The development of the purse seine fishery on drifting Fish Aggregating Devices in the Eastern Pacific Ocean: 1992-1998

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Abstract

Since the early 1990s, drifting Fish Aggregating Devices, or FADs, have rapidly become the dominant type of floating object used by the purse seine fishery in the Eastern Pacific Ocean to capture tunas. The development of this fishery for larger vessels is described using data collected by observers aboard vessels of more than 363 metric tons fish-carrying capacity. Bamboo rafts, equipped with radio-transmitters that allow for semi-continuous monitoring, are typically used as FADs. Old purse seine netting is often suspended below the bamboo raft to give the FAD an enhanced underwater profile. Similar to the fishery on flotsam between 1992-1998, most sets on FADs were made before 8 am, with skipjack and bigeye being the dominant tuna species caught, and yellowfin tuna captured in lesser amounts. Discard ratios of skipjack and bigeye were comparable for the two modes of fishing; however, the success rate on FADs for bigeye was more than twice that on non-FAD floating objects ("logs"). In addition, the fishery on logs was largely a coastal fishery, while the fishery on FADs extended west to 150°W, into areas that had not been significantly utilized by the purse seine fleet. The capture of tunas per set varied most with area, season and year. Nonetheless, capture per set for at least one of the three tuna species was also found to vary with the depth of the purse seine net and the amount of the netting hanging below the FAD. The effect of net depth and FAD depth on tuna capture varied by area, season and FAD color.

Introduction

The Eastern Pacific tuna purse seine fishery replaced the baitboat fishery in the late 1950s to more effectively exploit yellowfin *(Thunnus albacares)*, skipjack *(Katsuwonus pelamis)*, and bigeye *(Thunnus obesus)* tunas. There are three main methods of detecting tuna schools that lead to three types of sets (a set is the operation of deploying the net around a school). A school of tunas may be detected by evidence of its presence on the surface of the water ("school set"; Scott, 1969; Hall *et al.*, 1999a). Schooling tunas, primarily yellowfin tuna, may be detected in association with dolphin herds ("dolphin set"), particularly spotted *(Stenella attenuata)*, spinner *(S. longirostris)* and common *(Delphinus delphis)* dolphins (Perrin, 1968; Anon., 1989; Hall *et al.*, 1999a). Schools of tunas may also be found associated with floating objects (Greenblatt, 1979; Hall *et al.*, 1999a). Floating objects include parts of trees, plant material, human-originated flotsam and FADs (Greenblatt, 1979; Hall *et al.*, 1999b). We define a FAD to be any floating object that has been constructed or modified by fishermen.

In the late 1980s, the fishery on floating objects in the Eastern Pacific Ocean (EPO) was a coastal fishery, based mostly on natural objects (e.g., tree trunks, kelp patties) and on human-originated flotsam coming from coastal cities and shipping lanes (e.g., wooden pallets, tires) (Greenblatt, 1979; Hall *et al.*, 1999b). Between 1987 and 1990, less than 10% of the observed sets on floating objects were FAD sets (Hall *et al.*, 1999b). Floating objects encountered at sea were typically modified by fishermen and then redeployed as FADs. In contrast to FAD fisheries in other oceans which utilize anchored FADs (Aprieto, 1991; Polovina, 1991; Cayré, 1991), only drifting FADs have been routinely used by the fishermen in the EPO. Since 1992, there has been an almost three-fold increase in the number of sets on floating objects by vessels with greater than 363 metric tons (mt) fish-carrying capacity, whereas the number of dolphin and school sets made by larger vessels did not show the same overall trend (fig. 1). The composition of floating object sets during this time period changed from approximately 30% FAD sets in 1992 to over 80% in 1998 (fig. 2).

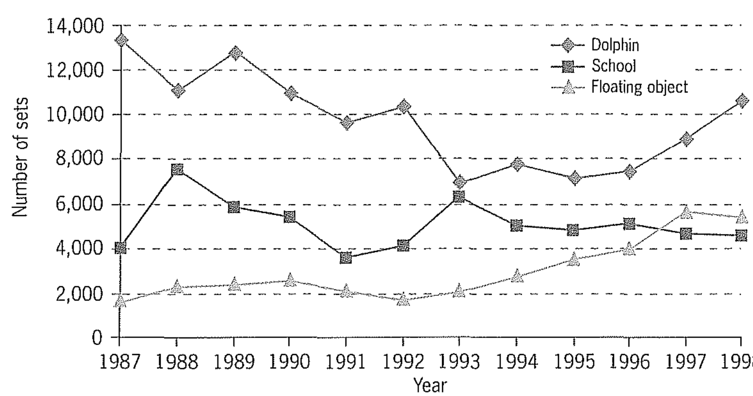
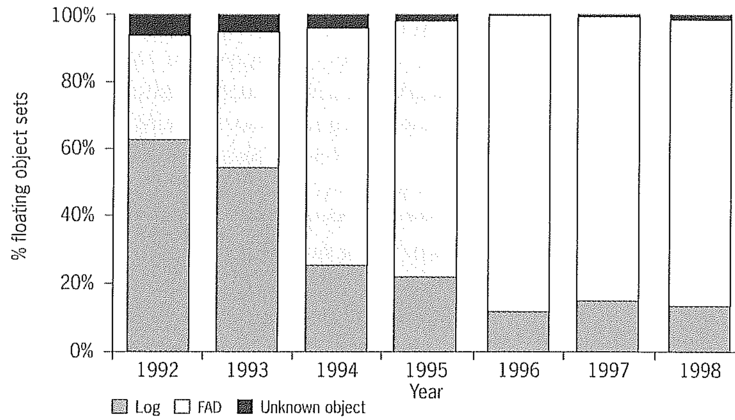


Figure 1
Total number of sets by set type for vessels with more than 363 mt fish-carrying capacity, 1987-1998.

In this paper, we describe the FAD fishery in the EPO from 1992 through 1998 for large vessels, including tonnage of tunas captured (tonnage of fish encircled with the purse seine net), spatial distribution of sets, percentage discards of tuna species, tuna captures in repeated sets on the same FADs and length-frequency distributions of the tunas landed. We also explore variability in capture per set of the three target species of tunas due to area, season and characteristics of the FADs.

Figure 2
Percentage of floating objects sets that were FAD sets, log sets and unknown floating object sets for vessels with more than 363 mt fish-carrying capacity, 1992-1998.



Data sources

Most of the data presented in this paper were collected by observers of the Inter-American Tropical Tuna Commission (IATTC) aboard vessels of the international purse seine fleet with fish-carrying capacity of more than 363 mt in the EPO. From 1992 to 1998, over 85% of the floating object sets made by such vessels were observed by IATTC observers, and, for over 95% of these sets, data were recorded about the characteristics of the floating objects. The number of floating object sets observed by IATTC observers aboard larger vessels, by year, were 1,542 (1992), 2,025 (1993), 2,614 (1994), 3,227 (1995), 3,908 (1996), 5,439 (1997), and 5,346 (1998). Length-frequency data were collected by IATTC staff at the time of vessel unloading (Tomlinson *et al.*, 1992). These data represent predominantly larger vessels. Estimated length frequencies were computed from the observed distributions of sizes by weighing the estimated catch. The total number of sets, by set type, for larger vessels were computed using both IATTC observer data and data collected by observers of the Programa Nacional de Aprovechamiento del Atún y Protección de Delfines of Mexico aboard Mexican-flag vessels.
Tons of tuna captured were used in all analyses of tuna catch. We have used tons of tunas captured, as opposed to tons of tuna loaded into the vessels' wells, because we believe that capture better reflects the effect of the fishery on the environment. Loaded weights are not only a function of the capture, but also market prices, species composition, fish size and perhaps vessel carrying capacity. The difference between capture and loaded weights is the amount of tuna discard. Discards primarily represent tonnage of tunas returned to the ocean; however, some "discards" can be fish that were given to another vessel. In 1997, IATTC observers began recording the fate of all discards. All weights were estimated by the observers and are therefore subject to error. We use the tuna species identification made by the observers without correction; the data presently available allow us to verify or correct species identifications on a per-set basis. Methods

to improve species identification, particularly of yellowfin and bigeye tunas, are currently being explored.

The FAD fishery

From 1992 to 1998, the purse seine fishery on FADs expanded from a largely coastal fishery to 150°W longitude on both sides of the equator (fig. 3), an area that had not been significantly utilized previously (Watters, 1999). The expansion of the FAD fishery at low latitudes and west of the Galapagos Islands began around 1994.

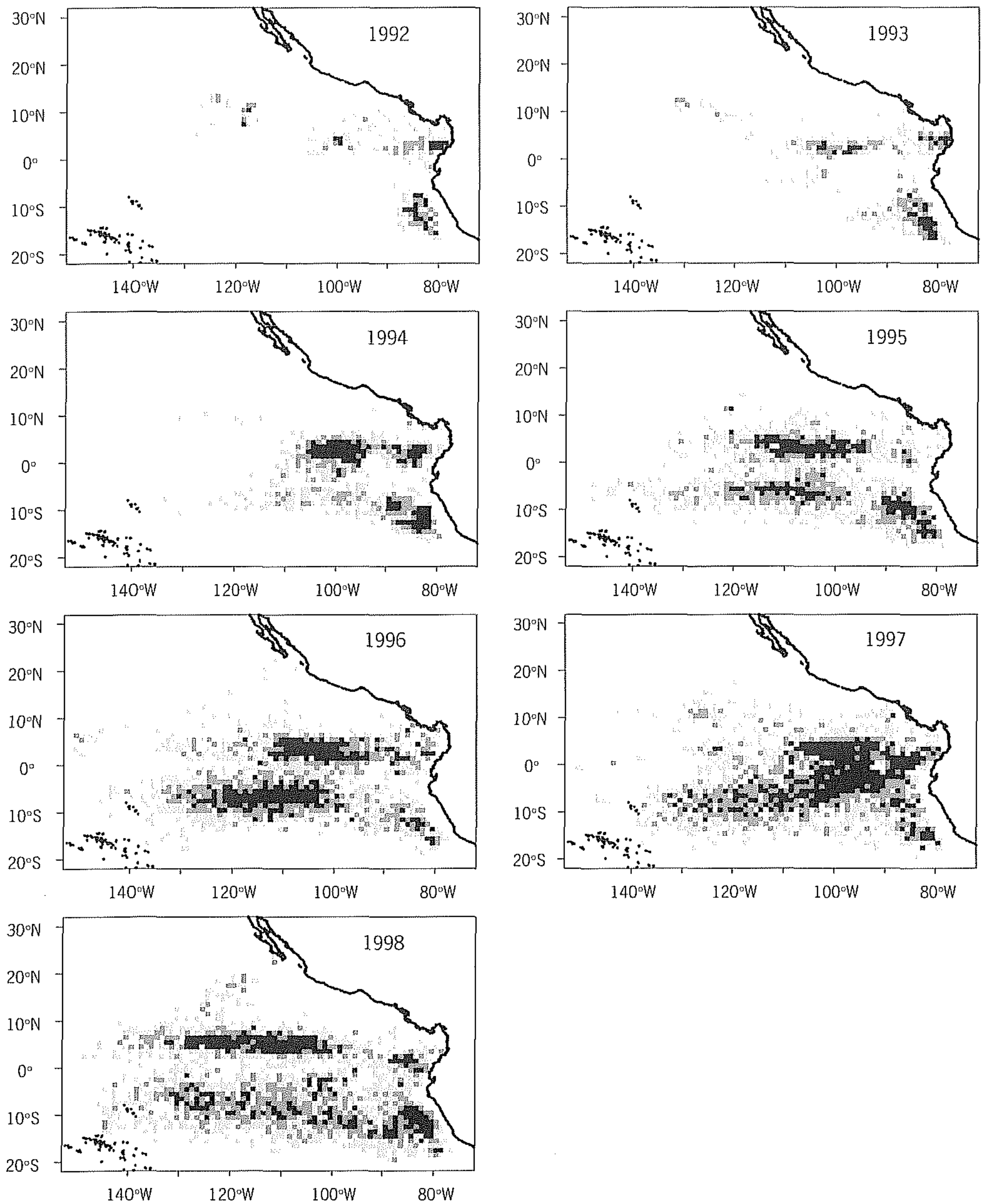


Figure 3
Number of FAD sets by year by 1° square, for 1992-1998. Light gray: 1-2 sets; intermediate gray: 3-5 sets; black: ≥ 6 sets.

