# The potential use of time-area closures to reduce catches of bigeye tuna (*Thunnus obesus*) in the purse-seine fishery of the eastern Pacific Ocean

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**Abstract**—Skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye (*Thunnus obesus*) tunas are caught by purse-seine vessels in the eastern Pacific Ocean (EPO). Although there is no evidence to indicate that current levels of fishing-induced mortality will affect the sustainability of skipjack or yellowfin tunas, fishing mortality on juvenile (younger than 5 years of age) bigeye tuna has increased, and overall fishing mortality is greater than that necessary to produce the maximum sustainable yield of this species. We investigated whether time-area closures have the potential to reduce purse-seine bigeye catches without significantly reducing skipjack catches. Using catch and effort data for 1995–2002, we identified regions where the ratio of bigeye to skipjack tuna catches was high and applied simple closed-area models to investigate the possible benefits of time-area closures. We estimated that the most optimistic and operationally feasible 3-month closures, covering the equatorial region of the EPO during the third quarter of the year, could reduce bigeye catches by 11.5%, while reducing skipjack tuna catches by 4.3%. Because this level of bigeye tuna catch reduction is insufficient to address sustainability concerns, and larger and longer closures would reduce catches of this species signficantly, we recommend that future research be directed toward gear technology solutions because these have been successful in many other fisheries. In particular, because over 50% of purse-seine catches of bigeye tuna are taken in sets in which bigeye tuna are the dominant species, methods to allow the determination of the species composition of aggregations around floating objects may be important.

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The Inter-American Tropical Tuna Commission (IATTC) was established by an international convention in 1950 and is responsible for the conservation of tunas and management of fisheries for tunas and other species taken by tuna-fishing vessels in the eastern Pacific Ocean (EPO). Such conservation and management is accomplished by measures imposed by the nations participating in the fishery in response to recommendations by the scientific staff of the IATTC. Currently, the IATTC has adopted two measures to ensure the conservation of bigeye tuna in the EPO (IATTC[1]): catch limits for each longline fleet (based on their 2001 catch levels) and a series of closures for the purse-seine fleet. In this article, we examine the use of the temporary closure of a given area, referred to as a "time-area closure," for management of the purse-seine fishery.

Since the early 1990s, considerable purse-seine fishing effort in the EPO has been directed at tunas associated with floating objects, including manmade fish-aggregating devices (Lennert-Cody and Hall, 2000). The predominant species captured are skipjack (*Katsuwonus pelamis*), bigeye (*Thunnus obesus*), and yellowfin (*Thunnus albacares*) tunas. The floating-object (FOB) fishery has had no noticeable affect on skipjack tuna abundance (Maunder, 2002a) and little effect on yellowfin tuna because the catches of yellowfin tuna from the floating object fishery are small compared to the catches from other purse-seine fisheries (Maunder, 2002b). However, the FOB has led to a considerable increase in fishing mortality on juvenile bigeye tuna (Maunder and Harley, 2002; Harley et al., 2005).

The most recent bigeye tuna stock assessment (IATTC, 2004) has indicated that overall fishing effort should be reduced by at least 38% to allow the stock to produce the maximum sustainable yield (MSY). This assessment is based on a single EPO stock with no net migration between the eastern and western Pacific; however, a "Pacific-wide" assessment has provided a very similar picture of low movement rates for bigeye tuna in the EPO (Hampton et al.[2]).

Since the expansion of the FOB fishery, catches of bigeye tuna from the purse-seine fishery have exceeded those from the longline fishery in some years (Table 1). The bigeye tuna

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[1] IATTC (Inter-American Tropical Tuna Commission). 2003. Resolution on the conservation of tuna in the eastern Pacific Ocean, 3 p. Resolution C-03-12, IATTC, 8604 La Jolla Shores Drive, La Jolla, California 92037.

[2] Hampton, J., P. Kleiber, Y. Takeuchi, H. Kurota, and M. Maunder. 2003. Stock assessment of bigeye tuna in the western and central Pacific Ocean, with comparisons to the entire Pacific Ocean, 81 p, SCTB16 BET-1. Sixteenth meeting of the standing committee on tuna and billfish, Mooloolaba, Queensland, Australia; 9–16 July 2003.

**Table 1**

Annual catches (metric tons) of bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*) tuna from purse-seine (PS) fisheries by set type (FOB=floating object associated school, UNA=tuna school unassociated with dolphins, and DOL=tuna school associated with dolphins) and longline fisheries from the eastern Pacific Ocean, east of 150°W, as used in the stock assessments.

| | Bigeye tuna | | | | | | Skipjack tuna | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | FOB | UNA | DOL | PS total | Longline total | Annual total | FOB | UNA | DOL | PS total | Longline total | Annual total |
| 1990 | 3360 | 1351 | 0 | 4711 | 98,990 | 103,700 | 34,980 | 35,788 | 867 | 71,635 | 42 | 71,677 |
| 1991 | 1963 | 1739 | 38 | 3740 | 104,159 | 107,874 | 37,655 | 22,958 | 786 | 61,399 | 33 | 61,432 |
| 1992 | 1154 | 4343 | 0 | 5497 | 84,396 | 89,893 | 45,556 | 35,333 | 869 | 81,758 | 24 | 81,782 |
| 1993 | 6274 | 4724 | 134 | 11,132 | 72,351 | 80,420 | 48,144 | 34,865 | 714 | 83,723 | 63 | 83,786 |
| 1994 | 37,901 | 2624 | 0 | 40,525 | 71,360 | 100,734 | 47,992 | 22,916 | 516 | 71,424 | 69 | 71,493 |
| 1995 | 45,204 | 6291 | 0 | 51,495 | 58,076 | 95,403 | 81,253 | 50,715 | 1032 | 133,000 | 74 | 133,074 |
| 1996 | 66,568 | 4280 | 0 | 70,848 | 46,771 | 98,124 | 74,260 | 34,635 | 729 | 109,624 | 40 | 109,664 |
| 1997 | 69,293 | 1868 | 48 | 71,209 | 52,078 | 103,693 | 123,002 | 29,510 | 6004 | 158,516 | 94 | 158,610 |
| 1998 | 43,226 | 5183 | 91 | 48,500 | 45,632 | 80,787 | 115,370 | 25,108 | 2879 | 143,357 | 65 | 143,422 |
| 1999 | 49,452 | 6574 | 0 | 56,026 | 32,565 | 73,176 | 178,824 | 84,036 | 1214 | 264,074 | 94 | 264,168 |
| 2000 | 83,489 | 3266 | 0 | 86,755 | 46,424 | 116,579 | 116,508 | 81,551 | 440 | 198,499 | 29 | 211,049 |
| 2001 | 56,753 | 1273 | 14 | 58,040 | 60,572 | 103,421 | 115,571 | 20,163 | 1218 | 136,952 | 61 | 144,949 |
| 2002 | 61,230 | 1166 | 0 | 62,396 | 68,195 | 103,394 | 118,485 | 32,471 | 2093 | 153,048 | 145 | 157,593 |

caught in the longline fishery are larger (110–160 cm) and considerably more valuable than the smaller bigeye tuna (50–80 cm) caught mostly by the purse-seine fishery.

Improving the long-term sustainability of the bigeye tuna fisheries could be achieved by reducing the fishing mortality of the smaller individuals that are caught predominantly in the FOB fishery. Annual catches of skipjack tuna from the purse-seine fishery in the EPO are larger and more economically important than those of bigeye tuna (Table 1). Furthermore, there are no concerns regarding sustainability of the skipjack tuna population in the EPO (Maunder, 2002a). Thus, bigeye tuna caught by the FOB fishery are essentially bycatch of the targeted skipjack tuna fishery; thus determining a mechanism by which the catches of bigeye tuna are reduced while minimizing losses in the catches of skipjack tuna is an important management issue.

