Abstract—Billfishes are a component of offshore ecosystems; thus it is important to quantify the impact of the tuna fishery on these species in the world's ocean. The aim of this study was to assess the bycatch of billfishes generated by the tropical tuna purse-seine fishery in the eastern Atlantic Ocean. Information on bycatch was collected by observers at sea during the European Union Bigeye Program. With a total of 62 observers' trips, conducted on Spanish and French vessels between June 1997 and May 1999, this project is the biggest observer program ever carried out in the European tuna purse-seine fishery. This study showed that billfish bycatch by the purse seiners is very low (less than 0.021% of the total tuna catches and less than 10% of the total billfish catches currently reported). A Monte Carlo simulation was performed to account for some uncertainties in the fishing strategies of purse seiners operating in this ocean. One of the findings of this study indicated that the temporary moratorium on fishing with FADs (fish aggregating devices), adopted by the European purse-seine fishery in the eastern Atlantic Ocean, produced a decrease in incidental catches of marlins from 600–700 metric tons (t) to less than 300 t. In contrast, this trend was reversed for sailfishes, for which the bycatch increased from 25 t to 45 t. The difficulty of defining indices that express the conservation status in marine fishes and that gauge key ecosystem parameters and the need to promote an ecosystem approach for large-pelagic-resource management which takes into account biologic and socioeconomic criteria are briefly discussed.

Manuscript accepted 27 May 2002.
Fish. Bull. 100:683–689 (2002).

Bycatch of billfishes by the European tuna purse-seine fishery in the Atlantic Ocean

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In the spirit of the code of conduct for responsible fisheries it is important to quantify discards and bycatches taken by the main fishing fleets in the world's ocean. Despite recommendations made by different fishery agencies, such as the tuna commissions, this information is rarely reported by skippers in their commercial logbooks. Thus the level of catches of billfishes taken incidentally by the tropical tuna purse-seine fishery is not well-known. In contrast to the recreational fishery, or to some specific small-scale fisheries, billfishes are not targeted by the purse-seine fishery but they can be taken incidentally during the setting operation. In the eastern Atlantic Ocean, parts of bycatch, including billfishes, are kept and are sold in the local African fish market (Romany et al., 2000).

The purpose of this study was to estimate the amount of billfish taken as bycatch by fishing modes (i.e. by FAD [fish aggregating devices] sets, school sets [sets without the use of FADs], and seamount sets) and as bycatch by the Spanish and the French purse seiners in the eastern Atlantic Ocean. Because bycatch information is not recorded in commercial purse seiner logbooks, observations collected by scientific observers aboard purse seiners appeared to be a useful way to assess the amount of bycatch taken by this fleet. Although the European Union Bigeye Program focused on the study of the increase in catch of bigeye tuna (*Thunnus obesus*) by the European tuna-purse seiners in the Atlantic Ocean (Ariz and Gaertner, 1999), information on bycatch was also collected by observers on these purse seiners. We used this data set to estimate the bycatch of billfish in the European purse-seine fishery. These estimates will contribute to the calculation of the total bycatch of billfishes taken in the Atlantic Ocean.

Materials and methods

Data

A total of 62 observer trips (44 for the Spanish fleet and 18 for the French fleet) were conducted opportunistically between June 1997 and May 1999, except from November 1998 through January 1999, a period when there was a moratorium on the use of FADs in fishing operations. In spite of this limitation, this project was the largest observer program ever carried out in the European tuna purse-seine fishery (a total of 2706 fishing days, with 1884 observed sets). The catch of commercial tunas reached 34,693 t, whereas discards (composed mainly of small tuna species or of juveniles of commercial tuna species) were estimated at about 737 t and total bycatch (billfishes,

Table 1

Probabilities of setting with a specific fishing mode k (observed values for a standard year with moratorium and averaged values for a standard year without moratorium; see explanations in the text) and observed conditional probabilities that a specific group of billfish s is associated with this fishing mode. These values were used to perform the Monte Carlo simulation. School sets were made without FADs.