Since 1995, FAD sets have been made predominantly in two latitudinal bands: one band extends along ~2°-7°N, the other band extends along ~4°-10°S. However, inter-annual variability in the spatial distribution of FAD sets is evident (fig. 3), possibly influenced by the El Niño conditions present in 1997. The spatial distribution of FAD sets also varied seasonally. Within the two latitudinal bands, most FAD sets (78%) made north of 0° occurred in the latter half of the year, and most FAD sets (90%) made south of 0° between the Galapagos and the coast occurred in the first half of the year. FAD sets made west of the Galapagos and south of 0° were more uniformly distributed throughout the year. Log sets overlapped spatially with FAD sets predominantly in the coastal areas of the Panama Bight and offshore of Peru (fig. 4). In contrast, dolphin sets were made predominantly north of 5°N, with the majority of sets occurring between 7° and 15°N, and school sets were made predominantly in coastal areas off Mexico, Colombia and Ecuador (fig. 5).

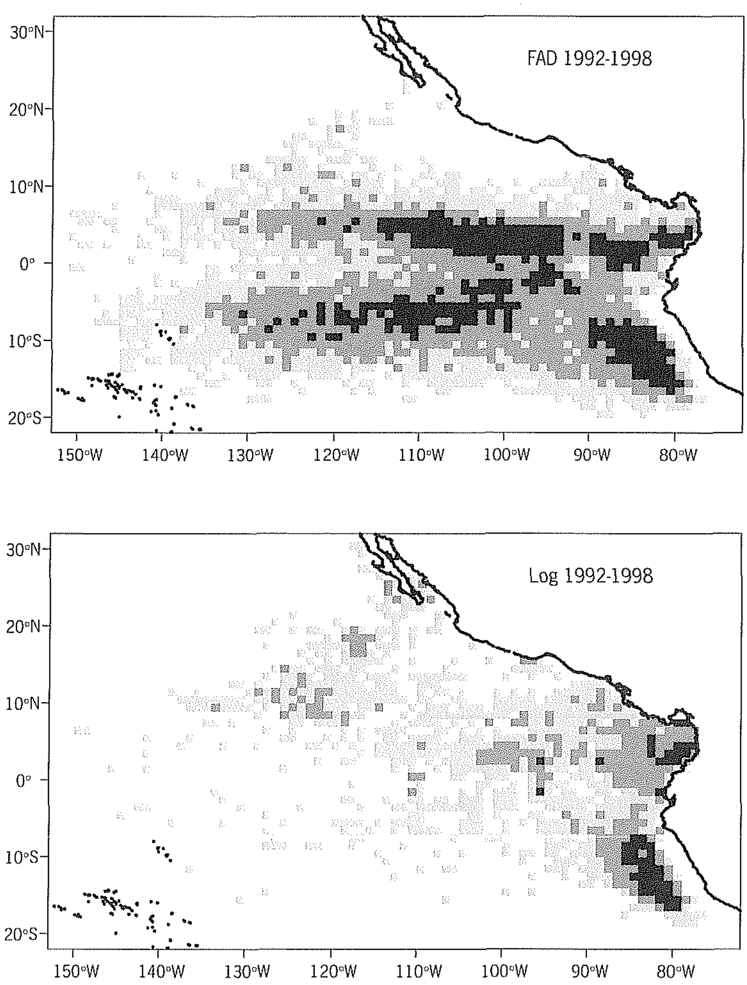


Figure 4
Number of FAD sets and log sets by 1° square, pooled for 1992-1998.
Light gray: 1-5 sets; intermediate gray: 6-20 sets; black: ≥ 21 sets.

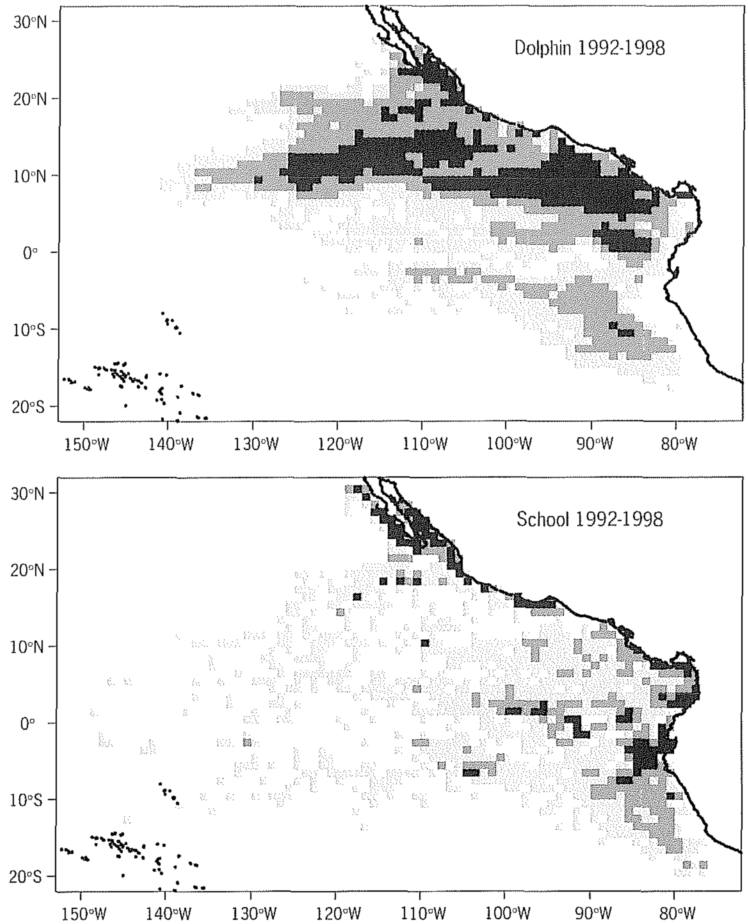


Figure 5
Number of dolphin sets and school sets by 1° square, pooled for 1992-1998.
Light gray: 1-10 sets;
intermediate gray: 11-50 sets;
black: ≥ 51 sets.

The majority of sets on FADs occurred during the early morning, as was the case with sets on logs (tab. 1). Most FAD sets (77%) occurred between 5 am and 8 am, *possibly because the association of tunas with floating* objects may be stronger during the night, and the schools leave the floating objects at sunrise. In contrast, most dolphin and school sets occurred after 7 am, and the numbers of these types of sets remained relatively high into the late afternoon.

Table 1 - Number of sets by time of day (hour, local time) for each type of purse seine set. Data are pooled for 1992-1998.

Hour	Dolphin	School	Log	FAD
≤4	0	42	6	19
5	6	88	508	3170
6	488	648	1419	8975
7	2436	1577	514	2184
8	4088	1800	346	704
9	4457	1964	363	676
10	4097	2023	354	703
11	3630	2113	347	576
12	3704	2010	323	475
13	3790	2147	282	386
14	4064	2130	260	271
15	4390	1930	191	187
16	4696	1964	146	100
17	2603	1774	66	58
18	403	836	22	12
≥19	16	148	0	4

FADs can be constructed out of many types of materials, but currently most FADs are bamboo rafts. These FADs frequently have a piece of old netting hanging from the raft, and in many cases, a bucket containing fish scraps is suspended below the raft. FADs frequently carry radio-transmitters, or occasionally satellite transmitters, that allow for monitoring of their location. Black (72%) and brown (18%) were the most common FAD colors, due to the netting hanging from the FAD and the presence of fouling organisms. For approximately 50% of FADs, epibiota covered 20% or less of the FAD, with the percentage coverage generally greater for FADs drifting further offshore (fig. 6). The median depth of netting below the raft was 16 m, with 90% of FADs extending

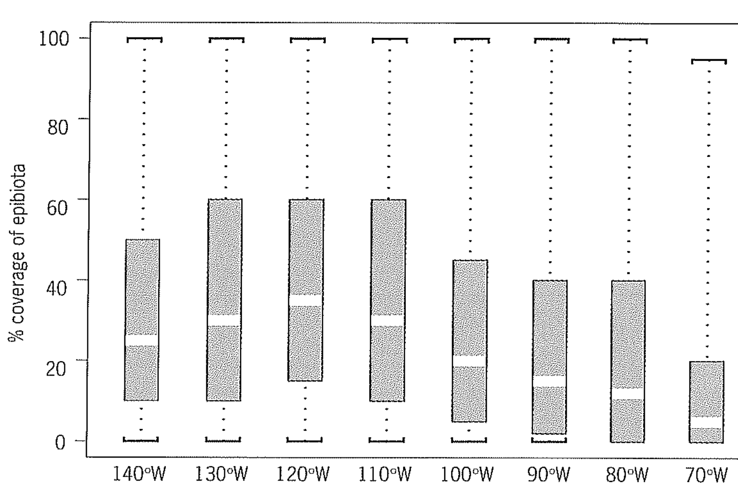


Figure 6
Percentage of the FAD covered with epibiota versus longitude, by 10° longitude bins. White bars show the median percentage coverage, gray boxes the inner-quartile range, and the whiskers the full range of the data.

less than 27 m below the surface. The depth of the FAD below the surface was found to be positively correlated with the longest dimension of the FAD (Spearman's rank correlation coefficient = 0.98, p-value <0.01), suggesting that FADs are typically constructed to emphasize the subsurface profile.