Hall (1996) argued that to understand and solve bycatch problems it is important to classify the problem by a number of factors (e.g., time, space, and the level of control that fishermen have). With this information, there are many potential tools that can be used by fisheries managers to reduce fishing mortality, e.g., gear regulations, catch limits, closed seasons, and closed areas (Beverton and Holt, 1957). Time and area closures (time-area closures) are recommended as a means to reduce catches of sharks (Baum et al., 2003), protect billfishes from exploitation by the longline fishery (Goodyear, 1999), and protect biodiversity hotspots (Worm et al., 2003). Although time-area closures are not particularly appropriate for fisheries managed under quota systems, they may be beneficial for effort-managed fisheries (Horwood et al., 1998) or fisheries targeting multispecies (Hilborn et al., 2004), such as those for tunas in the EPO.

In this study, we investigated the potential of time-area closures to reduce bigeye tuna catches while minimizing impacts on the catches of skipjack tuna. In contrast to common closure-strategy studies, i.e., those studies devoted to fisheries targeting a single species, we investigated the potential impacts of time-area closures on two species: a large and highly productive skipjack tuna stock, and a considerably smaller and less productive bigeye tuna stock.

We used catch and effort data from the purse-seine fishery to search for potential time-area hotspots for bigeye catches and then applied simple "in-sample" closed-area models to predict the potential impact of closures of these areas. We discuss the likely use of such closures in the light of our findings, alternative management actions that could possibly reduce bigeye tuna catches, and finally, the strengths and weaknesses of the approach used for the closed-area models.

Although yellowfin tuna form an important part of the purse-seine fishery in the EPO, where annual catches are greater than those for bigeye and skipjack tuna combined, we did not consider them in our analysis. Within the EPO purse-seine fishery there are essentially two fleets: one targets yellowfin tuna schools associated with dolphins or schools not associated dolphins and the other targets mainly skipjack tuna associated with floating objects. In our study, we focused on the second fleet and there are many reasons to believe that effort could not be transferred from one fleet to the other, e.g. markets, technological differences (the vessels require different equipment), geographical

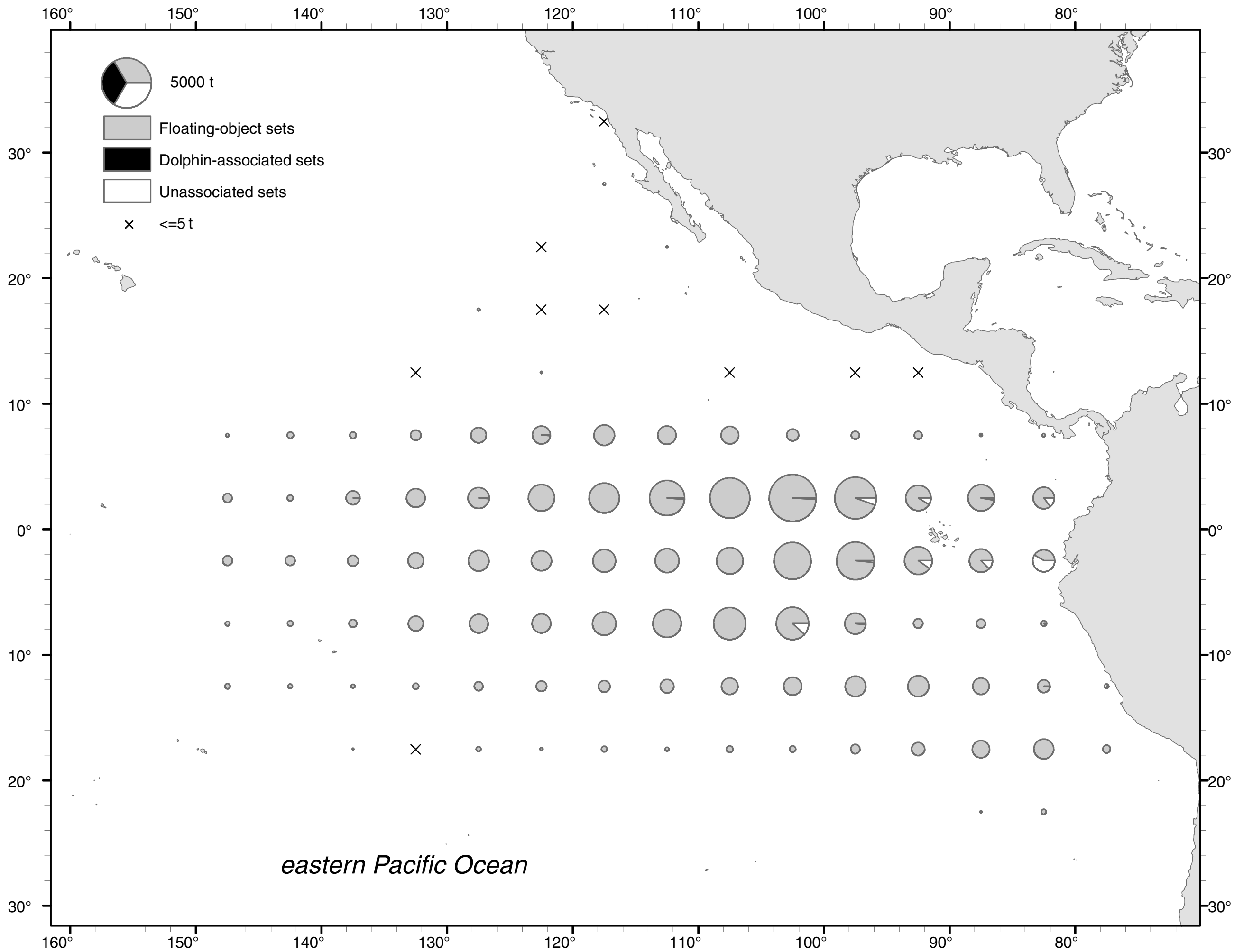


**Figure 1**

Average annual distribution of the purse-seine catches of bigeye tuna (*Thunnus obesus*), by set type and 5-degree latitude by 5-degree longitude area, in the eastern Pacific Ocean, 1995–2002. The size of the circles is proportional to the catch in each area.

(the fisheries have limited spatial overlap), and restrictions on dolphin mortality limits. In addition, only a small proportion (about 10%) of the purse-seine catches of yellowfin tuna are taken in floating-object sets. Later we discuss extensions to our analysis to include not only yellowfin tuna, but a range of bycatch species taken in the different purse-seine fisheries.

## Materials and methods

### Data

We used set-by-set catch and effort data from purse-seine vessels that operate in the EPO. The majority of the data was obtained by scientific observers. In the absence of observer data, we used records from the logbooks of the vessels. Data were grouped by 5-degree latitude by 5-degree longitude areas (hereon referred to as 5°×5°areas) by seasonal quarter. The FOB fishery, which is responsible for over 90% of the purse-seine catches of bigeye tuna, was in an expansion phase during 1992–94; therefore we restricted our attention to data for 1995–2002 (Table 1). Because very small amounts of bigeye and skipjack tuna are caught in dolphin-associated (DOL) sets, we excluded these from the analysis and instead focused on sets of tuna associated with floating objects and sets on schools not associated (UNA) with dolphins. For 1995–2002, these two set types were responsible for over 99% of bigeye and skipjack tuna catches from the purse-seine fishery (IATTC, 2004). These two set types were combined in the closed-area model because it was possible to switch effort between those two types of sets. The spatial distribution of catches by set type for bigeye and skipjack tuna are provided in Figures 1 and 2.