		Prob. {fishing mode=k}		Prob. {s present | k}	
Fishing mode	Number of observed sets	Moratorium	Without moratorium	Marlins	Sailfishes
FAD sets	373	0.2932	0.5500	0.3539	0.0134
School sets	859	0.6753	0.4185	0.0408	0.1036
Seamount sets	40	0.0315	0.0315	0.2500	0.0750

sharks, other fish, etc.) at about 762 t (Ariz and Gaertner, 1999).

Based on the ecological provinces in the oceans established by Longhurst (1998), the eastern tropical Atlantic Ocean (from 25°N to 15°S and from 35°W to the African coasts) was stratified by quarters into two areas:

the Senegalese area (from latitude 12°N to 25°N),
the remaining areas, termed "equatorial" areas.

Owing to time constraints during the set (and bearing in mind that this program was directed at bigeye tuna), it was very difficult for the observer to accomplish some additional bycatch tasks. Consequently, in some circumstances the billfish species may not have been correctly identified. For this reason we established two groups; the blue marlin (*Makaira nigricans*) and the white marlin (*Tetrapterus albidus*) in one group and the sailfishes (*Istiophorus albicans*) and the longbill spearfish (*T. pfluegeri*) in the second group. The weight ranges of billfishes captured as incidental catch by the purse seiners were approximately 130–150 kg for blue marlin, 10–20 kg for sailfish and 45–70 kg for nonidentified marlins (there were no weight estimates for white marlin and longbill spearfish because of their low numbers in the bycatch).

On the basis of a study made on tuna size classes by set type in this fishery (Pallares and Petit, 1998), the sets made on whales and on whale sharks (*Rhiniodon typus*) were classified as school sets (i.e. sets made without FADs) and as FAD sets, respectively. In contrast, it must be stressed that seamounts constitute a specific environment for small size classes of tuna species. In the Atlantic Ocean 2000–3000 t of tunas can be taken yearly on some seamounts (Fonteneau, 1991). Because large pelagic species can be concentrated on seamounts (e.g. sphyrnids, Klimley et al., 1988), we distinguished the sets made on seamounts from the usual tuna fishing modes (i.e. school sets and FAD sets).

Methods

For the two groups of billfishes (i.e. sailfishes and marlins) the total bycatch taken by the European tuna purse-seine fishery in the eastern Atlantic Ocean was estimated for a period of 12 months. The period between October 1997 and September 1998 was considered the best representative standard year for the observer program because it included the best coverage in terms of tuna catches (approximately 17% of the total tuna catch is taken by the European purse seiners from October 1997 to September 1998). Assuming that billfish bycatch was proportional to the tuna catch, the observed bycatch for each billfish group was raised to the total European purse-seine catch with the use of a raising factor RF_{sijk} as in the following equation:

$$TBC_s = \sum_k \sum_j \sum_i RF_{sijk} BC_{sijk},$$

where TBC_s = total bycatch for the group s during a standard year;
RF_{sijk} = total purse seine tuna catch$_{ijk}$/observed aboard purse seine tuna catch$_{ijk}$;
BC_{sijk} = bycatch for the group s, in area i, quarter j, and fishing mode k;
and i = 1, 2; j = 1, 2, 3, 4; k = school set, FAD set, set on seamount.

Sources of uncertainty in the calculation of the billfish bycatch are caused by 1) changes in fishing strategies adopted by the fishermen over the year, e.g. the probability of choosing the fishing mode k and 2) some features of the bycatch species, e.g. the conditional probability for a given group of billfish s to be present in a set of type k, as well as the probability of obtaining x tons of group s in the set (Table 1). To account for some of these uncertainties our approach differed from that of Perkins and Edwards (1996), who used a modified negative binomial distribution to model bycatch per set. We used computer-intensive methods, such as a Monte Carlo simulation, to estimate the total bycatch generated by the European tuna purse-seine fishery. Monte Carlo methods of simulation introduce a large number of random inputs into a model while recording the range of outputs (Gaertner et al., 1996; Shelton et al., 1997).