The increase in the number of FAD sets between 1992 and 1998 had the greatest effect on the distribution of bigeye catches among set types. The percentage of the total capture of yellowfin tuna in sets on FADs increased from 2% in 1992 to 9% in 1998; the majority of yellowfin capture occurred in dolphin sets (fig. 7). For skipjack tuna, the change was much more pronounced. Capture of skipjack went from 23% in 1992 to 73% in 1998, at the expense of skipjack captures in school and log sets (fig. 8). Even more significant, in relative terms, was the change in bigeye captures in FAD sets, which increased from 11% in 1992 to 92% in 1998 (fig. 9). Very little skipjack or bigeye tuna was captured in dolphin sets.

FAD sets had the greatest success rate for skipjack and bigeye tunas, as compared to other set types (tab. 2). We define a successful set for a particular tuna species as one that captured at least one metric ton of that species. The percentage of successful FAD sets for yellowfin ranged from 49 to 69% between 1992 and 1998, similar, but slightly less than that on logs sets and well below the success rate on dolphin sets. On the other hand, the percentage of successful FAD sets for skipjack ranged from 83 to 89%, consistently above the success rate for skipjack on log

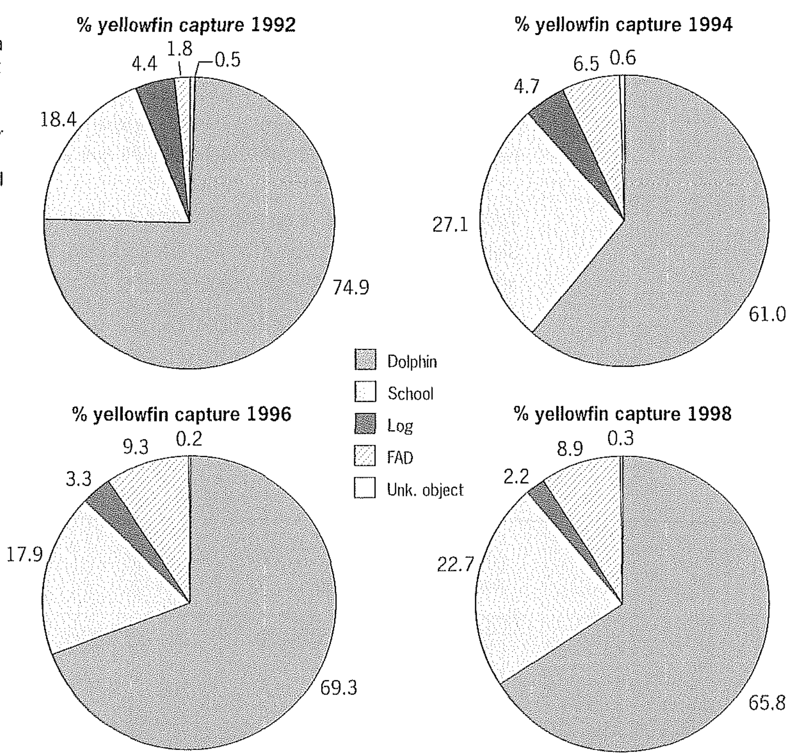


Figure 7
Percentage of yellowfin tuna captures by purse seine set type for 1992, 1994, 1996 and 1998. Percentages are based on IATTC observer data, adjusted for observer coverage. Estimates of total yellowfin capture (mt) per year: 214,613 (1992); 198,972 (1994); 214,148 (1996); 227,648 (1998). "Unk. obj." refers to sets on floating objects where it could not be determined if the object was a FAD or a log.

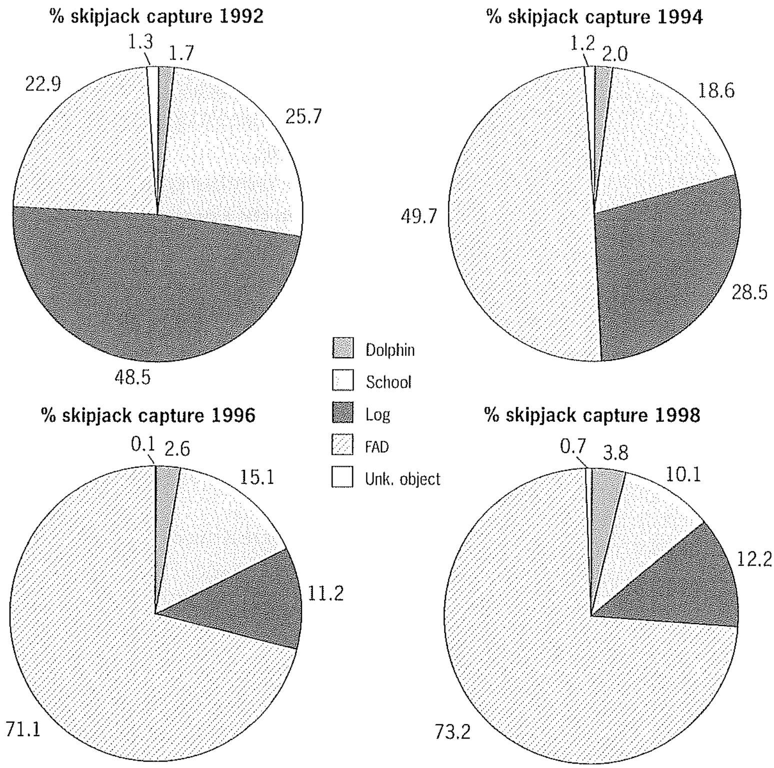


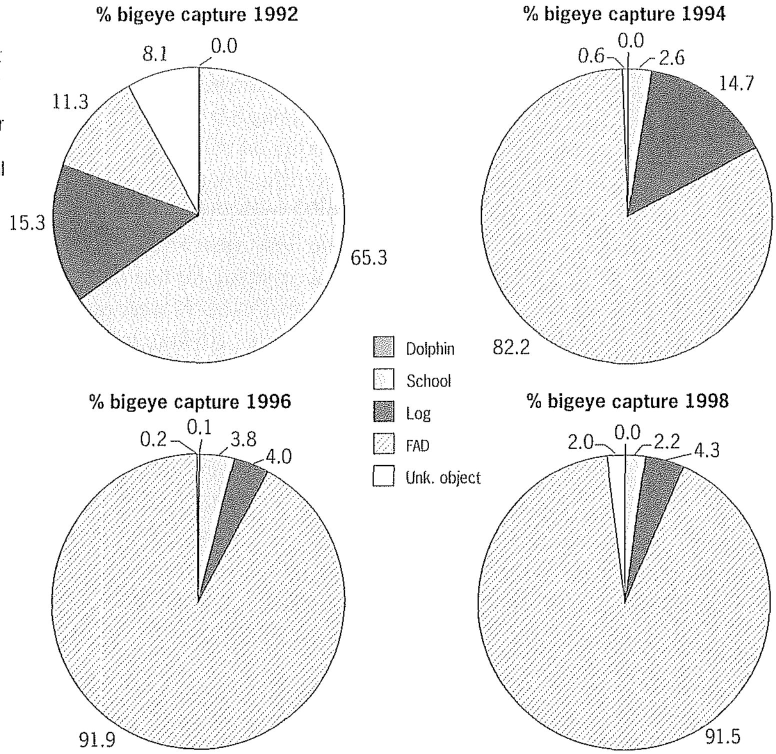
Figure 8
Percentage of skipjack tuna captures by purse seine set type for 1992, 1994, 1996 and 1998. Percentages are based on IATTC observer data, adjusted for observer coverage. Estimates of total skipjack capture (mt) per year: 64,754 (1992); 73,333 (1994); 108,071 (1996); 140,510 (1998). "Unk. obj." refers to sets on floating objects where it could not be determined if the object was a FAD or a log.

sets of 66 to 76%, and more than twice the success rate for skipjack on dolphin and school sets. The percentage of successful FAD sets for bigeye has increased from 9% in 1992 to 64% in 1998. The percentage of successful logs sets for bigeye shows some increase over the same time period, but has remained less than 25 per cent.

Table 2 - Percentage of successful sets per year and set type, for yellowfin, skipjack and bigeye tunas. The numbers of sets on which these percentages are based are shown in parentheses in the yellowfin sub-table.

Year	Dolphin	School	Log	FAD
Yellowfin tuna				
1992	83 (6,724)	42 (2,933)	66 (945)	69 (522)
1994	89 (5,350)	53 (3,662)	60 (709)	54 (1,830)
1996	88 (5,833)	42 (2,960)	55 (484)	49 (3,404)
1998	89 (8,018)	46 (3,217)	52 (663)	55 (4,588)
Skipjack tuna				
1992	3	25	76	84
1994	3	19	69	83
1996	6	31	66	87
1998	11	18	74	89
Bigeye tuna				
1992	< 1	5	6	9
1994	< 1	1	16	46
1996	< 1	4	20	66
1998	< 1	2	24	64

Figure 9
Percentage of bigeye tuna captures by purse seine set type for 1992, 1994, 1996 and 1998. Percentages are based on IATTC observer data, adjusted for observer coverage. Estimates of total bigeye capture (mt) per year: 5,583 (1992); 30,843 (1994); 58,070 (1996); 41,623 (1998). "Unk. obj." refers to sets on floating objects where *it could not be determined* if the object was a FAD or a log.



The ratio of discards to capture for tunas caught in FAD sets was greatest for yellowfin and skipjack (tab. 3). Approximately 10 to 23% of yellowfin captured on FADs were discarded, as were 15 to 29% of the skipjack and 7 to 12% of the bigeye. The discard rates were similar to those for log sets, but generally more than those from school and dolphin sets, although dolphin sets capture almost no bigeye (tab. 3; fig. 9).

Table 3 - Percentage of tons of tunas discarded per year and set type for yellowfin, skipjack and bigeye in successful sets.

Year	Dolphin	School	Log	FAD
Yellowfin tuna				
1992	0.52	5.36	16.54	22.78
1994	0.57	1.33	18.83	14.44
1996	0.67	2.41	13.04	18.62
1998	0.38	1.42	19.60	10.31
Skipjack tuna				
1992	5.76	11.43	17.69	15.31
1994	2.07	6.15	16.06	18.32
1996	7.19	4.45	17.65	29.02
1998	0.76	10.93	20.23	17.21
Bigeye tuna				
1992	<0.01*	4.66	10.29	12.46
1994	14.29*	7.95*	7.99	8.02
1996	<0.01*	1.12	9.22	10.28
1998	<0.01*	1.55	9.23	7.01

* indicates fewer than 50 sets.

Capture per set in repeated sets on the same FAD showed depletion that persisted for over 10 days. Whenever observers were able to identify a FAD or a log, they recorded all repeated sets on the object by the particular vessel. Although it was not possible to know whether other vessels were also setting on the same floating object, these data provide some information on the frequency of repeated sets and their catches. As compared to 1992, when over 57% of the sets on FADs were repeated sets on the same FAD, most FADs since 1995 were set on only once, with repeated sets accounting for less than 25% of the FAD sets (tab. 4). Most repeated FAD sets (70-80%) were made before 8 am, similar to the distribution of all FAD sets. Although most repeated sets were made in the early morning, they were not necessarily made one day apart (tab. 5). Fifty per cent or less of second sets were made within one day of the first set. Only twenty per cent or less of fifth sets were made within five days of the first set. For FADs that were set upon at least three times, with the first sets a successful set (≥ 1 mt of yellowfin or skipjack or bigeye captured), capture per set in repeated sets for all three species of tunas showed a decrease with time for at least ten days after the first set (fig. 10). During this 10-day period, 60-70% of third sets, 50-60% of fourth sets and approximately 50% of fifth sets had been made (tab. 5).

