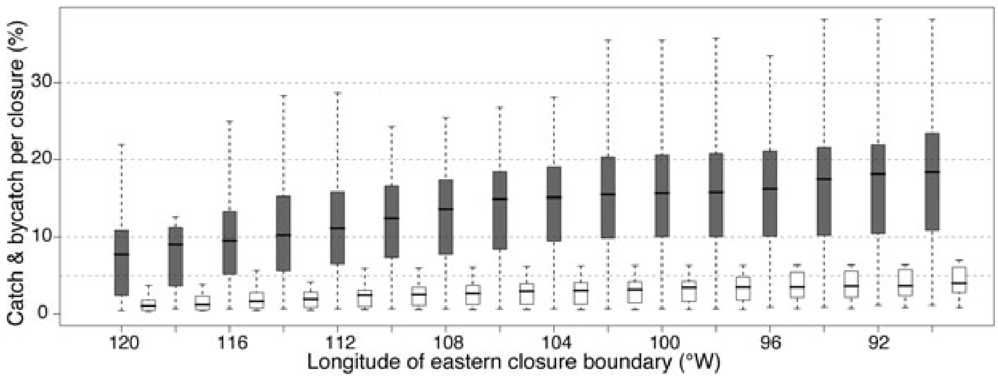

Figure 3. Interannual variability of candidate fishery closures in terms of catches and bycatches per closure. Each spatial closure had fixed latitudinal boundaries (7°N and 15°N) and a fixed western boundary (140°W). Eastern longitudinal boundaries varied in 2° increments. Closure areas get successively larger from left to right (eastern boundary is moved farther to the east). Shaded and open boxes, respectively, represent the hypothetical percentage of total bycatch reduction and tuna catch lost for each closure if all fishing effort was removed from a closure and not reallocated. Error bars span the first and fourth quantiles of the 12-year interannual variability, whereas boxes depict the second and third quantiles; means are the horizontal bars.

the eastern boundary was shifted from 120°W to 104°W, with only modest increases beyond this range.

We extended this analysis to consider alternative latitudinal boundaries, tuna catch retained by species (each of which has different market values), and bycatch reduction for other species of conservation concern (Table 1). For this analysis, we considered the largest closure (eastern boundary = 90°W) for each possible southern boundary (5°N–10°N). Because the southern boundary of the hypothetical closure moved northward, the amount of tuna catch lost was approximately equal to the amount of effort that occurred in each area. Nevertheless, the closures had a larger effect on yellowfin and skipjack tuna (lowest percentage of retained catch) compared with bigeye tuna. Reductions in the bycatch of turtles were slightly greater than would be expected on the basis of allocation of historical effort in each of the areas. In contrast, the percent reductions of oceanic whitetip shark and hammerhead shark bycatch were less than the reductions in effort in each candidate area. Thus, these

Table 1. Mean bycatch and catch that would have been conserved and retained, respectively, by fishery closures that were simulated with different southern boundaries.*

	Totals (entire fishery)	*Closure southern boundary*					
		5°N	*6°N*	*7°N*	*8°N*	*9°N*	*10°N*
Data	*No. of sets*	*Sets per closure (%)*					
Effort (sets)	48,417	13.4	7.6	4.6	3.0	1.9	1.4
Bycatch group	*No. individuals*	*Bycatch conserved per closure (%)*					
Total silky sharks	186,245	33.6	25.0	18.4	13.4	9.3	6.0
Large silky sharks	68,598	17.9	10.7	7.5	5.9	4.1	2.7
Medium silky sharks	76,890						
Small silky sharks	40,834	50.2	34.8	23.4	16.2	11.7	7.3
Oceanic whitetip sharks	28,400	10.8	5.2	3.3	2.5	2.2	1.8
Hammerhead sharks	10,492	7.2	3.4	1.5	1.2	1.2	0.8
Turtles	783	17.2	9.5	6.8	4.0	2.8	2.5
Target catch group	*Tonnes*	*Catch retained per closure (%)*					
Total tuna	2,207,284	88.0	93.4	95.9	97.2	98.0	98.5
Yellowfin tuna	337,522	84.7	90.4	93.6	95.3	96.5	97.2
Bigeye tuna	551,707	92.9	97.6	99.1	99.7	100.0	100.0
Skipjack tuna	1,291,054	87.1	92.8	95.6	97.0	97.9	98.5