In the present analysis, the model mimics the fishing operations made by the purse seiners over a standard

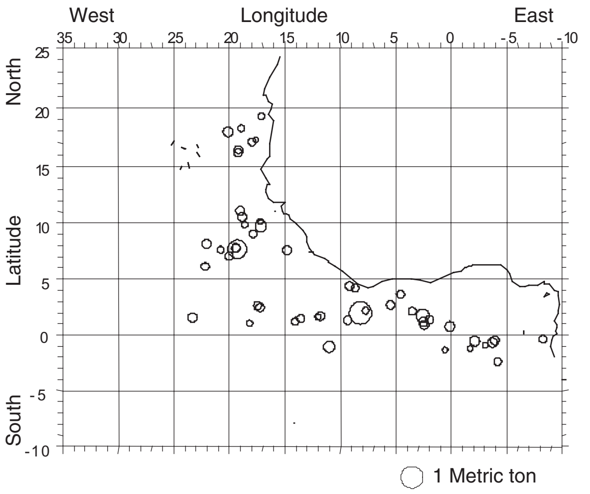

Figure 1

Spatial distribution of the bycatch (t) per school set for the marlin group from the observers' trips during the European Union bigeye tuna program.

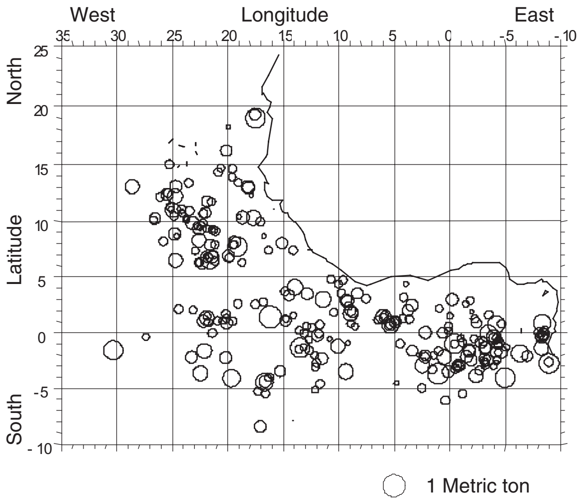

Figure 2

Spatial distribution of the bycatch (t) per FAD set for the marlin group from the observers' trips during the European Union bigeye tuna program.

year. That means that we take into account the probability of setting on the fishing mode k, and the conditional probability that group s is present in this type of set. For each group s, the simulated input (i.e. the bycatch generated by one set) is drawn from the observed distribution of the bycatch by set for the fishing mode k. Note that the calculation of the total bycatch is based on the proportion of total sets (including those made on trips without observers at sea) recorded in commercial logbooks in each strata by fishing mode. That means that the observed bycatch in each set was previously raised by the corresponding raising factor: RF_{ijk}. A single set is then generated by randomly selecting inputs from the distributions of bycatch per set. This is repeated 1272 times (the total number of sets reported by observers aboard) to give the total bycatch of group s during the standard year. 500 Monte Carlo simulations were generated to determine the amount of variation expected in the yearly bycatch estimates. Confidence limits for total bycatch by group were performed by the percentile method.

However, the results obtained in our study may have been affected by the moratorium on fishing with FADs adopted by the French and the Spanish tuna purse-seine companies in the eastern Atlantic Ocean. This temporary ban was adopted over a large area from the African coast to 20°W and from 5°N to 4°S, between 1 November and 31 January in 1997–98 and in 1998–99, respectively. With this consideration in mind, the Monte Carlo simulation was performed a second time to simulate a standard year without a moratorium. We assumed that the probability of setting on FADs (estimated at 0.293 during a year with a moratorium) increases to 0.55 during the years without a moratorium (estimated from commercial logbooks). Consequently, the second Monte Carlo simulation was conducted with the following probabilities: 0.55 (for FAD sets), 0.419 (school sets) and 0.031 (for seamount sets, assuming that the percentage of sets made on seamounts was not affected by a ban on fishing on logs, Table 1).