Table 4 - Percentage of log and FAD sets that were first sets (1) and repeated sets (2 = second set, 5 = fifth set, ≥ 5 = sixth and greater sets) on the same FAD, per year.

	1	2	3	4	5	> 5
1992						
Log	80.4	11.9	4.0	1.9	0.9	1.0
FAD	42.9	33.7	14.0	4.8	2.1	2.5
1994						
Log	80.7	13.1	3.4	2.1	0.4	0.3
FAD	62.0	23.4	9.1	3.4	1.2	0.9
1996						
Log	80.0	13.6	4.3	1.2	0.4	0.4
FAD	79.2	14.9	3.4	1.2	0.5	0.7
1998						
Log	83.3	9.8	4.1	1.5	0.8	0.6
FAD	76.8	16.4	4.9	1.1	0.5	0.3

Table 5 - Quantiles (0.1, 0.9) of the distribution of decimal days since the first set on a given FAD, by repeated set number (2 = second set, 5 = fifth set). Data were pooled for years 1992-1998. Min. = minimum, Max. = maximum.

	Min.	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	Max.
2	0.08	0.67	0.88	1.0	1.0	2.0	3.05	5.43	8.98	13.95	37
3	0.21	1.69	2.04	3.27	5.0	7.0	9.21	13.96	18.96	25	57
4	0.92	2.67	3.79	5	6.88	8.92	11	13.04	20.62	28.96	53.04
5	2.0	3.92	5	6.97	9.02	10	12.4	16.13	18.43	27.2	46.12

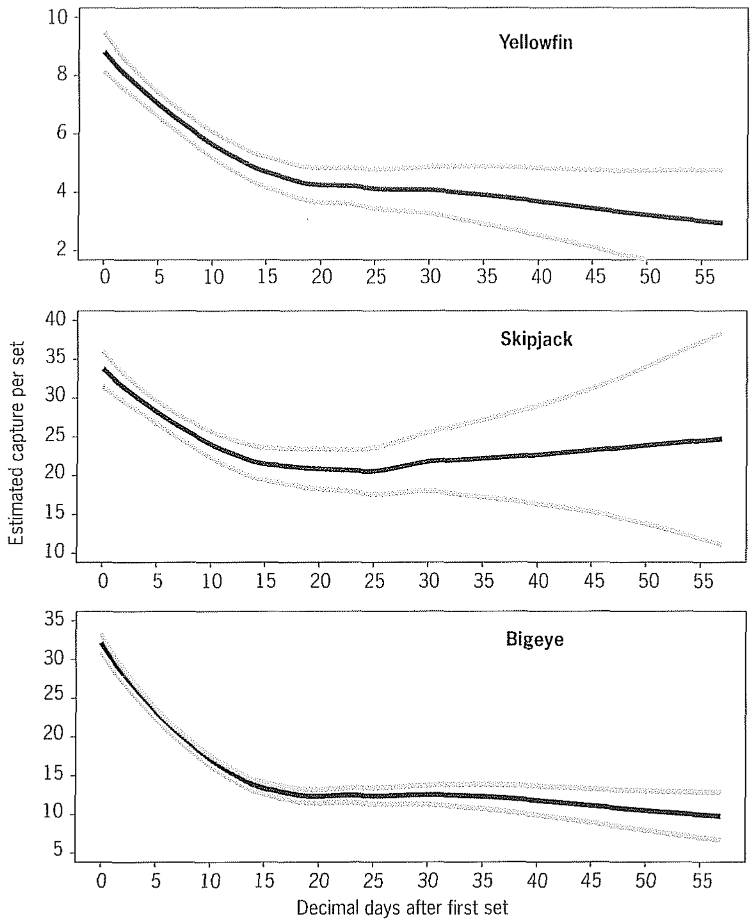


Figure 10
Capture per set in repeated sets on the same FAD. Shown are smoothed fits of capture per set to the *number of decimal days* since the first set. Black lines show the smoothed estimate, gray lines show the point-wise 95% confidence intervals. Data are for FAD sets with ≥ 3 repeat sets on the same FAD where the first set yielded a catch of tunas of more than 1 metric ton. Only FAD sets *made within the equatorial* band outlined by the sum of the 8 areas shown in figure 16 were included in the analysis. A total of 899 "different" FADs were available for this analysis (see Discussion for problems with FAD identification). Smoothed fits were computed using generalized *additive model* techniques (locally-weighted moving line with a smoothing parameter of 0.9 and assuming a gamma distribution, log link, for capture per set).

The length-frequency distributions of tunas caught on floating objects at low latitudes (areas 7, 9-12 in fig. 11) between 1994 and 1998 show a mode between 40 and 50 cm for all three species (fig. 12). For skipjack there is the suggestion of a second peak in length at 68 cm that is not apparent for the other species. By area, these larger fish were caught most often along the equator between 95°W and 110°W (fig. 13), an area that yielded mostly small bigeye (fig. 14). School sets made at low latitudes yielded smaller bigeye, but larger yellowfin than floating object sets (fig. 15). The larger yellowfin (>115 cm) were caught predominantly south of 0°, between 90°W and 110°West. However, of the three types of purse seine sets, dolphin sets typically yield the greatest percentage of yellowfin of more than 100 cm length (Hall *et al.*, 1999a). Although, we are currently unable to separate length-frequency data by type of floating object, the spatial distribution of FAD sets as compared to that for log sets between 1992 and 1998 (fig. 4) suggests that most of the floating object sets made at low latitudes were FAD sets.

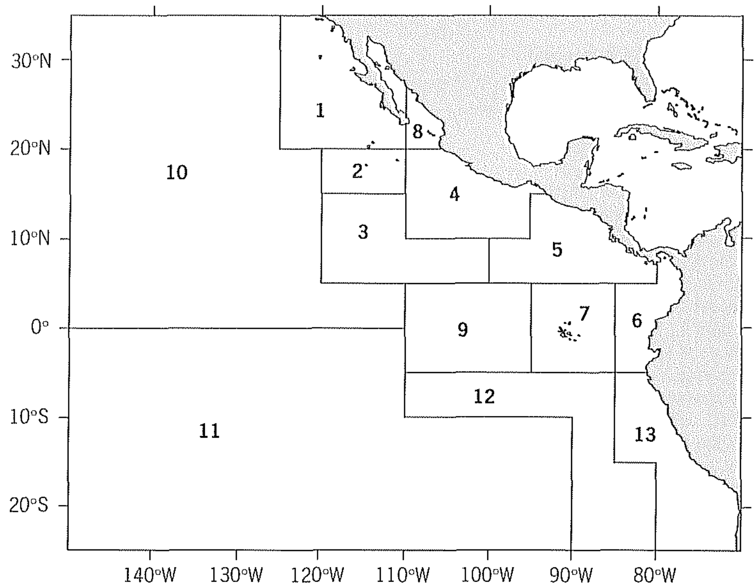


Figure 11
Map of the EPO showing sampling areas for tuna length-frequency data.
Only length-frequency data from measurement areas 7, and 9-12 are presented.

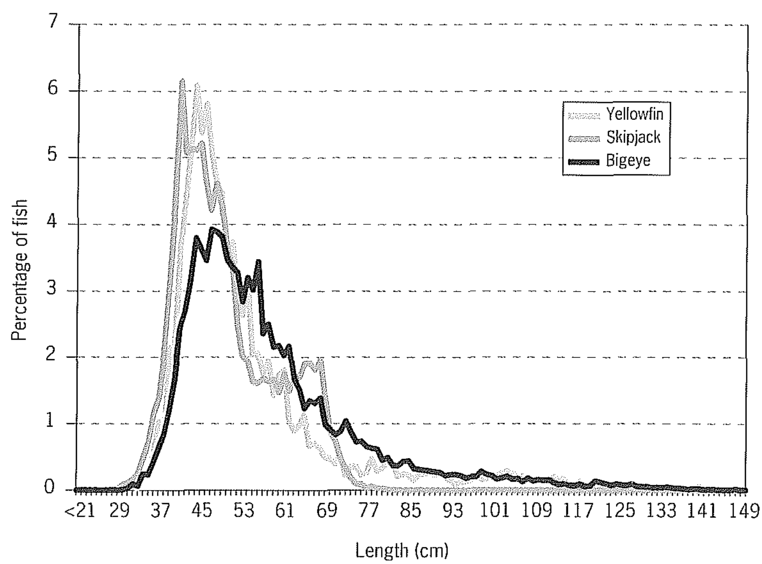


Figure 12
Length-frequency distributions of yellowfin, skipjack and bigeye tunas caught on floating-object sets. Data were pooled for years 1994-1998.

Figure 13
Length-frequency distributions of skipjack tuna caught on floating object sets, by area (see figure 11 for areas). Data were pooled for years 1994-1998.

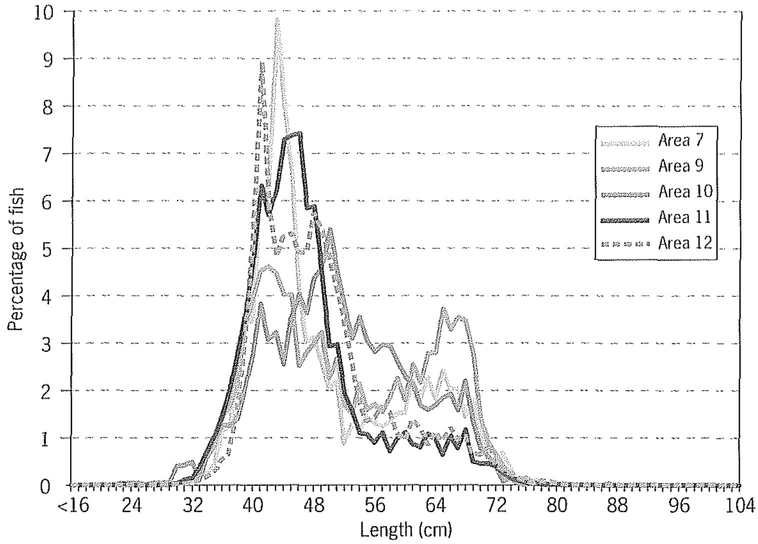
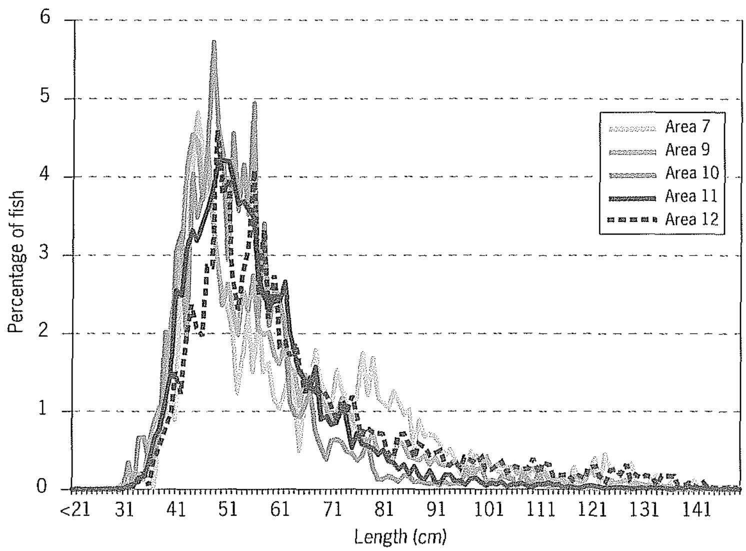


Figure 14
Length-frequency distributions of bigeye tuna caught on floating object sets, by area (see figure 11 for areas). Data were pooled for years 1994-1998.