### Definition of "hotspot"

In defining the spatial and temporal extent of the bigeye catches, we looked for areas where the ratio of bigeye to

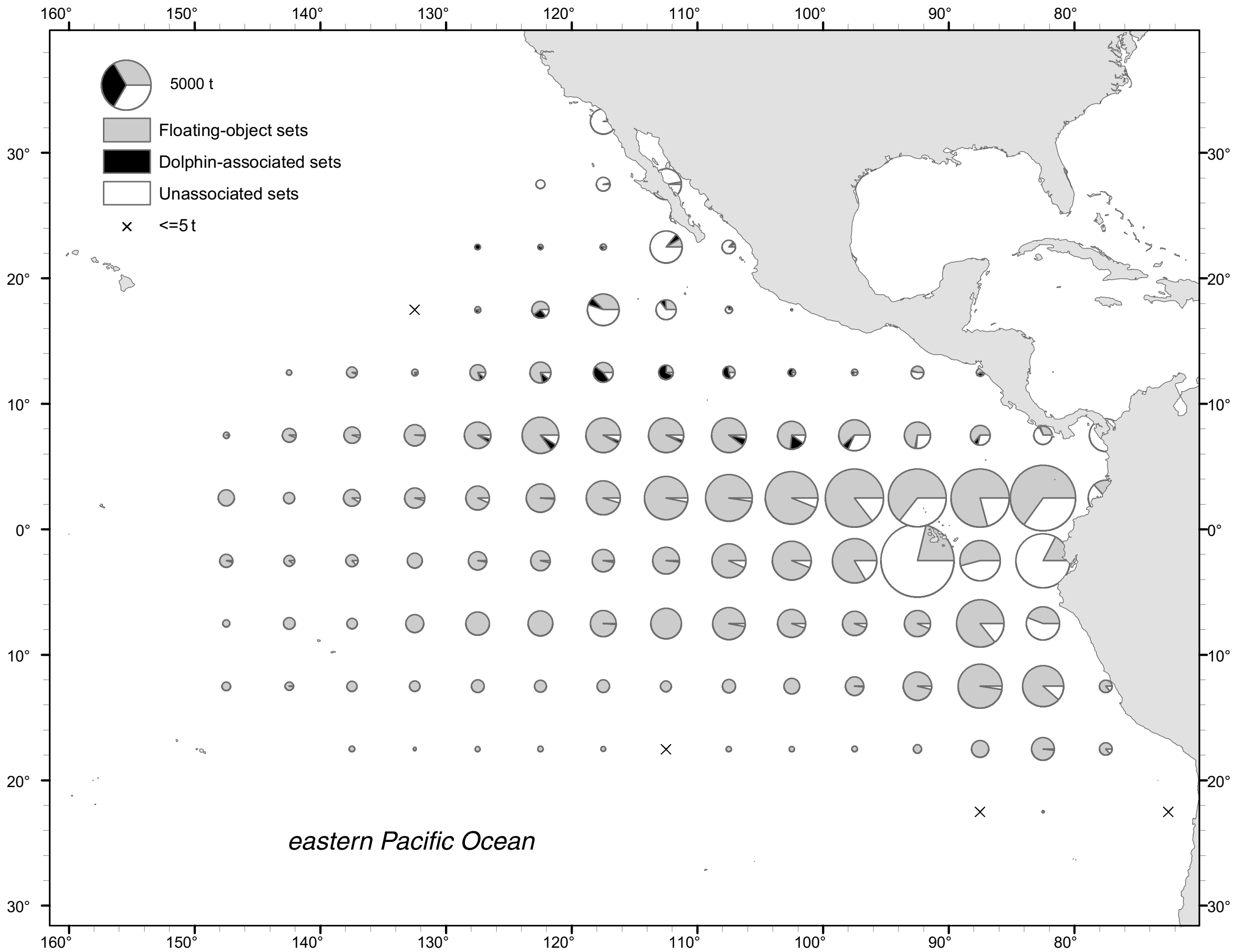


**Figure 2**

Average annual distribution of the purse-seine catches of skipjack tuna (*Katsuwonus pelamis*), by set type, in the eastern Pacific Ocean, 1995–2002.

skipjack tuna catches was high, rather than just areas of high bigeye tuna catches, because we wanted areas where the losses in skipjack tuna catches would be minimized. We chose 5°×5° areas by quarter of the year as the scale for the individual hotspots.

We defined an index for each time-area strata for each year. The index was a ratio of bigeye tuna catch to skipjack tuna catch that was robust to annual fluctuations in the abundance of either species. We then summed the annual indices over the time period to find areas that consistently resulted in high bigeye to skipjack tuna ratios. The indices were calculated separately for each year so that they were not dominated by data from years with exceptionally high or low catches of either species.

The data used for this and the closed-area analysis were the following:

$B_{i,j,t}$ = bigeye catch in quarter $i$ in area $j$ in year $t$;
$S_{i,j,t}$ = skipjack catch in quarter $i$ in area $j$ in year $t$.

We standardized catches within a year on the basis of the median catch of the year.

$$b_{i,j,t} = B_{i,j,t}/\text{median}(B_{.,.,t});$$
$$s_{i,j,t} = S_{i,j,t}/\text{median}(S_{.,.,t}).$$

The location of hotspots did not differ noticeably if we standardized by the mean or total catch for each year, rather than the median.

Using the standardized catches, we defined the annual index for a single 5°×5°area by quarter, $\theta_{i,j,t}$ as

$$\theta_{i,j,t} = \begin{cases} 0 & \text{where} \quad b_{i,j,t} = 0 \\ 1 & \text{where} \quad s_{i,j,t} = 0 \\ f(b_{i,j,t}, s_{i,j,t}) & \text{otherwise} \end{cases} \tag{1}$$

$$\text{where } f(b_{i,j,t} s_{i,j,t}) = \frac{b_{i,j,t}/s_{i,j,t} - \min(b_{i,j,t}/s_{i,j,t})}{\max(b_{i,j,t}/s_{i,j,t}) - \min(b_{i,j,t}/s_{i,j,t})}. \tag{2}$$

Note that the index is scaled to be between 0 and 1, and the larger values within this range were associated with greater bigeye-skipjack ratios. To obtain an overview of the hotspots over the 1995–2002 period we summed the annual indices

$$\tilde{\theta}_{i,j} = \sum_{t=1995}^{t=2002} \theta_{i,j}. \qquad (3)$$

We defined hotspots as those time-area regions where the summed index was in the top 20% of the values.

### Closed-area model

The basic model is summarized in four steps:

1 Choose an area to close in a given time period.
2 Re-allocate effort from the chosen area during the period of the closure to other areas in proportion to the effort in each area. Leave the effort outside the closure period unchanged.
3 Calculate the new catch of each species expected in each area based on the new effort and catch per unit of effort (CPUE) for each species in each area.
4 Compare new annual catches to original catches.

The possible consequences of these assumptions and alternative modeling approaches are detailed in the discussion.

The data used for the closed-area analysis were similar to those used in the hotspot analysis. The definitions of catches remained the same (e.g., $B_{i,j,t}$), although the spatial strata reflected by $j$ differed, depending on the closure considered.