Table 2

Estimated bycatches of billfishes (t) and observed commercial tuna catches (t) taken by fishing modes by the European purse seiners in the eastern Atlantic Ocean for a standard year (October 1997–September 1998). School sets were made without FADs.

Fishing mode	Marlins	Sailfish	Tuna catches
FAD sets	200.8	7.6	49,214
School sets	42.8	34.7	88,456
Seamount sets	1.5	0.1	1,285
Total	245.1	42.4	138,955

Results

Table 2 shows the estimated bycatch of billfishes taken by each fishing mode during a standard year. The results indicate that 245 t marlin and 42 t sailfishes were taken as bycatch by the European purse seiners in the eastern Atlantic Ocean. Figures 1 and 2 depict the spatial distribution by fishing modes of the marlin bycatch in the eastern Atlantic for all data collected during the observer program. Figure 2 shows that marlin bycatch in FAD sets were spread across a large area in the eastern Atlantic Ocean. When compared to FAD sets, the occurrence of marlins bycatch in school sets was lower, specifically in central

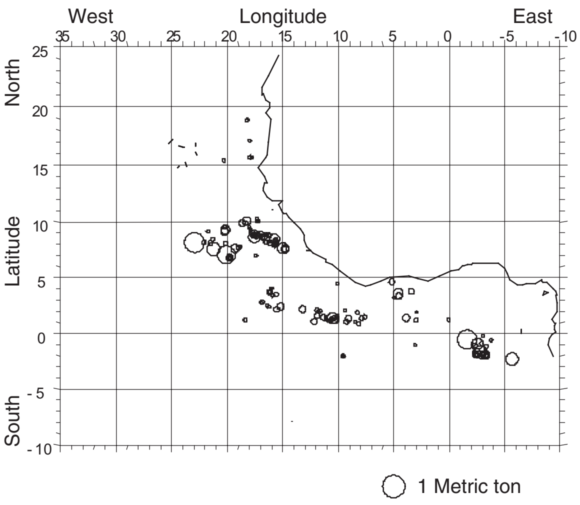

Figure 3

Spatial distribution of the bycatch (t) per school set for the sailfish group from the observers' trips during the European Union bigeye tuna program.

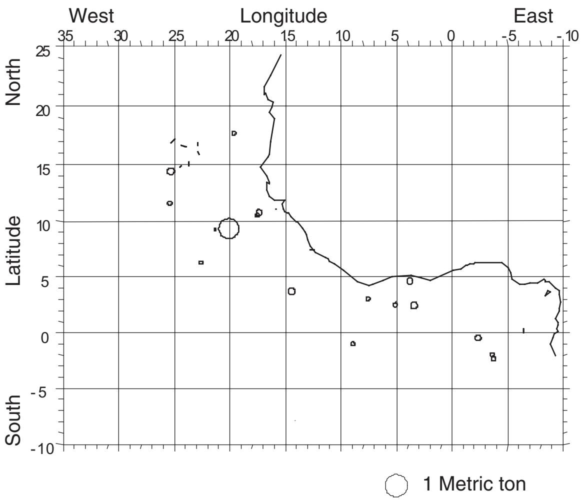

Figure 4

Spatial distribution of the bycatch (t) per FAD set for the sailfish group from the observers' trips during the European Union bigeye tuna program.

Table 3

Results of the Monte Carlo simulation for a standard year with and without a moratorium on FAD sets. Monte Carlo estimates are the average bycatch (t) taken by the European purse seiners in the eastern Atlantic Ocean and the confidence intervals (CI, in tons). "The ratio of billfish to tuna" is the ratio of billfish bycatch to tuna catch (in tons), and corresponding confidence intervals.