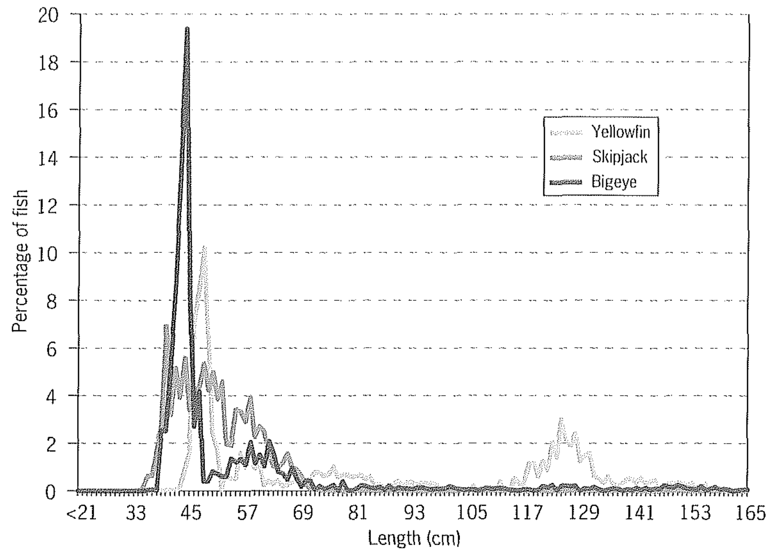


Figure 15
Length-frequency distributions of yellowfin, skipjack and bigeye tunas caught on school sets. Data were pooled for years 1994-1998.

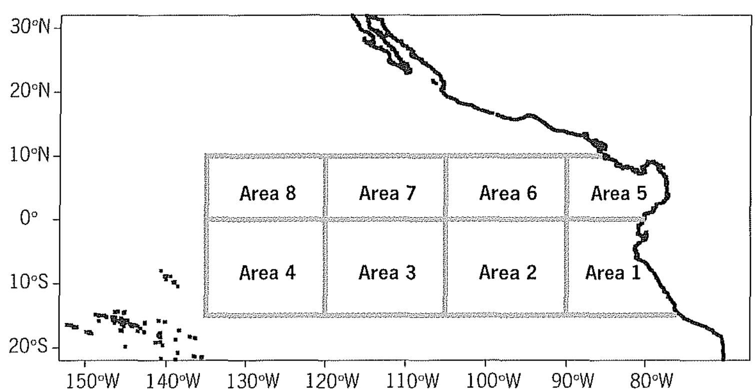
Tuna capture per set on FADs

The relative contribution of location, season and FAD characteristics to variability in tuna capture per set on FADs was explored by studying factors affecting the probability of making a successful set (*p*) and capture per successful set (CPSS) for each species. As has been done in other catch studies (e.g., Lo *et al.*, 1992; Stefánsson, 1996), the analysis was done in two parts to improve our ability to identify sources of variability. This analysis used data from 1995 to 1998 (n = 14,262 FAD sets) when the spatial extent of the purse seine fishery on FADs was similar (fig. 3). The variables considered in these analyses were: season (January-March, April-June, July-September, October-December), area (fig. 16), time of day (hour, local time), depth of the net (in fathoms, "f") and some FAD characteristics, including shape (irregular, aggregated), color (red or orange, yellow, green or blue, brown, black, white, gray), underwater depth (extent of the FAD below the surface, in metres, "m"), and percentage covered with epibiota. The depth of the purse seine net was obtained from measurements of the amount of netting (an "out-of-water" depth). The underwater depth of the FAD was estimated by the observer, typically when the FAD was on deck or being deployed. Year, season, area, shape and color were treated as categorical variables, whereas hour, net depth, percentage coverage with epibiota and under-water depth were treated as continuous variables.

Generalized linear model techniques (McCullagh & Nelder, 1989) were used to assess the relative importance of the effects of the various covariates on *p* and CPSS. In this analysis, we have assumed that *p* and CPSS for each species were independent of the presence of the other tuna species. We assumed a linear logistic model (Collett, 1991) for *p*, analysed separately for each species. A stepwise procedure was used to select covariates based on the greatest reduction in the Akaike statistic (AIC; Hastie, 1987), and covariate selection stopped when no terms that could be added to or removed from the current model further reduced the AIC. To study CPSS, we assumed that CPSS followed a gamma distribution and that the natural logarithm of the mean CPSS was linearly related to the covariates. An identical stepwise selection procedure was used to select influential covariates. For both analyses, the stepwise selection procedure was performed over all main effects and first-order interactions. Continuous variables were included as linear terms. In the stepwise selection procedure, several different starting models were used including the null model (overall constant only), a model with only a year effect, and a model with area and season main effects and an area-season interaction.

The relationships between p and CPSS, and influential covariates identified in the analysis described above were explored in more detail using generalized additive model techniques (Hastie & Tibshirani, 1991) to assess non-linearities of the relationships between influential covariates, and p and CPSS. Smoothing was done using a locally-weighted moving line (Cleveland, 1979; *loess* with a smoothing parameter of 0.9). As in the analysis described above, a linear logistic model was assumed for p, and CPSS was assumed to be distributed according to a gamma distribution, with the mean CPSS linearly related to the covariates on the log-scale.

Figure 16
Areas used in the analysis of capture per set.



Probability of a making a successful set (p)

For all three tuna species, spatial effects on p dominated over seasonal effects, the characteristics of the FAD, and the depth of the purse seine net (tab. 6). Inclusion of a seasonal effect was closely followed by season-area or season-year interaction terms, suggesting the importance of spatial and temporal interactions, and inter-annual variability, on p. Of those FAD characteristics tested, only the shape of the FAD appeared to have relatively little effect on p for all three species. Final models that started from an initial model of year, area and season main effects and first-order interactions contained fewer terms, and typically did not contain interaction terms involving color, and area, season or year (tab. 6). The effects of the characteristics of the FAD and the net depth on *p* were often modified by interactions (tab. 6). The relationships between *p* and some of these covariates are discussed below in more detail.

Table 6 - Results of stepwise selection of covariates in a linear logistic model for tuna capture presence/absence data.

Yellowfin	Yellowfin	Skipjack	Bigeye
(null 19,643)	year x season x area* (19,232)	(null 8,826)	(null 18,085)
year* (19,623)	percentage coverage (19,137)	year* (8,813)	year* (17,981)
area (19,465)	color (19,059)	area (8,617)	area (15,800)
percentage coverage (19,370)	underwater depth (19,001)	hour (8,565)	year:area (15,676)
color (19,292)	color:underwater depth (18,940)	year:area (8,505)	color (15,564)
year:area (19,231)	color:percentage coverage (18,933)	season (8,471)	underwater depth (15,506)
year:color (19,157)	hour (18,927)	color (8,441)	hour (15,459)
underwater depth (19,117)	shape (18,927)	year:season (8,422)	color:underwater depth (15,438)
area:color (19,081)	shape:underwater depth (18,918)	percentage coverage (8,411)	area:underwater depth (15,428)
color:underwater depth (19,054)	shape:percentage coverage (18,913)	net depth (8,401)	net depth (15,418)
season (19,036)	shape:hour (18,913)	area:net depth (8,395)	net depth:area (15,395)
season:area (18,933)		shape (8,391)	color:net depth (15,381)
year:season (18,876)		area:shape (8,378)	season (15,372)
season:color (18,864)		shape:net depth (8,374)	area:season (15,226)
season:percentage coverage (18,856)		underwater depth (8,371)	season:year (15,196)
hour (18,852)		season:underwater depth (8,355)	color:season (15,175)
year:hour (18,849)		year:underwater depth (8,347)	shape (15,173)
year:underwater depth (18,847)		hour:percentage coverage (8,343)	shape:year (15,163)
season:hour (18,846)		shape:percentage coverage (8,340)	shape:hour (15,159)
shape (18,845)		shape:color (8,335)	net depth:year (15,158)
year:shape (18,795)		season:area (8,330)	underwater depth:year (15,157)
shape:color (18,790)			underwater depth:season (15,155)
season:shape (18,786)			shape:area (15,154)
area:shape (18,780)			net depth:season (15,153)
shape:underwater depth (18,778)			
season:underwater depth (18,776)			
shape:hour (18,776)			
shape:percentage coverage (18,775)			
season:hour (18,775)			

* indicates starting model. Value of the AIC statistic is shown in parentheses. ":" indicates an interaction term.
"year x area x season" indicates a model with year, area and season main effects and first-order interactions.
Percentage reduction in the deviance for the final model: yellowfin, 6%; skipjack, 7%; bigeye, 17%.

Area and season effects on *p* showed the greatest differences among species. South of 0°, *p* for yellowfin was greater coastally between January to March, and greatest offshore between July to September (fig. 17).