**All closures had a northern boundary at 15°N and east and west boundaries at 90°W and 140°W, respectively.*

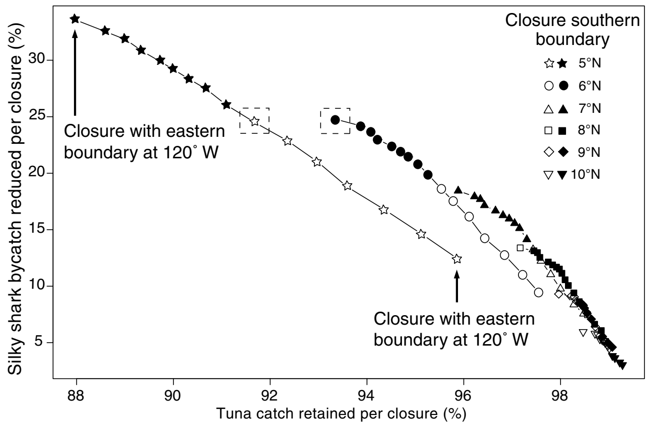

Figure 4. Trade-offs between total tuna catch and total bycatch of silky sharks for hypothetical closure of areas in the eastern Pacific Ocean. Catch (abscissa) is expressed as the percentage of the total tuna catch occurring outside each closure, whereas bycatch (ordinate) is expressed as percentage of the total shark bycatch occurring within each closure. Each point represents a different closure and all closures share the same northern (15°N) and western boundaries (140°N). Southern boundaries vary from 5°N to 10°N. For closures with each of the southern boundaries, eastern boundaries are changed in 2° increments, from 90° to 120°W (left to right). The 2 points within dashed boxes represent 2 closures with similar amounts of bycatch (ordinate value is equal), but the more optimal closure (right) is associated with a higher catch retained (abscissa value differs). Solid points (filled symbols) thus illustrate the optimal candidates for closures that maximize catch for a given level of bycatch reduction.

northern closed areas would have the greatest impact on the total catches of skipjack tuna, yellowfin tuna, silky sharks, and sea turtles.

We extended our analysis of trade-offs between closed areas by using the mean values averaged over all years to consider 96 hypothetical closures that differ with respect to latitudinal and longitudinal boundaries (16 eastern longitudinal boundaries for each of 6 southern boundary latitudes). We used this to identify nonoptimal closures with respect to maximizing tuna catch retained while minimizing total silky shark bycatch by plotting these results as a pareto frontier (Fig. 4). Plot symbols (shapes) differentiate closures at each southern boundary and for each of these southern boundaries longitudinal changes are illustrated from left to right. For example, the left most point in the figure represents the largest closure, with an eastern boundary at 90°W and a southern boundary at 5°N. As the eastern boundary is moved (closures get smaller), the amount of bycatch conserved by successive closures declines at an almost linear rate (down and to the right). This method showed that several closures with southern boundaries at 6°N would conserve as much or more bycatch as several closures at 5°N while retaining a higher level of tuna catch. Such closures optimize the ratio between catch and bycatch and help identify nonviable candidate closures on the basis of alternatives that outperform them.

The 2 closures within the dashed boxes illustrate this optimization; they conserve equivalent bycatch but the one on the right retains more tuna catch. For the 96 total closures, this method of comparison yielded a pareto frontier of 54 optimal closure candidates (Fig. 4; filled plot symbols). The slopes of each of the segments of the pareto frontier get steeper as the southern boundary of closures moves north. Thus, although many closures are present in the far right portion of Fig. 4, successive closures reveal slighter differences, suggesting diminishing returns for conservation and lower ratios between bycatch and catch.

Discussion

Our analyses did not reveal any persistent, small-scale hotspots of bycatch (e.g., a 5° latitude–longitude square), but we did identify regions smaller than the entire fishery that exhibited temporally persistent high rates of bycatch of silky sharks. Although interannual differences in the locations of these regions existed, the spatial patterns of this bycatch were persistent. Moreover, there were regions of high bycatch that were spatially distinct from regions with the greatest tuna catch. This suggests that spatial fishery closures might be effective in reducing silky shark bycatch without incurring large reductions in tuna catch. Nevertheless, the majority of the bycatch in these regions consisted of small silky sharks. Larger individuals were captured throughout the range of the fishery, and our models were unable to predict persistent regions of high bycatch of this size class. As a result a best-case closure would have reduced total silky shark bycatch by about 33.6% from 1994 to 2005, consisting primarily of small-sized silky sharks.

Large silky sharks range throughout the EPO, making them a difficult target for conservation efforts. Nevertheless, the spatially dispersed nature of these reproductively valuable animals indicated that some portion of large silky sharks, as much as 17.9%, was present in most closures simulated. Although scarce data on silky sharks prevent us from proposing a relative value of large versus small individuals, aggregations in the north may be indicative of spawning or parturition grounds, which are arguably worth protecting (Walker 2005). Nevertheless, the overall impact of spatial closures will depend on the manner in which the fleet reallocates effort, the resulting impact on large sharks, and the overall sensitivity of the growth rate of silky shark populations to changes in the mortality rates of small versus large sharks.