We incorporated effort in terms of the number of sets, $E_{i,j,t}$, and defined the CPUE of bigeye and skipjack tuna in tons per set,

$$U^b_{i,j,t} = \frac{B_{i,j,t}}{E_{i,j,t}} \qquad (4)$$

and

$$U^s_{i,j,t} = \frac{S_{i,j,t}}{E_{i,j,t}}. \qquad (5)$$

We allocated effort from a time-area closure ($i$=$x$ and $j$=$y$) to the remaining areas in that time period on the basis of proportion of effort in each area ($P_{i,j,t}$) (excluding the closed area) e.g.,

$$P_{i,j,t|i=x,j\neq y} = \frac{E_{i,j,t}}{\sum_{i=x,j\neq y} E_{i,j,t}}. \qquad (6)$$

For each time-area closure we determined the new effort allocation, $E_{i,j,t|x,y}$, as

$$E_{i,j,t|x,y} = \begin{cases} 0 & \text{where } i = x \text{ and } j = y \\ E_{i,j,t} + E_{x,y,t} \cdot P_{i,j,t/x,y} & \text{where } i = x \text{ and } j \neq y. \\ E_{i,j,t} & \text{where } i = x \end{cases} \qquad (7)$$

The new catch for each time-area closure was estimated as the new effort multiplied by the original CPUE:

$$B_{i,j,t/x,y} = E_{i,j,t|x,y} \cdot U^b_{i,j,t} \qquad (8)$$

and

$$S_{i,j,t/x,y} = E_{i,j,t|x,y} \cdot U^s_{i,j,t}. \qquad (9)$$

because it was assumed that CPUE in an area will not change when additional effort is added with closure.

The summary statistic for each simulated closure was the percentage change in bigeye and skipjack tuna catches, compared to the catches observed in the absence of a closure.

$$\Delta B_{x,y,t} = \frac{\sum_{i,j} B_{i,j,t|x,y} - \sum_{i,j} B_{i,j,t}}{\sum_{i,j} B_{i,j,t}} \times 100 \qquad (10)$$

and

$$\Delta S_{x,y,t} = \frac{\sum_{i,j} S_{i,j,t|x,y} - \sum_{i,j} S_{i,j,t}}{\sum_{i,j} S_{i,j,t}} \times 100. \qquad (11)$$

We repeated the calculations for the catch and effort data in each year (1995–2002) to consider the potential variability in the effect of a closure due to interannual variation in the spatial distribution of fish and fishing effort.

In addition to the model described above, we also considered a "two set-type" model in which FOB and UNA sets were redistributed separately (i.e., we did not allow switching between set types). Although this model gave very similar results, it was probably less realistic; therefore the results are not presented here.

### Simulated closures

We compared the performance of two closed areas for each quarter and year. The first closed area corresponded to the hotspots (those 5°×5° areas for a quarter for which $\tilde{\theta}_{i,j,t}$ was in the top 20%) associated with each quarter. A closure of the hotspots should be optimal in the sense of reducing bigeye tuna catch with minimal impact on skipjack tuna catch but may not be practical from a management perspective because the 5°×5° areas are not continuous. The second closed area approximated the hotspot closure, but it was a more practical, continuous region. It extended from 5°N–10°S, to 90°–120°W. The total area of this closure was the same as the total area of the hotspot regions. We refer to this as the practical closure. In each case, effort during the closure period was redistributed between two areas, one north and one south of the equator, in proportion to the effort in each open area. Summaries of the effort and CPUE data, stratified by the areas that we used in the practical closure analysis, are provided in Table 2.

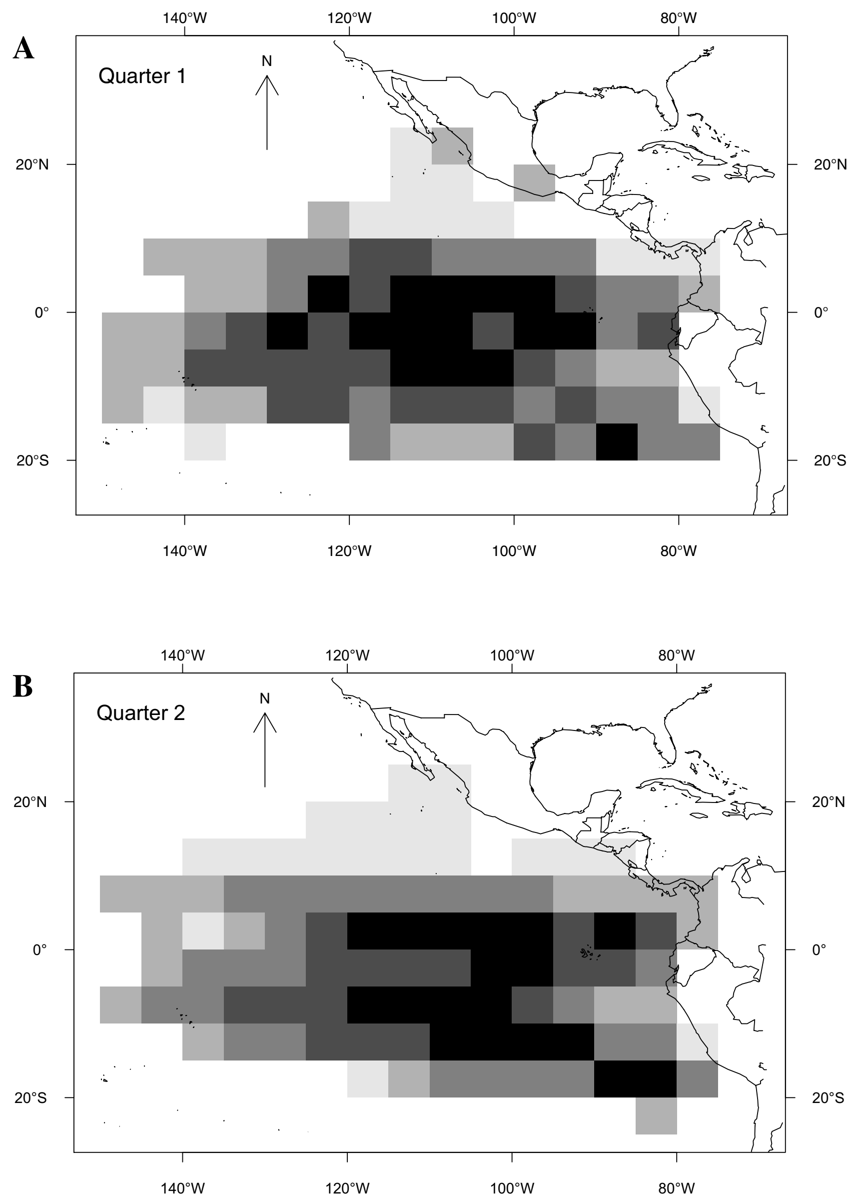


**Figure 3**

Hotspots of bigeye tuna (*Thunnus obesus*) catches in relation to skipjack tuna (*Katsuwonus pelamis*) catches by seasonal quarter and 5°×5° region for 1995–2002 as measured by our hotspot index (Equations 1–3). Plots **A–D** represent quarters 1–4. Shades are used for different percentiles of the index, and darker regions indicate areas of higher bycatch rates. The black regions represent those time and area strata for which the hotspot index was in the top 20%.

## Results

### Hotspots

The hotspots were not evenly spread over the year; the third seasonal quarter contained more 5°×5° hotspots (24) than the other quarters (15–18 each) (Fig. 3). During quarters 1 and 4, most of the hotspots were located between 5°N and 10°S, whereas during quarters 2 and 3, the hotspots extended south to 15°S. Over all time-area strata, 90% of the hotspots were west of 90°W and east of 135°W, and over 95% were between 5°N and 15°S—indicating that the hotspots are found within a fairly restricted area.