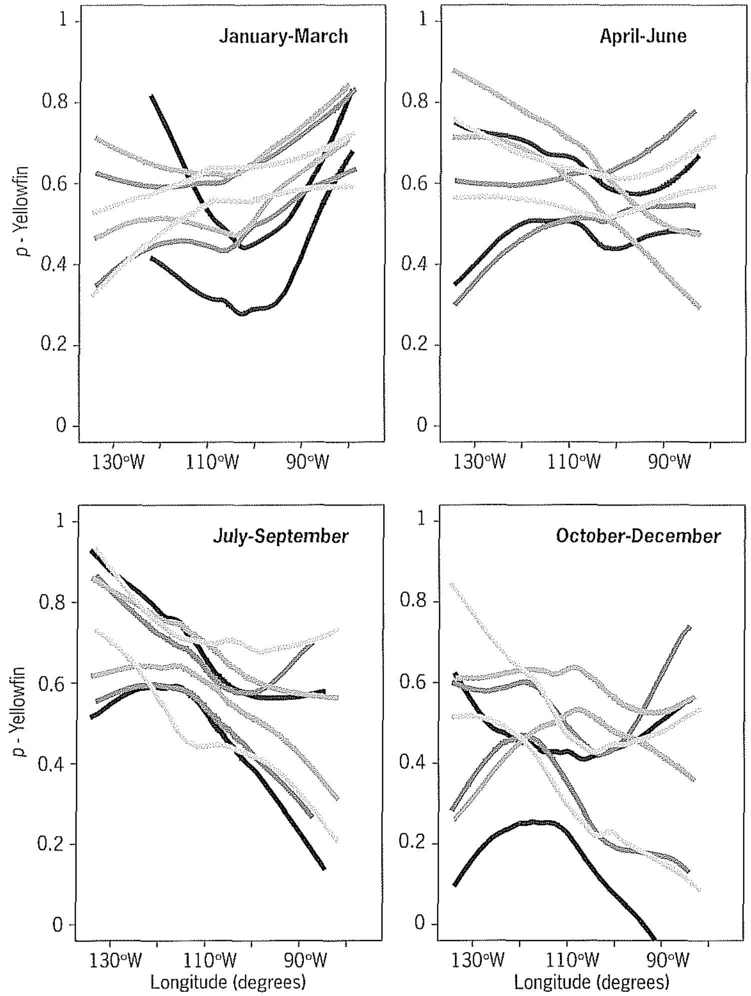


Figure 17
Approximate pointwise 95% confidence intervals for *p* for yellowfin as a function of longitude south of 0°, by season for each of years 1995-1998.
Black, 1995;
dark gray, 1996;
intermediate gray, 1997;
light gray, 1998.

Inter-annual variability in *p* for yellowfin was generally greater north of 0°; the best agreement between years occurred from January to March when *p* for yellowfin was high coastally and reached a minimum between 95°W and 110°W (fig. 18). On the other hand, *p* for skipjack was largely invariant with longitude between 110°W and 135°W, across seasons and years, both south (fig. 19) and north of 0° (not shown). From July to December, *p* for skipjack decreased towards the coast south of 0° (fig. 19), although the amount of decrease varied by year. Less of a decrease in *p* towards the coast was seen north of 0°. For bigeye, *p* was lowest coastally early in the year (fig. 20). South of 0°, *p* for bigeye remained high offshore throughout the year, was lowest coastally from January to March, and reached its highest values coastally between July and December. A similar pattern was observed north of 0° with the exception that there was greater variability between years.

Figure 18
Approximate pointwise 95% confidence intervals for *p* for yellowfin as a function of longitude north of 0°, between January and March for each of years 1995-1998.
Black, 1995;
dark gray, 1996;
intermediate gray, 1997;
light gray, 1998.

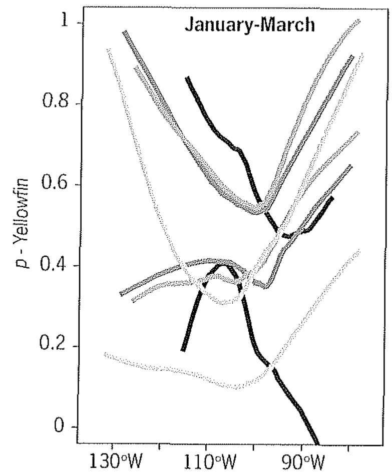


Figure 19
Approximate pointwise 95% confidence intervals for *p* for skipjack as a function of longitude south of 0°, by season for each of years 1995-1998.
Black, 1995;
dark gray, 1996;
intermediate gray, 1997;
light gray, 1998.

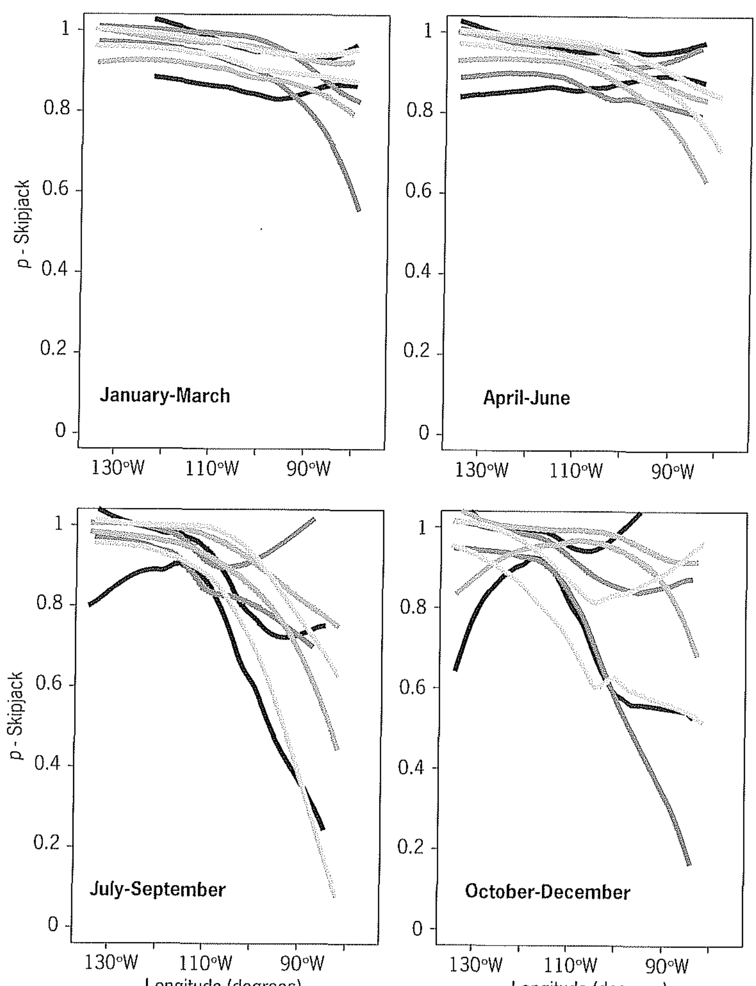
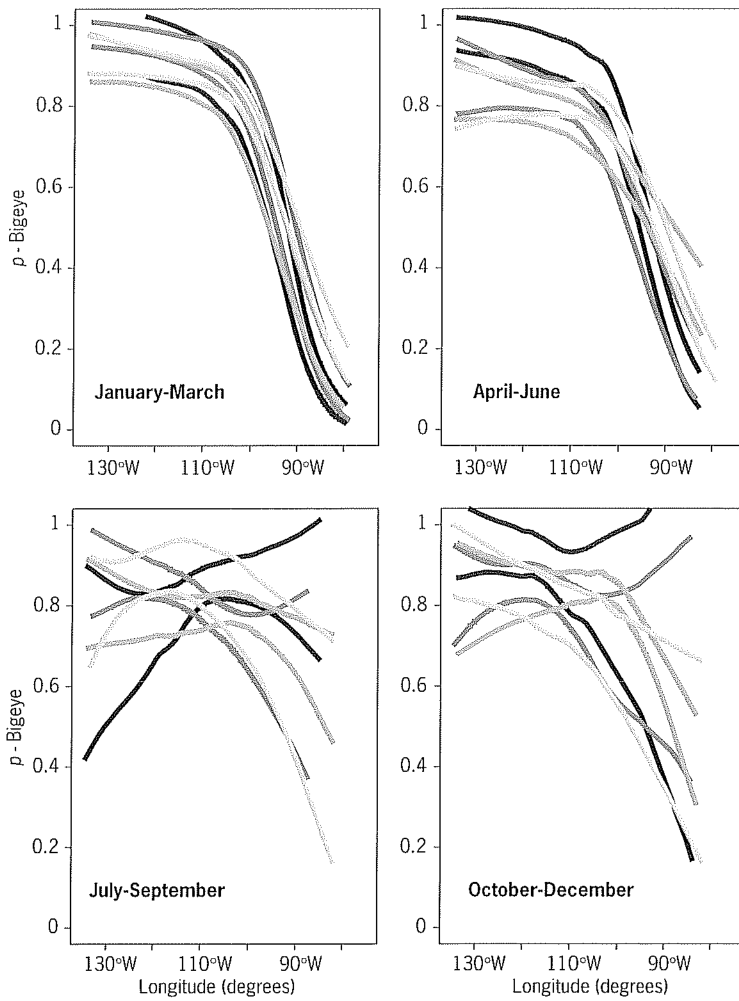


Figure 20
Approximate pointwise 95% confidence intervals for p for bigeye as a function of longitude south of 0°, by season for each of years 1995-1998.
Black, 1995;
dark gray, 1996;
intermediate gray, 1997;
light gray, 1998.



In general, p was greater for deeper nets, deeper FADs and FADs with greater percentage coverage of epibiota (fig. 21), although these effects were typically less than those due to area and season (figs 17 to 20). For yellowfin on black FADs (the most prevalent color), the rate of increase of p with underwater depth was greatest at underwater depths of less than 20 m; however, for other colors, the greatest rate of increase of p for yellowfin often occurred at underwater depths of more than 20 metres. For yellowfin, p generally increased the most with percentage coverage of epibiota at low percentage coverage values, although a linear rate of increase for some colors could not be excluded.

For skipjack, p increased with net depth; however, the rate of increase of p with net depth varied by area (fig. 21). South of 0°, p for skipjack increased the most with net depth between 90°W and 105°W, with no effect of net depth on p west of 120°West. North of 0°, p for skipjack increased slightly with net depth offshore, varied little with net depth between 90°W and 120°W and increased the most with net depth east of 90°West. Although *p* for skipjack increased with the percentage coverage of epibiota, the rate of increase was minimal (< 10 percentage points as percentage coverage with epibiota increased from 0% to 100%).

For bigeye, the rate of increase of *p* with both net depth and underwater depth also varied by area (fig. 21). South of 0°, *p* for bigeye increased with net depth in a manner similar to that for skipjack, with the greatest effect occurring east of 105°West. North of 0°, *p* was greatest for the shallowest and deepest nets west of 105°W and for net depths between about 100 to 120 fathoms east of 90°West. The greatest rate of increase of *p* for bigeye with underwater depth occurred north of 0° and at underwater depths below 20 fathoms. South of 0°, the greatest effect of underwater depth on *p* for bigeye occurred between 90°W and 120°W and *p* increased approximately linearly with underwater depth.

Although *p* for yellowfin varied little with the time of day (tab. 6), *p* for both skipjack and bigeye decreased during the day, particularly for bigeye (fig. 22). The reduction in *p* with time of day largely occurred in the early morning before 10 am.

Variability in *p* with FAD color was largely due to gray FADs (tab. 7). Consistent with the estimated coefficients of the linear logistic models for *p* by species, gray FADs had the greatest *p* for skipjack and bigeye, yet the lowest *p* for yellowfin. For FAD colors other than gray, *p* varied little with color for yellowfin and skipjack. Slightly more variation was seen in *p* for bigeye among colors; however, for the dominant FAD colors (black and brown), *p* for bigeye was relatively similar.

Table 7 - Observed p by FAD color for yellowfin, skipjack and bigeye. Data are pooled for 1995-1998.