	Marlins		Sailfishes	
Group case	Moratorium	Without moratatorium	Moratorium	Without moratorium
Monte Carlo estimates (t)	238.79	396.38	37.52	14.86
Lower CI 0.025	192.86	338.25	23.22	2.89
Upper CI 0.975	283.51	450.54	53.91	33.38
Ratio of billfish to tuna	1.718E-03	2.853E-03	2.700E-04	1.069E-04
Lower CI 0.025	1.388E-03	2.434E-03	1.671E-04	2.076E-05
Upper CI 0.975	2.040E-03	3.242E-03	3.879E-04	2.402E-04

tropical areas. If we compare the spatial distribution of the sailfishes with the spatial distribution of the marlin, we find that the bycatch of sailfishes was associated more with school sets than with FAD sets (Figs. 3 and 4). However, the "sampling scheme" adopted for assessing these incidental catches was constrained by the purse seiners' fishing-effort distribution. Consequently, because purse seiners move seasonally from one area to another, there is a lack of information about the presence of billfishes when the fishing area is temporarily abandoned.

In both runs of the Monte Carlo simulation we used the same conditional probability about the presence of each billfish group by fishing mode (Table 1), as well as for the observed distribution of the bycatch per set by fishing mode. Results indicated that the bycatch of marlins decreased during the moratorium from 396 t to 289 t (Table 3 and Fig. 5). This result is a consequence of the larger association of marlins with floating objects than with school sets. In looking at Table 1, we can see that the occurrence of marlin was around 35% for FAD fishing operations compared to only 4% for school sets. Marlin were also present in 25% of the seamount sets but, from the small number of sets made on seamounts, we could not determined any apparent effect on the total bycatch for this group. Sailfishes were more commonly observed in school sets than in FAD sets (Table 1). Thus it appeared that the bycatch of sailfish increased from about 15 t to 38 t with a moratorium on FADs, as summarized in Table 3 and Figure 5.

Table 4

Estimates of the total bycatch (t) taken by the entire purse-seine fishery in the eastern Atlantic Ocean based on the results of the Monte Carlo simulation applied to the European purse seiners. Because of the moratorium on FAD sets, a decrease of the percentage of FAD sets was assumed for the last three years.

		Marlins			Sailfishes		
Year	Total tuna catch (t)	Estimated bycatch (t)	Lower CI 0.025	Upper CI 0.975	Estimated bycatch (t)	Lower CI 0.025	Upper CI 0.975
1990	211,882	604.50	515.72	686.92	22.65	4.40	50.89
1991	246,110	702.15	599.03	797.89	26.31	5.11	59.12
1992	204,040	582.13	496.63	661.50	21.81	4.24	49.01
1993	249,086	710.64	606.28	807.54	26.63	5.17	59.83
1994	225,646	643.77	549.22	731.54	24.12	4.68	54.20
1995	218,735	624.05	532.40	709.14	23.38	4.54	52.54
1996	194,173	553.98	472.62	629.51	20.76	4.03	46.64
1997	168,826	290.04	234.33	344.41	45.58	28.21	65.49
1998	172,478	296.32	239.40	351.86	46.57	28.82	66.90
1999	157,933	271.33	219.21	322.18	42.64	26.39	61.26

Introducing some elements of uncertainty in the inputs highlighted the large variability of the bycatch estimates (see the values obtained for the lower and upper CI [confidence intervals]; Table 4.). However, even including uncertainty in the inputs, these values remained very low compared with bycatches reported from other fisheries. Based on these results, the total bycatch of billfishes taken by the entire purse-seine fleet operating in the eastern Atlantic was tentatively estimated. This calculation is supported by the facts that 1) the European fleet is the main component of the purse-seine fishery operating in this part of the ocean and 2) it is reasonable to assume that other fleets of purse seiners adopted the same fishing strategies as the European fleet. With this approach, the ratio of the billfish bycatch per tons of tunas (obtained from the European fleet; Table 3) was raised to the total tuna catch taken by the entire purse-seine fishery (Table 4). To account for the change in fishing strategies caused by the ban on FAD fishing operations, we performed new billfish ratio estimates for the years 1997, 1998, and 1999. These results give an indication of the bycatch of billfishes in the eastern Atlantic purse-seine fishery (Table 4).