When we compared the hotspots to the practical closure, 75% of the hotspots were found within the prac-

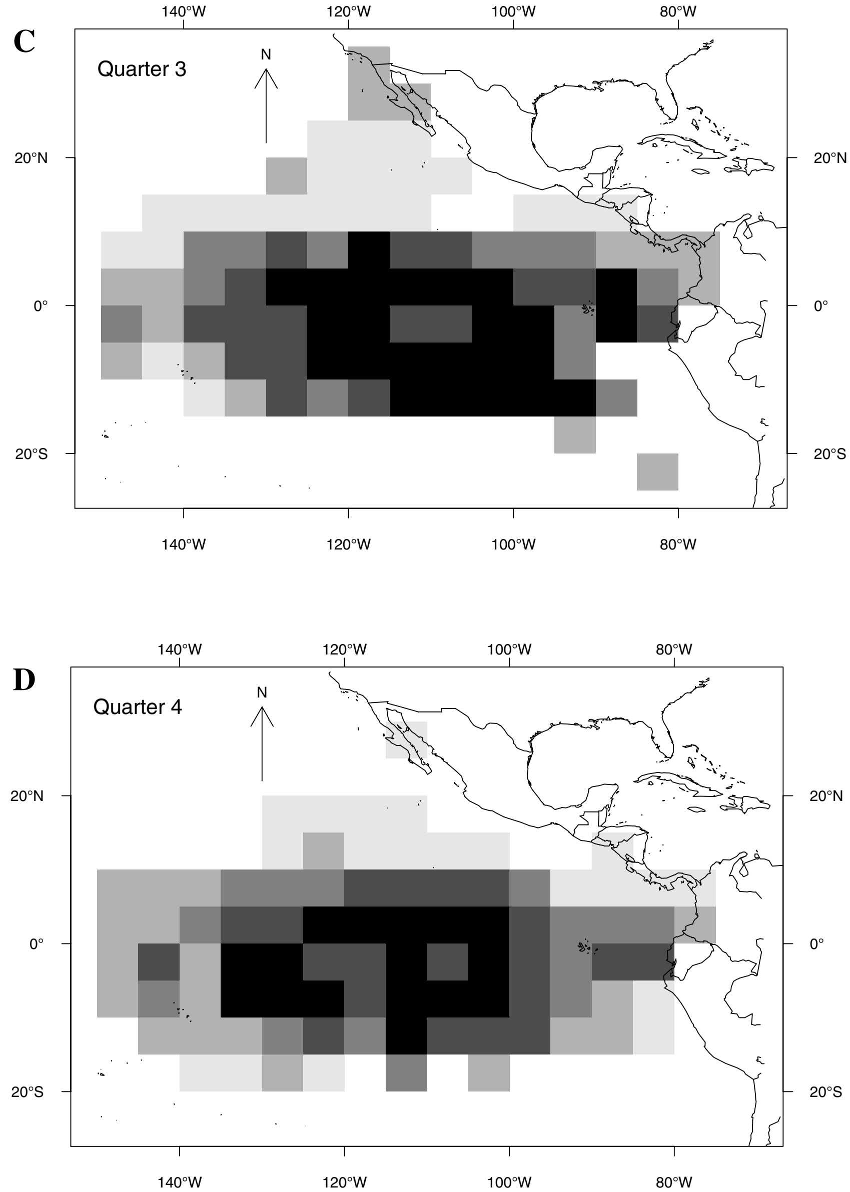


**Figure 3 (continued)**

tical closure area. Of the remaining 25% of hotspots, most were west of 120°W.

### Time-area simulations

Over all years and quarters, the predicted decrease in bigeye tuna catches associated with the hotspot closure ranged from 2.8% to 23.7%, whereas the change in skipjack tuna catches ranged from a 0.9% increase to a 14.1% reduction (Fig. 4). The greatest reductions in bigeye tuna catch were associated with second- and third-quarter closures (mean reduction=14.6%). The mean reductions in skipjack tuna catches did not vary much across quarters (means ranged from 2.8% to 3.7%). For several years, there was little or no predicted reduction in skipjack tuna catch associated with a hotspot closure. Based on the median of the ratios, the greatest contrast between bigeye and skipjack tuna catch reductions was associated with a third quarter closure; the average percentage reduction in bigeye tuna catch was 14.6%, versus 2.8% for skipjack tuna. The performance of second-quarter closures was similar to that of third-quarter closures, but the former was much more variable across years.

The performance of the practical closure was generally similar to that of the hotspot closure. Over all years and