	Red	Green	Yellow	Black	White	Brown	Gray
Yellowfin	0.45	0.49	0.49	0.51	0.47	0.47	0.33
Skipjack	0.81	0.84	0.82	0.88	0.87	0.86	0.95
Bigeye	0.57	0.51	0.5	0.66	0.46	0.6	0.88

Capture per successful set (CPSS)

Similar to the results of the analysis of *p*, spatial effects dominated the variability in the CPSS of all three species of tunas (tab. 8). Seasonal effects (and interactions involving season and area) were often included earlier in the stepwise selection process than for the analysis of *p* (tab. 6). In the case of yellowfin, seasonal effects only entered into the stepwise selection process as a result of an area-season interaction. Of secondary importance for at least one of the three species was the time of day, the net depth, and the percentage coverage with epibiota. As with the analysis of *p*, color tended not to be included in models that started with area and season main effects and an area-season interaction (tab. 8). The relationships between *p* and some of these covariates are discussed below in more detail.

Figure 21
Approximate pointwise 95% confidence intervals for *p* by tuna species as a function of selected FAD characteristics and net depth, pooled for 1995-1998. Panels from upper left to lower right: *p* for yellowfin versus underwater depth by FAD color (dark gray, black FADs; light gray, brown FADs); *p* for yellowfin versus percentage coverage with epibiota by FAD color (black, black FADs; dark gray, brown FADs; light gray, yellow FADs); *p* for skipjack versus net depth, by area (dark gray, area 5; light gray, area 2); *p* for bigeye as a function of net depth, by area (dark gray, area 2; light gray, area 8); *p* for bigeye as a function of underwater depth by area (dark gray, area 6; light gray, area 2). See figure 16 for description of areas.

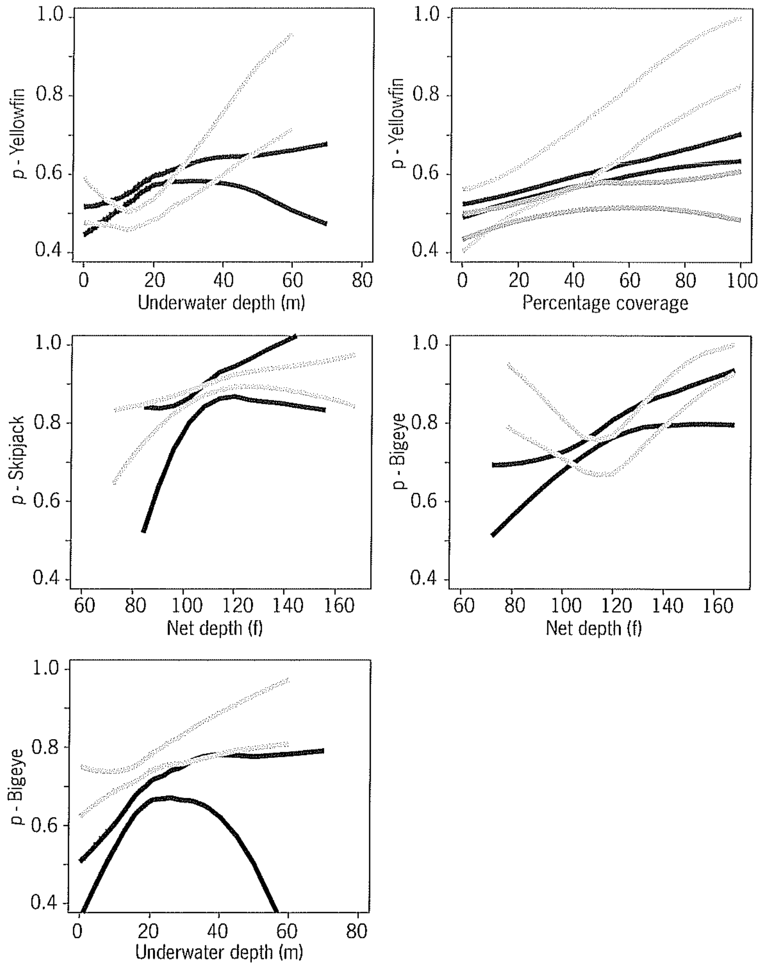


Figure 22
Estimated *p* for skipjack (black solid line) and bigeye (gray solid line), and approximate pointwise 95% confidence intervals (dashed lines), versus time of day. Data have been pooled for years 1995-1998.

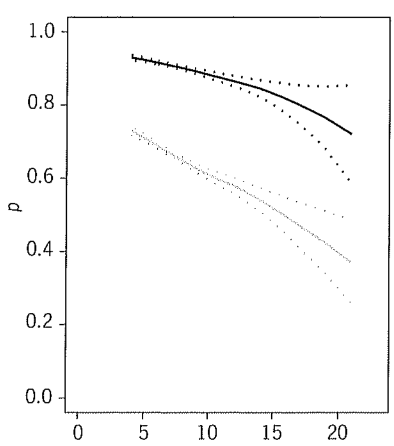


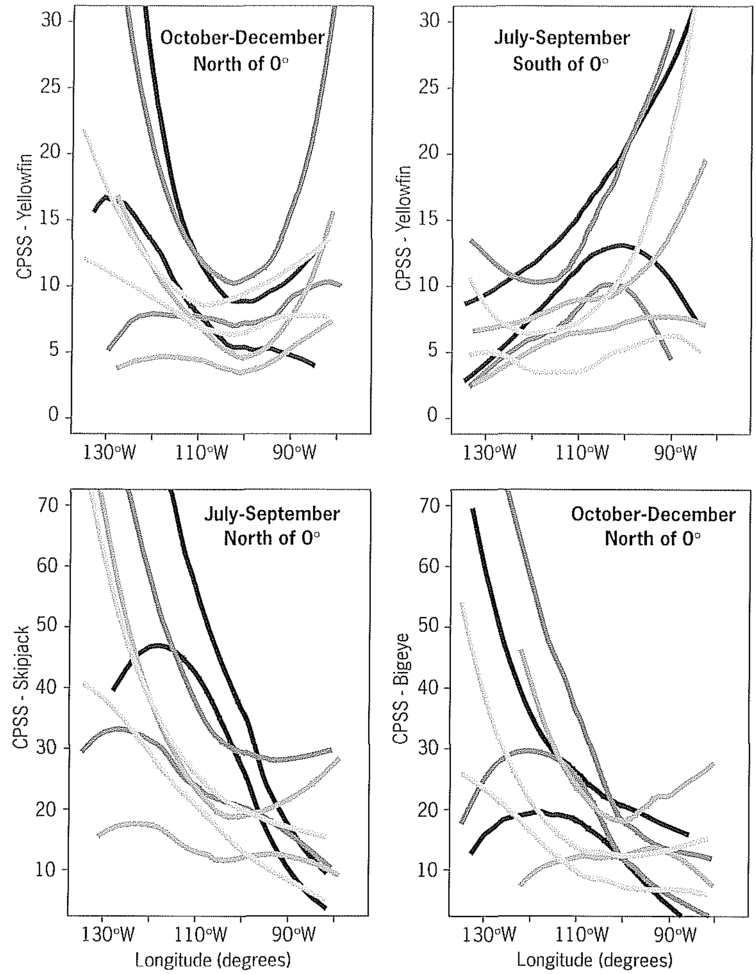
Table 8 - Results of stepwise selection of covariates in model for CPSS by tuna species.

Yellowfin	Yellowfin	Skipjack	Bigeye
(null* 8,775)	(area x season* 8,542)	(null* 15,995)	(null* 12,398)
year (8,570)		season (15,648)	year (11,859)
area (8,379)	year (8,296)	area (15,477)	area (11,538)
net depth (8,233)	net depth (8,166)	hour (15,257)	hour (11,407)
year:area (8,179)	year:season (8,054)	season:area (15,104)	year:area (11,322)
percentage coverage (8,136)	percentage coverage (8,012)	year (14,969)	season (11,225)
year:percentage coverage (8,109)	season:net depth (7,979)	year:season (14,787)	season: area (11,113)
year:net depth (8,095)	year:area (7,956)	year:area (14,703)	year:season (11,052)
area: percentage coverage (8,078)	year:net depth (7,944)	net depth (14,690)	net depth (11,010)
underwater depth (8,071)	year:percent coverage (7,933)	area:net depth (14,681)	season:net depth (11,001)
area:underwater depth (8,020)	area:percentage coverage (7,928)	shape (14,671)	percentage coverage (10,991)
underwater depth:percent coverage (8,005)	season:percentage coverage (7,924)	area:shape (14,657)	area:percentage coverage (10,980)
year:underwater depth (7,992)	underwater depth (7,919)	percentage coverage (14,649)	area:net depth (10,979)
color (7,991)	area:underwater depth (7,875)	season:percentage coverage (14,637)	underwater depth (10,978)
color:net depth (7,984)	underwater depth: percentage coverage (7,861)	underwater depth (14,630)	hour:underwater depth (10,971)
color:underwater depth (7,977)	year:underwater depth (7,852)	year:percentage coverage (14,624)	underwater depth: percentage coverage (10,970)
	hour (7,850)	percentage coverage: net depth (14,619)	
	year:hour (7,834)	shape:underwater depth (14,616)	
	year:area (7,833)	area:underwater depth (14,612)	
	season:hour (7,832)	hour:percentage coverage (14,610)	
	underwater depth: net depth (7,831)	shape:net depth (14,609)	
		hour:underwater depth (14,607)	
		season:shape (14,606)	
		year:hour (14,606)	

* indicates starting model. Value of the AIC statistic is shown in parentheses. Percentage reduction in the deviance for the final model: yellowfin, 13.5%; skipjack, 10.4%; and bigeye, 13.5%. ":" indicates a first-order interaction term; "x" indicates main effects and first-order interactions.

In contrast to the results of the analysis of *p* (figs 17-20), spatial and seasonal effects on CPSS were similar among species, although there was considerable variability between years (fig. 23). North of 0°, CPSS of yellowfin was often greater offshore in the latter part of the year; however, in the latter part of the year south of 0°, the greatest values were often found coastally. North of 0°, CPSS of skipjack and bigeye increased with distance offshore in the latter part of the year and were highly variable amongst years between January and June (not shown). CPSS peaked offshore for skipjack from July to September and for bigeye from October to December. South of 0°, variability in CPSS of skipjack between and within years led to no remarkable patterns; CPSS of bigeye showed a slight increase between approximately 95°W and 115°W in the first part of the year (not shown).

Figure 23
Approximate pointwise 95% confidence intervals for CPSS versus longitude, by selected seasons, for each year from 1995 to 1998: upper row - yellowfin; lower left - skipjack; lower right - bigeye. Black, 1995; dark gray, 1996; intermediate gray, 1997; light gray, 1998.



The effects of time of day and net depth on CPSS were also similar among species (fig. 24). CPSS by time of day decreased for both skipjack and bigeye, with the greatest values of CPSS occurring in the early morning. CPSS generally increased for all three species with net depth. However, the effect of net depth on CPSS varied by area and season. For most seasons and areas, there appears to be limited benefit in deepening the net below 120 fathoms. The greatest increases in CPSS with net depth occurred in January to March for both bigeye and yellowfin, and between 90°W and 120°W north of 0° for skipjack. CPSS of skipjack actually decreased with net depth south of 0° west of 120°West.