Discussion

The ecosystem approach to assessing and managing large coastal marine ecosystems has been developing since the early nineties (Sherman and Duda, 1999). To date, with the exception of the central Pacific Ocean (Kitchell et al., 1999), this approach generally has not been used for monitoring large pelagic fisheries in offshore waters. Our study, in presenting data on bycatch of billfishes taken by the tuna purse-seine fishery, helps to extend this approach to the monitoring of the eastern Atlantic epipelagic ecosystem.

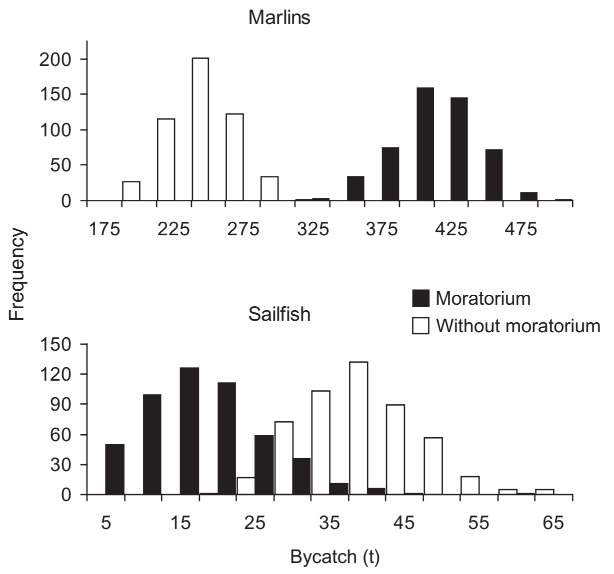

Figure 5

Histograms of Monte-Carlo-generated total billfish bycatch (marlin group in the upper histogram and sailfish group in the lower histogram) taken by the European Union tuna purse-seine fishery, taking into account whether a moratorium on FAD fishing was applied or not, in the eastern Atlantic Ocean.

A purse-seine fishery cannot be assessed purely in terms of the tuna catch. In the eastern Atlantic Ocean, it can be assumed that the large catches of tunas taken by the purse seiners (around 200,000 t per year in the last decade, Table 4) affect the abundance of billfishes 1) directly, by generating bycatch and 2) indirectly, by increasing or decreasing the abundance of predators or competitors, thereby changing the ratio of predators to prey in the trophic chain.

That the bycatch of Istiophoridae represents less than 0.021% of the total tuna catch and less than 10% of the total catches of billfishes currently reported for the eastern Atlantic Ocean (assumed to fluctuate around 7000–8000 t per year) suggests that the direct impact of the purse-seine fishery on these stocks is weak. By comparison, previous research has shown that the discards of small tunas and the total bycatch (billfishes, sharks, other fishes, etc.) generated by this fishery were close to 2% and 1.9%, respectively (Ariz and Gaertner, 1999). Compared with the longline fishery, the European tuna purse-seine fishery generates less bycatch of billfishes than the longline fisheries targeting tuna (Matsumoto and Miyabe, 2000; Gonzalez Ania et al., 2001), swordfish (Mejuto et al., 2000), or both species (Cramer, 2000; Marcano et al., 2000).

One of the more general implications of our findings concerns the impact of the ban of FADs by the purse-seine fishery on the bycatch of Istiophoridae. Our analysis suggests that this moratorium led to a decrease in incidental catch of marlin from 600–700 t to less than 300 t. In contrast, this trend was reversed for sailfishes, but the corresponding bycatch increased only from 25 t to 45 t. Because in the present study we did not take into account different probabilities (see Table 1) for each strata, it could be argued that the Monte Carlo simulations lead to only a partial exploration of the uncertainty in the calculation of the total billfish bycatch. However, it would be interesting to consider this source of uncertainty in the future. Consequently, the potential for possible regulations at different spatial and temporal scales needs further exploration.