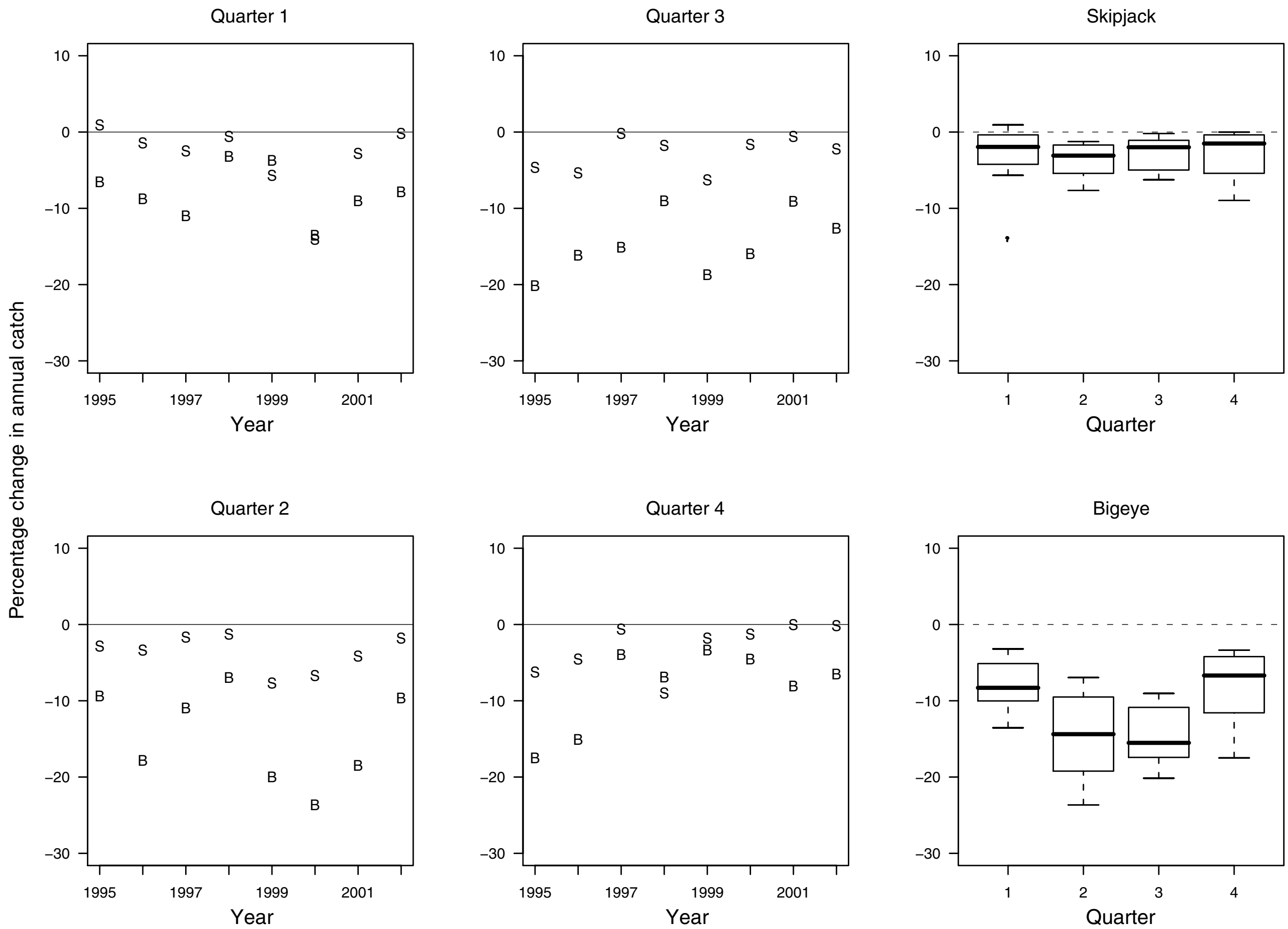


**Figure 4**

Predicted changes in annual purse-seine catches of bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*) tuna associated with a closure of the hotspot areas from Figure 1 for each quarter of the year. The left and middle panels indicate the change in annual catch for bigeye (B) and skipjack (S) tuna estimated to occur in each year of the 1995–2002 period if that area was closed in the 1st, 2nd, 3rd, and 4th quarter, respectively. The plots on the right summarize the predicted changes in bigeye and skipjack tuna catch over the eight years for a closure in each seasonal quarter. The white bar indicates the median change, the dark rectangle indicates the interquartile range (25th–75th percentiles), and the outer lines indicate the extremes. The horizontal dashed line represents zero (i.e., no change in catch).

**Table 2**

Summary of annual purse-seine effort and catch per unit of effort for bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*) tuna by set type (FOB=tuna school associated with floating object(s); UNA=tuna school not unassociated with floating object(s)) for the three areas modeled in the "practical" closure. A "practical" was a more practical, continuous region. It extended from 5°N–10°S, to 90°–120°W. The total area of this closure was the same as the total area of the hotspot regions. The means and standard deviations (SD) were calculated from annual values for 1995–2002.

| | | Number of sets | | Bigeye catch per set | | Skipjack catch per set | |
|---|---|---|---|---|---|---|---|
| Area | | FOB | UNA | FOB | UNA | FOB | UNA |
| Practical closure | Mean | 532 | 229 | 14.75 | 0.9 | 21.64 | 9.97 |
| | SD | 228 | 295 | 7 | 1.27 | 9.9 | 8.61 |
| North | Mean | 474 | 882 | 4.4 | 0.1 | 19.42 | 5.65 |
| | SD | 301 | 517 | 2.53 | 0.12 | 10.19 | 4.17 |
| South | Mean | 404 | 296 | 10.43 | 0.44 | 17.43 | 5.48 |
| | SD | 377 | 278 | 6.35 | 0.53 | 7.4 | 5.14 |

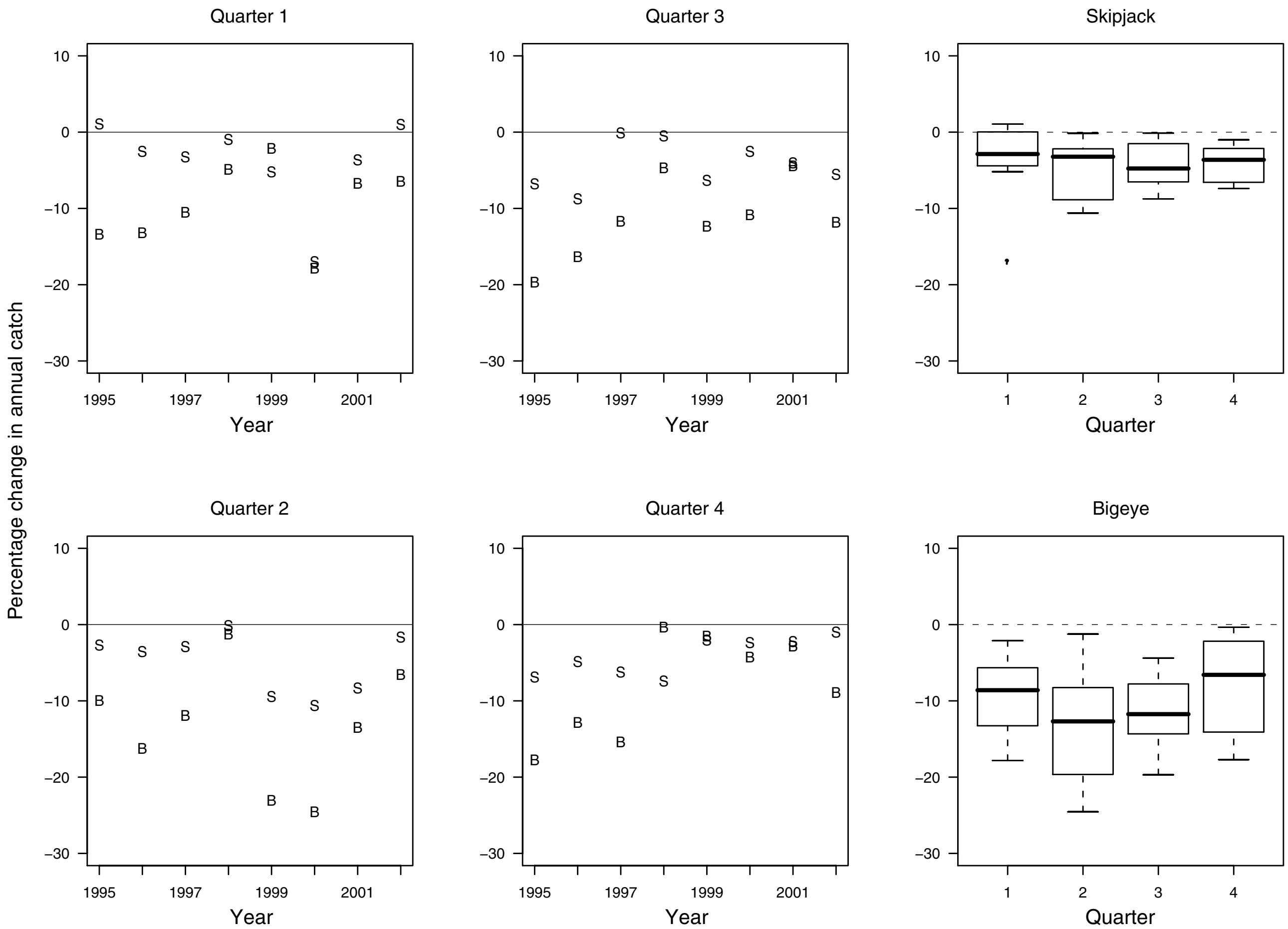


**Figure 5**

Predicted changes in annual purse-seine catches of bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*) tuna associated with a closure of the area between 5°N–10°S and 90°–120°W for each quarter of the year. See Figure 4 for further description of the panels.

quarters, the predicted reductions in bigeye tuna catches associated with the practical closure ranged from 0.3% to 24.5% (777 metric tons [t] to 20,206 t), and the change in skipjack tuna catches ranged from a 1.1% increase to a 17.0% reduction (1204 t to 32,773 t) (Fig. 5). The extreme values of skipjack tuna catch were associated with first-quarter closures. As with the hotspot closure, the greatest reductions in bigeye tuna catch were associated with second- and third-quarter closures (average reductions of 13.4% and 11.5%, respectively, across years) and again the mean reduction in skipjack tuna catches did not vary greatly across quarters (mean reductions ranging from 3.8% to 4.9%). Based on the median of the ratios, the greatest contrast between bigeye and skipjack tuna reductions was associated with a second-quarter closure; the average percentage reduction in bigeye tuna catches was 13.4%, versus 4.9% for skipjack tuna catches.