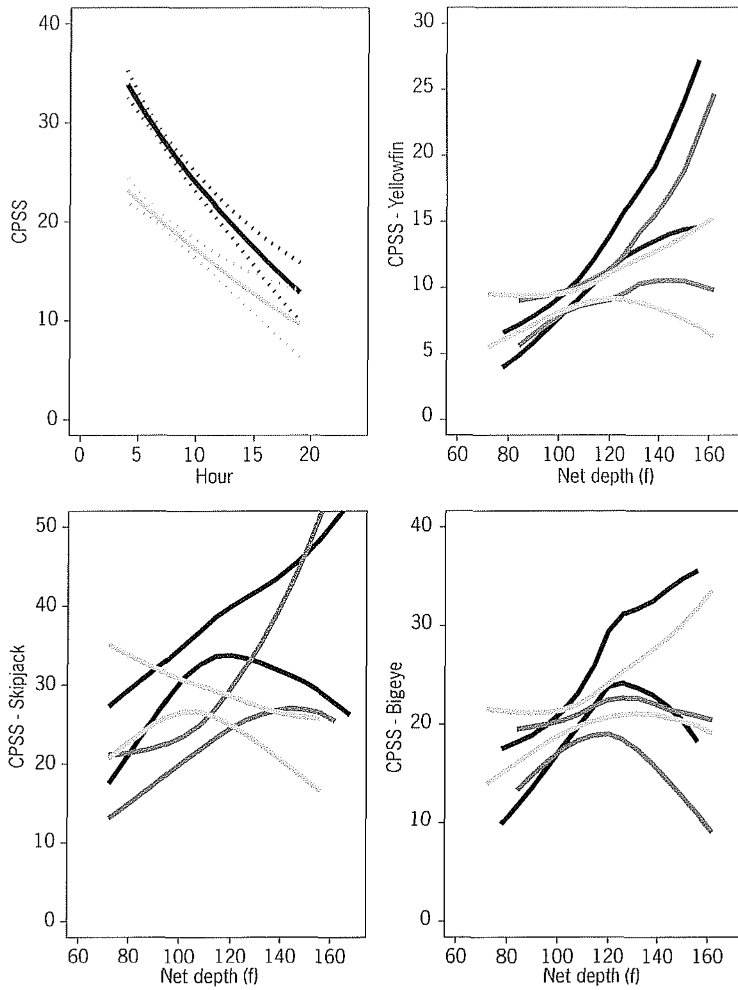


Figure 24
CPSS by time of day and FAD characteristics, pooled over years 1995-1998. Upper left: estimated CPSS for skipjack (black line) and bigeye (light gray line), and approximate 95% pointwise confidence intervals (dashed lines) as a function of time of day; upper right: approximate 95% pointwise confidence intervals for CPSS of yellowfin as a function of net depth, *January to March (black lines)*, April to June (dark gray lines) and October to December (light gray lines); lower left: approximate 95% pointwise confidence for CPSS of skipjack as a function of net depth, area 7 (black lines), area 6 (dark gray lines) and area 4 (light gray lines); lower right: approximate 95% pointwise confidence intervals for CPSS of bigeye as a function of net depth, January to March (black lines), April to June (dark gray lines) and October to December (light gray lines). See figure 16 for description of areas.

Summary and discussion

In this paper we have presented fishery statistics and a description of factors affecting capture per set for the purse seine fishery on drifting FADs in the EPO from 1992 to 1998. Although the fishery on FADs has replaced the fishery on flotsam as the dominant purse seine mode of *capturing skipjack and bigeye tunas, the two fisheries were similar in* several respects: the majority of the sets were made in the early morning, and skipjack and bigeye dominated the tuna capture, with comparable discard ratios. However, the success rate for bigeye on FADs was more than twice that on logs. In addition, FAD sets were made predominantly in latitudinal bands north and south of the equator, extending offshore to 150°W, whereas log sets were coastal. The probability of making a successful set and the capture per successful set for each of the three species varied most with area, season and year. More successful sets for yellowfin were generally made coastally in the early part of the year and offshore between July and September. More successful sets were made for skipjack and bigeye offshore than coastally; however, more successful sets were made for skipjack coastally in the first half of the year, whereas more successful sets were made for bigeye coastally in the latter part of the year. Capture per successful set was highly variable spatially and temporally, but showed a tendency to be greatest offshore in the latter half of the year north of 0° for all three species. Of secondary importance were time of day, underwater depth of the FAD and net depth. More successful sets and greater captures of bigeye and skipjack were made early in the morning and with deeper nets, although the effect of net depth varied by area. In addition, more successful sets for yellowfin and bigeye were made on FADs with deeper netting, although these effects varied with area and FAD color. Capture per successful set for all three species increased with net depth, although the rate of increase varied seasonally and spatially.

Although our results suggest that capture per set of tunas varied with the area, season and some FAD characteristics, inter-annual variation, and spatial and temporal variability in the importance of FAD characteristics, indicate that the processes that lead to successful sets and large captures of fish are complex. In general, interaction terms appeared to be as important as main effects, and even the largest generalized linear model explained at most 17% of the variability in the data. The use of different link functions, different distributional assumptions, additional covariates and higher-order interactions may improve the fit of the models to the data and could be explored. In addition, analysis of these data is complicated by spatial and temporal variation in FAD characteristics. In fact, the effects of FAD characteristics such as color on the probability of making a successful set or capture per successful set may reflect a non-linear response of tuna capture to spatial and temporal variability in the environment not accounted for by the models fitted.

We have used sets that captured less than one metric ton of tunas as representative of "unsuccessful" sets. These unsuccessful sets may be an indication of the presence of only a few fish at the FAD or of a large school of fish that escaped capture. An additional source of information would be FAD observations that did not lead to sets ("sightings"). For the depth of the purse seine net to be meaningful in our analysis of the probability of making a successful set, we did not use sighting data. However, the use of sightings as an indicator of the absence of fish could be explored with regard to other factors (e.g., area and season).

Both small (≤ 363 mt fish-carrying capacity) and large vessels participate in the purse seine fishery on floating objects in the EPO. Between 1992 and 1998, an estimated 67-84% of all floating object sets were made by larger vessels (Anon., 2000). Observers generally are not placed aboard small vessels, and thus there is almost no information available on the characteristics of the FAD fishery of smaller purse seine vessels. Conclusions drawn from analysis of FAD data for larger vessels may not be applicable to these smaller vessels.

Our analyses suggest that the location and the time of year of FAD sets had more of an effect on capture per set of tunas than the characteristics of the FAD or the depth of the purse seine net. The probability of making a successful set varied by as much 0.6 with longitude by season, and capture per successful set often varied by as much as 50% with longitude by season. On the other hand, the effects of net depth and FAD depth were typically 0.2 or less for the probability of a successful set, and typically less than 50% for capture in successful sets. These results suggest that the benefits of modifications to FAD and purse seine net characteristics may be potentially less than changing fishing areas and seasons. Variation in the effect of net depth and FAD depth on capture per set by area or season may reflect spatial or temporal changes in the thermocline depth or other variation in the physical environment.

We found that capture per set of bigeye and skipjack tunas on FADs varied with time of day, whereas capture per set of yellowfin did not. More successful sets and higher catches in successful sets for bigeye and skipjack tunas occurred in the morning. It is unknown why catches of yellowfin would not vary in a similar manner. In general, captures per set of yellowfin in FAD sets were much less than captures of bigeye and skipjack, and perhaps we were unable to detect changes in capture of yellowfin with time of day because the effect, if it existed, was small and obscured by variability due to other factors. Alternatively, there may be species-specific differences in the association of tunas with floating objects. Skipjack and bigeye tunas may be strongly "attracted" to floating objects at night, whereas yellowfin are weakly "attracted" to floating objects throughout the day.

Concerns that the rapid increase in fishing effort on FADs could cause significant impacts to yellowfin, but especially to bigeye tunas, led to the adoption of a series on management actions to try to contain, and eventually reduce these impacts (Anon., 1999). Since 1992, the captures of bigeye tuna have increased considerably as a result of the purse seine fishery on FADs. In addition, discards of yellowfin and bigeye tunas tend to be greater for FAD (and log) sets than for school or dolphin sets. The discarded fish that are captured in FAD sets are usually small, and mostly likely immature. Since 1998, actions to reduce the ecological impact of this mode of fishing have included a ban on setting on floating objects and area closures. In 1998, all fishing for yellowfin tuna inside the IATTC regulatory area was banned after a quota of 225,000 mt of yellowfin was reached on November 26. In 1999, all setting on floating objects was prohibited after November 8. In addition, catches of yellowfin tuna were restricted in some areas after October 14, with a complete restriction effective on November 23 inside the IATTC regulatory area. For 2000, limits have been established for the catches of both yellowfin and bigeye tunas.

There are several reasons why some yellowfin, skipjack or bigeye tunas may be discarded during a set, including size (fish too small), storage space limitations (vessel wells full with only a partial catch loaded), and fish quality (fish may spoil during very long sets). By far, the size is the prevailing reason for discarding of fish. However, economic conditions (price, labor costs, demand), the availability of fish, regulations, and company policies, may affect the discarding decisions of a particular trip. These conditions may also change over time, following price changes and other fluctuations. Besides the main commercial tuna species for this fishery, individuals of many other species are also captured in sets on FADs (IATTC, 2000). These include sharks, rays, billfishes, dolphinfish, wahoo, yellowtail, rainbow runners, as well as tunas of other species such as *Auxis* and black skipjack. Most of these species are discarded; however, catches of some species are kept for consumption on board, or kept in small freezers for later sale. By-catches of tunas and of other species are typically much higher in sets on FADs and logs than in sets on school or dolphin-associated tunas (Hall, 1998; IATTC, 2000). Sets on dolphins have the lowest by-catches, probably because the average cruising speed of the tunas and dolphins involved, and the speed during the chase that precedes the set, prevent small individuals or slow-moving species from keeping up with the tunas and dolphins.

The areas developed by the purse seine fishery on FADs in the 1990s include two westward extensions, south and north of the equator, mainly within the general regions of the South Equatorial Current and the Equatorial Countercurrent (Wyrtki, 1965). Historically, these areas have been regions with high levels of productivity (Berger *et al.*, 1988). Thus, differences in the spatial distribution of FAD sets between years may reflect differences in current structure, as well as changes in productivity. For example, the presence of higher numbers of FAD sets along the equator during 1997 (fig. 3) may reflect changes in the physical and biological characteristics of the Eastern Tropical Pacific that accompany El Niño events. A study of spatial and temporal variation in the distribution of FAD sets, and associated catches, in connection with physical and biological data for the Eastern Tropical Pacific would undoubtedly provide useful insights into the influence of the environment on the FAD fishery.

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