Large bycatches of billfishes could affect the food web of the epipelagic ecosystem inhabited by other apex predators. However, the "zero bycatch solution" propounded by some environmentalist groups could accelerate the change in biomass ratios between the different trophic levels of the ecosystem. In a critique of the conventional risk factors (e.g. biological reference points) used to define the risk of extinction in marine fishes, Musick (1999) introduced other interesting criteria, such as rarity of a species, the small distribution range of a species, endemic species, and specialized habitat requirements. As can be seen in Figures 1–4, the range of spatial distribution of the billfishes is very large. It could be argued that billfishes are relatively widespread but occupy very specific habitats within their range, and as a consequence, habitat loss could be examined as a risk factor. However there is no clear evidence to support this hypothesis for billfishes.

The difficulty of objectively measuring an ecological risk when it concerns unexploited components of the ecosystem must be stressed because of the vagueness of this concept (Antoine et al., 1998). As a consequence, estimating the ecological risk is reduced to the analysis of the impact of a fishing practice on a limited number of symbolic species (e.g. dolphins, sea turtles; Hall, 1996). Nevertheless, there is no reason to believe that these charismatic species play a larger role in the food web of the epipelagic ecosystem than other targeted or nontargeted species. As shown by Kitchell et al, (1999), there was no clear conclusion on the ecological role of apex predators (including billfishes) in foods webs of the central North Pacific. Furthermore, if a decision is made to reduce the ecological impact of the bycatch in a given fishery, management actions cannot be focused only on providing full protection for a single species (Hall, 1996). Although everybody understands what "ecosystem overfishing" means, Murawski (2000) highlighted the lack of consensus for defining this concept and suggested the need for objective metrics that gauge properties associated with the main features of the ecosystem (e.g. production, diversity, and variability).

In addition, decision makers need to evaluate management options that are both scientifically credible and economically practical regarding the use of the ecosystems. Because billfishes are sold on the local African fish market (Romany et al., 2000), the effects of the fishing on the ecological processes, as well as on human activities, must be evaluated. Although in the past the regulatory process did not account for sharing of gains nor the social costs associated with fishing practices (Antoine et al., 1998), evidence suggests that the ecosystem approach for managing marine resources should also include these socioeconomic considerations in a multicriteria analysis (Chesson et al, 1999, Sherman and Duda, 1999).

Conclusion

This study examined the bycatch taken by the European tuna purse-seine fishery in the eastern Atlantic Ocean. Results obtained from this fleet have been extrapolated to the entire purse-seine fleet operating in the same areas of this ocean. The main conclusion of this paper is that the direct impact of the purse-seine fishery on the billfish component of the epipelagic ecosystem is weak. Results of this study provide additional information on the effect of the moratorium on FAD fishing. Although some caution is required at this stage, due to limitations of the spatial and temporal sampling coverage, it was found that the ban on FAD fishing operations led to a substantial decrease in marlin bycatch.

The present state of knowledge allows us to reach only preliminary conclusions. However, it should be borne in mind that inadequate data can lead to the formation of misguided policies. It is clear that detailed information on bycatch is needed to counter the arguments of those who propose total bans on some fishing practices. Consequently tuna commissions must continue to pay attention to the collection of bycatch statistics and must encourage fishermen to report incidental catches in their logbooks, at least by large taxa (e.g. billfishes, sharks, etc.). In order to use accurate information for management purposes, we recommend that data from regularly conducted observer programs be used as part of any future research.

Acknowledgments

This research was funded in part by the European Commission (DG XIV) research project n° 96/028: "A study of the causes of the increase in the catches of bigeye tuna by the European purse-seiner tuna fleets in the Atlantic Ocean." This study would not have been possible without the help of the Spanish and French tuna companies and the skippers and crews who accepted observers aboard.

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