Overall, the hotspot closure predicted slightly greater reductions in bigeye tuna catches and slightly lesser reductions in skipjack tuna catches than did the practical closure, but the difference in the median of the ratios (5.0 times for the hotspot closure and 3.8 times for the practical closure) is probably not significant. Results for both closures may indicate that a closure during the second or third quarters is optimal. Because the predicted variability in performance was less for a third-quarter closure than a second-quarter closure (in both analyses), the former was preferred as a management tool.

## Discussion

Time-area closures are one of a number of fisheries management options (Hilborn et al., 2004). In our study we investigated, using simulations that use historical catch and effort data, whether time-area closures could be a useful tool to reduce bigeye tuna catches in the purse-seine fishery without leading to large reductions in the catches of skipjack tuna.

In the remainder of this article we discuss our findings in terms of the recent stock assessment recommendations for reductions in fishing effort—more specifically whether reductions predicted in our study would be sufficient to reach management objectives. We also discuss alternative measures for reducing bigeye tuna catches in the purse-seine fisheries of the EPO and describe potential improvements for our time-area closure modeling approach that may lead to a more accurate analysis of the likely performance of closures that may be considered in the future.

### Predicting performance of time-area closures

Following Hall (1996), we looked for time-area strata in which there were high bigeye tuna to skipjack tuna ratios. These areas were relatively confined geographically and did not vary greatly by quarter. For this reason, the hotspot and practical closures predicted similar results.

Simulation of a practical closure (and one that able to be implemented) indicated that moderate average reductions in bigeye tuna catch (11.5%) could be achieved with lesser average reductions in skipjack tuna catches (4.9%). When we considered these reductions in terms of total catch by weight, the annual bigeye tuna catch reductions ranged up to 20,206 t (average 5722 t) and up to 32,773 t (average 6,807 t) for skipjack tuna.

Based on the current mix of fishing gears in the bigeye tuna fisheries in the EPO, and the estimated maximum sustainable yield (MSY) of about 77,000 t (IATTC, 2004), the purse-seine share of the MSY was around 40,000 t (S. J. Harley, unpubl. data). Considering current purse-seine catches of over 60,000 t, and the 11.5% reduction predicted for the practical closure, we believe that these closures alone are unlikely to yield the required reductions in bigeye tuna catches from the purse-seine fishery.

The closures investigated in our study were based on strata where the ratio of bigeye tuna to skipjack tuna catches was the greatest. For these closures, the reduction in catches (in metric tons) is about the same for bigeye and skipjack tuna, but if a closure is larger or longer, the losses in skipjack catches would quickly outweigh the reductions in bigeye tuna catches. Therefore, although we did not examine larger or longer closures in our study, it is unlikely that these closures could lead to the necessary reductions in bigeye tuna catches without unacceptable losses in skipjack tuna catches.

The lack of effectiveness of the time-area closures is related to the extent of the interaction between skipjack and bigeye tunas. For the 1995–2002 period, 94% of the bigeye tuna caught by purse-seiners was taken in sets that also caught skipjack tuna (Table 3). This percentage is greater than the proportion of skipjack tuna catch that was taken in association with bigeye tuna (68%). Given this fact, it is not surprising that time-area closures are insufficient.

**Table 3**

Proportion of the annual floating-object fishery catches of bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*) tuna that are caught in sets with or without other species.

| Year | Bigeye tuna | | Skipjack tuna | |
|---|---|---|---|---|
| | Without | With | Without | With |
| 1995 | 0.05 | 0.95 | 0.31 | 0.69 |
| 1996 | 0.06 | 0.94 | 0.25 | 0.75 |
| 1997 | 0.05 | 0.95 | 0.25 | 0.75 |
| 1998 | 0.04 | 0.96 | 0.27 | 0.73 |
| 1999 | 0.02 | 0.98 | 0.39 | 0.61 |
| 2000 | 0.08 | 0.92 | 0.38 | 0.62 |
| 2001 | 0.11 | 0.89 | 0.44 | 0.56 |
| 2002 | 0.08 | 0.92 | 0.29 | 0.71 |
| Average | 0.06 | 0.94 | 0.32 | 0.68 |

### Management alternatives to reduce catches of bigeye tuna

We have shown that time-area closures alone are unlikely to result in the necessary reductions in fishing mortality for bigeye tuna; therefore alternative or supplementary management actions would be appropriate. In many instances, studies of fish behavior (Wardle, 1983) and gear technology (Larsen and Isaksen, 1993) have led to changes in gear configurations and deployment, resulting in significant reductions of catches of unwanted species. A good example of this type of change is the reduction of dolphin catch from tuna-dolphin aggregations in the EPO (NRC, 1997).

In the 1970s, many thousands of dolphins (mostly *Stenella* sp. and *Delphinus* sp.) were caught and killed by purse-seine vessels that set on dolphins in order to catch the yellowfin tuna that were associated with them (NRC, 1997). Through the introduction of fine-mesh net panels, use of a "back-down" procedure, and the avoidance of areas where oceanographic conditions could lead to net collapse, this mortality was reduced dramatically by the 1990s (NRC, 1997).

It is also possible to exploit behavioral differences among fish species. Through examination of the differential behavior of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), it was found that it was possible to configure bottom trawl nets to catch the target species and allow the other species to escape through larger meshes (Cotter et al., 1997). Sorting grids have also been used to allow the escape of unwanted species (Larsen and Isaksen, 1993; Misund and Beltestad[3]; IATTC[4]). Unless studies of bigeye and skipjack tuna be-

[3] Misund, O. A., and A. K. Beltestad. 1994. Size-selection of mackerel and saithe in purse seine. International Council for the Exploration of the Sea Council Meeting, 1994/B:28.

[4] IATTC (Inter-American Tropical Tuna Commission). 1999. Report of the bycatch working group, 25 p. 63rd Meeting of the IATTC; June 8–10, 1999. IATTC, 8604 La Jolla Shore Drive, La Jolla, California 92037.

havior determine a mechanism by which bigeye, but not skipjack tuna, can escape through a sorting grid in a purse-seine net, sorting grids are more likely to be useful for overall reductions in catches of small tunas than as a mechanism for reducing bigeye tuna catches without reducing skipjack tuna catches.

Lennert-Cody and Hall (2000) used a range of statistical models to determine factors (e.g., area, season, characteristics of the floating object and the purse-seine net) that were associated with higher catches of bigeye and skipjack tuna. Unfortunately, many factors were confounded because the fishing practices of the fleet often differ in time and space, making it difficult to determine which gear characteristics may be important. Thus, it appears unlikely that analysis of fishery-collected data will lead to technical measures with the potential to reduce catches of bigeye tuna.

Although it may be difficult to determine important factors relating to bigeye tuna catch rates, fisheries data can be used to examine the nature of the catches of this species. For example, we found that 94% of bigeye tuna are caught in sets that also caught skipjack tuna. We were interested in how the bigeye tuna catches were distributed; were they predominantly from a small number of sets with high catches or from a large number of sets with small catches? Our analysis of this question, based on data for 1995–2002, is presented in Figure 6. It shows than only 5% of bigeye tuna were caught in single-species sets, but that about 50% of bigeye tuna came from sets that contained at least 60% of this species. These sets are responsible for only 7% of the skipjack tuna catch from the floating-object fishery and a smaller proportion of the overall skipjack catch given that about 30% of skipjack tuna catch is still taken from schools unassociated with dolphins (IATTC, 2004).