Although our focus on bycatch has taken a single-species approach, the issues of bycatch are rarely such. Nevertheless, as demonstrated by different sizes of silky sharks, the factors that drive animals to aggregate around a FAD are likely to vary, and we do not know to what extent our models for silky sharks apply to other taxa. Because other vulnerable species are relatively rare in this fishery, the data were insufficient to model bycatch of oceanic whitetip sharks, hammerheads, or turtles in the same manner as silky sharks. Nevertheless, we extended our analyses of the proposed closures for silky sharks to suggest the ancillary effects on these additional taxa. Closures suggested substantially lower bycatch reductions for these species groups than for silky sharks (Table 1), which can likely be attributed to the relative rarity with which they are caught as bycatch and to greater interannual variability observed in their distributions. These findings highlight the flexibility of our method for including any, or as many, species as desired, and it further suggests the importance of assessing the persistence of bycatch in a particular area before proposing measures that might unnecessarily affect a fishery.

A key element needed to accurately predict the impact of spatial closures on any species is the reallocation of fishing effort that results from a closure. If closures displace fishers into areas with less catch or with higher bycatch, especially the bycatch of more vulnerable species or size classes, the net result could be detrimental to management objectives (Martell et al. 2005). In this case the reallocation of effort is especially problematic to predict because we identified closures explicitly for their high rates of bycatch and low rates of tuna catch. Our initial effort to model how reallocation might occur (not shown), which presumed that the fleet would redistribute among open areas on the basis of historical catch per set, actually resulted in increased tuna catch because it reallocated effort to more productive areas for fishing. In addition, because FADs drift for upward of a month after deployment before being fished on (Lennert-Cody & Hall 2000) and because their spatial distributions are highly susceptible to the dynamic oceanography of the EPO (Garcia et al. 1999), their locations are especially difficult to model and predict. More information is needed on localized catch rates to conduct even the most simplistic simulations of how fishing-effort reallocation will affect catches of tunas and bycatches of any species, in addition to the potential impact of reallocation on the larger, more reproductively valuable individuals.

The management of natural resources, fisheries in particular, involves the consideration of trade-offs. Trade-offs can be represented as pareto frontiers, which present management options as optimal combinations of different stakeholders' interests (Walters & Martell 2004), in this case, retention of target catch and conservation of bycatch species. By this construct, policy makers could select an area for closure on the basis of an acceptable level of catch of target species for a given level of conservation of bycatch species, or vice versa. If stock assessments existed for these vulnerable species, managers could choose a closure from the pareto frontier according to the spawning biomass needed to ensure the long-term viability of each species (Boyce 1992; Morris & Doak 2002). Nevertheless, the paucity of information about the stocks of vulnerable species caught as bycatch—in pelagic fisheries especially—often preclude such an analysis. Instead, conservation efforts must rely on fishery managers to identify acceptable levels of lost catch to obtain a particular decrease in bycatch.

The design of fishery closures for bycatch is often complicated by intrinsic overlap of the spatial distribution of catches and bycatches. For this reason, a closure designed to reduce bycatch or discards may often be unfeasible because it would have too great an impact on the fishery itself (Harley & Suter 2007) and may thus be too costly. By maintaining a focus on these costs of conservation, however, we present an approach to fishery closures that allows managers to identify a range of policy options that may increase the likelihood of implementation of a particular closure. This approach provides a pragmatic and transparent assessment of the trade-offs of conservation, and it can be applied broadly to different fisheries, regions, or species, but it is not without shortcomings. The simple ratio-based objective function assumes a fairly simple policy objective: minimize bycatch while maximizing catch. By this definition a unit of shark conserved is equivalent to a unit of tuna captured, with no diminishing utilities on either axis. Moreover, it considers only the mean catch rates and not the variances associated with them. There are a multitude of policy objective functions that might be reasonably defined, but we refrain from advocating for any particular policy because such a decision lies on the boundary between science and policy (Mangel et al. 2006).

We screened possible areas for closure and identified optimal subsets among these, and in doing so, several directions of future work have emerged. First, we believe a more complicated model would have been unlikely to identify substantially different areas for possible closure on the basis of the available data. As noted in Watson (2007), the negative binomial GAM exhibited some tendency to overestimate smaller bycatch values and underestimate large bycatch values. Nevertheless, we do not believe this tendency to oversmooth significantly affected our conclusions because the most likely outcome would be to increase the size of the starting candidate closure area used in the trade-offs analysis. Nevertheless, 2-stage models might be explored to more accurately estimate the magnitude of bycatch per set at certain locations (Minami et al. 2007). Although we screened a number of additional covariates for potential inclusion in our GAM approach, none of the available predictors altered the location of areas predicted to have high bycatch (Watson 2007), but other, presently unidentified covariates may better describe silky shark behavior. Furthermore, a better understanding of the population structure of silky sharks and the relative importance of distinct demographic parameters (Cortes 2002; Gallucci et al. 2006) will reveal whether conservation of small sharks—the size class most likely to benefit from spatial closures—is sufficient to ensure long-term viability of this population. Lastly, the nature and impacts of fleet reallocation on shark and tuna catches remains an important uncertainty in predicting the consequences of fishery closures in the context of finding policies that balance conflicting management trade-offs.

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