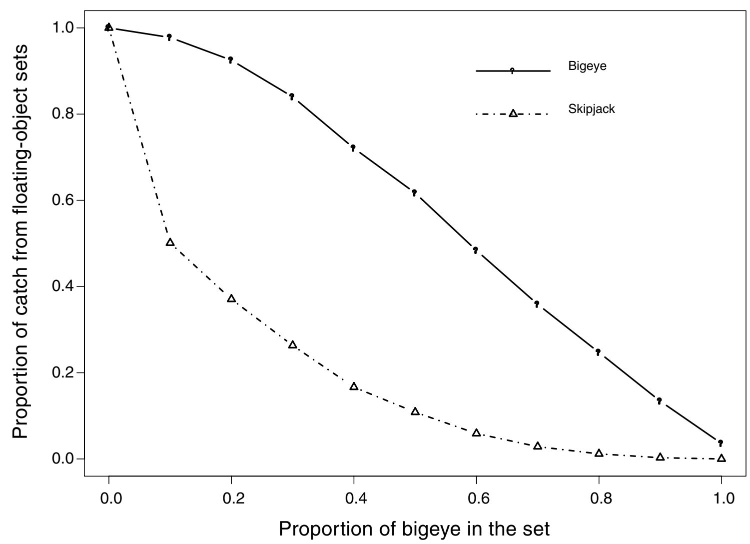


**Figure 6**

Proportion of bigeye (*Thunnus obesus*) and skipjack (*Katsuwomus pelamis*) tuna taken in sets where at least a given proportion of skipjack tuna were taken, for 1995–2002. For example, just over 60% of bigeye tuna came from sets where 50% or more of the tuna in the set was bigeye tuna, while only 15% of skipjack tuna were taken in these bigeye tuna dominated sets.

The analysis of the catch composition of purse-seine sets described above indicates that if fishing captains can determine, at least roughly, the species composition of an aggregation prior to setting (i.e., which species is dominant), large reductions in bigeye tuna catches could be achieved by not setting on bigeye-tuna–dominated aggregations. Such a measure would have little impact on overall skipjack tuna catches and would not require the fleet to be restricted in its activity by time-area closures.

Schaefer and Fuller (2005) used a range of electronic tags, supplemented with sonar images of fish aggregations around floating objects, to describe differences in the behavior of skipjack and bigeye tunas around floating objects. Exploitation of these differences, combined with the potential ability of fisherman to identify large aggregations of bigeye tuna around floating objects, may lead to the development of fishing practices that can reduce bigeye tuna catches with minimal impact on skipjack tuna catches.

Critical to this approach will be the establishment of incentives 1) to encourage both the identification of the schools and 2) not to set on bigeye-tuna–dominated aggregations. Similar to the dolphin mortality limits currently applied by the IATTC, it could also be possible to have individual vessel limits for bigeye tuna and let fishermen determine how best to modify their fishing operations in order to achieve a given limit. Harley et al.[5] used historical catch-by-vessel data and found that individual vessel limits of about 350 t would be sufficient to reduce purse-seine catches of bigeye tuna in the EPO by 50% in most years. Independent studies of fish behavior, coupled with experimental work investigating modifications in fishing practices and gear, could be fruitful.

## Modeling potential effects of time-area closures

We applied simple closed-area models that used historical catch and effort data. Several assumptions are implicit in these models. First, we assumed that the fishing fleet has the flexibility to reallocate effort out-

[5] Harley, S. J., P. K. Tomlinson, and J. M. Suter. 2004. Possible utility of catch limits for individual purse-seine vessels to reduce fishing mortality on bigeye tuna in the eastern Pacific Ocean, 8 p. Inter-American Tropical Tuna Commission, 5th working group on stock assessments, 11–13 May 2004, Document SAR-5-05 BET A. IATTC, 8604 La Jolla Shore Drive, La Jolla, California 92037.

side the closed area. We redistributed effort during the closure to other areas in proportion to historical effort within the same seasonal quarter. Previous studies have chosen not to redistribute effort (Goodyear, 1999), to redistribute effort in proportion to target catch (Worm et al., 2003), or to redistribute effort with the assumption that catch, rather than effort, is a limiting factor (Baum et al., 2003). A good understanding of fleet dynamics is necessary to determine appropriate models for effort redistribution.

Second, we assumed that redistributed effort would yield the same CPUE as previous effort in the area. Redistributed effort assumes that CPUE will remain unchanged when more fish are removed. It is likely that CPUE would decline with abundance as a result of increased effort, therefore it is possible that our analysis overestimates the catches during the closure. Similarly, our model assumes that CPUE is constant within each area, i.e. regardless of where one fishes within the area, one achieves the same CPUE. In reality, it is possible that fishermen could fish close to the edge of the closed area and potentially undermine the effectiveness of a closure.

Related to these first two points is the case of switching between fishing modes. By grouping FOB and UNA sets in our model, we allowed for switching between set types when fishing outside the closed area. Harley et al.[4] showed that the purse-seine vessels that catch the majority of the bigeye tuna, fish almost exclusively on floating-objects (over 90% of the sets). Even with this information, we still believe that the implicit assumption of grouping the two set types is acceptable. We did not consider dolphin-associated sets (that catch almost exclusively yellowfin tuna). We consider it much less likely that effort would be shifted towards dolphin-associated schools for several factors, including politics, market pressure, technological and gear differences, and the inexperience that many skippers who participate in the FOB fishery would have with this alternative mode of fishing.

Finally, we implicitly assumed in our model that fish not caught as a result of the closure could not be caught later in the year. This assumption could lead us to underestimate catches outside of the closure. Thus, we have two potential biases in opposite directions that could affect our conclusions. The best way to quantify these biases would involve a model that integrated population and fisheries dynamics.

A dynamic approach to modeling closed areas could take into account the abundance of fish in different areas and the movement of fish between areas during the year. Modeling the relationship between effort and catches in different areas should include accounting for abundance (e.g., through the use of the catch equation).

Tagging data are necessary to estimate stock parameters, such as residence times within a closed area and fish movement rates between the open and closed areas. In addition to conventional tagging data, information from electronic tagging of bigeye tuna (Schaefer and Fuller, 2002) could provide a basis for describing movement by means of simple movement models (e.g., those of Adam et al. [2003]). Because the vessels catch bigeye and skipjack tunas together, the model must include the movement patterns of both species.

This approach is extremely data demanding, and many of the data for this approach are not yet available. Notwithstanding these problems, future analysis of time-area closures should include consideration of important biological factors such as those described above, as well as socioeconomic data that may be important for predicting fleet dynamics.

Another extension of the modeling approach in our study is to consider additional target and bycatch species. Worm et al. (2003) considered bycatch from the United States swordfish and tuna longline fisheries in the Atlantic when modeling closed areas. With this approach it would be useful to include not only yellowfin tuna and dolphin sets in the model, but also the bycatch species that are taken in the different areas and fisheries.

## Conclusions

Time-area closures are one of the many management actions available for the regulation of fisheries. Because of the strong interactions between bigeye and skipjack tunas, we have shown that time-area closures alone are unlikely to be sufficient to address concerns regarding the sustainability of bigeye tuna because it may not be possible to achieve the necessary reductions in bigeye tuna catches without large losses in skipjack tuna catches. We suggest that it will be important to investigate aspects of fish behavior to determine measures that could be used either in conjunction with, or instead of, closures to help reduce mortality on juvenile bigeye tuna while sustaining the important skipjack fishery.

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