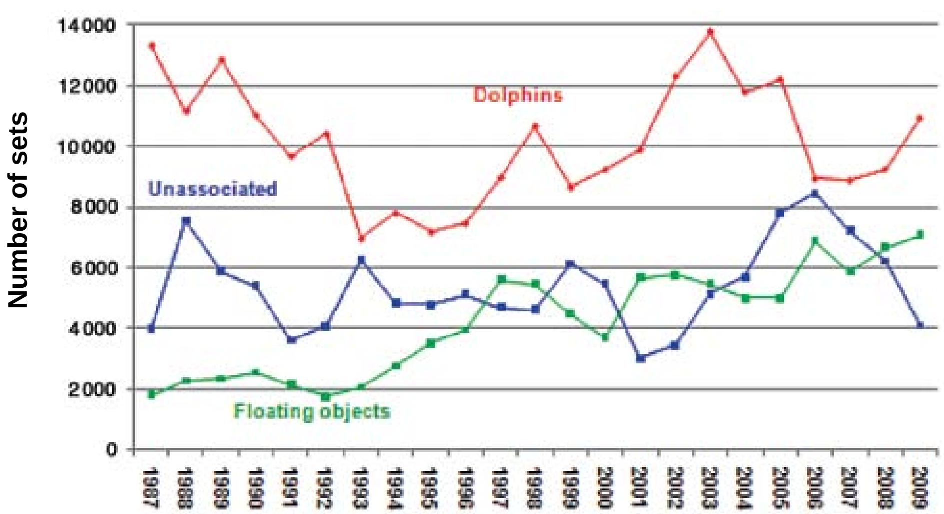
4. From log fishing to fishing on fish aggregating devices

The fishers began to modify encountered objects, tying two or three together, adding buckets with fish entrails, and adding devices to facilitate re-encounters (radar reflectors, flags, radio buoys). When an encountered object is modified in some way to enhance its attraction, and especially to improve the chances of locating it again, it is called a FAD (short for fish aggregating device) to indicate the human intervention in its characteristics. This definition of FAD was adopted early on, in the different observer programmes, and it was quite consistent across oceans.

During this period, there was still a reliance on encountered objects, but it became more common for fishers to transport the modified objects to other areas, if the vessel was changing its search area. Finally, fishers began to build and deploy their own floating objects, setting them adrift outfitted with different devices that allowed the tracking of their positions. The term FADs was used for these; the random encounters were replaced with a systematic planting of objects. These fishing operations are called FAD sets. The catches in these sets in all ocean areas are a mixture of skipjack, yellowfin and bigeye, with a clear predominance of skipjack. A characteristic of these sets is that the yellowfin and bigeye tend to be juveniles.

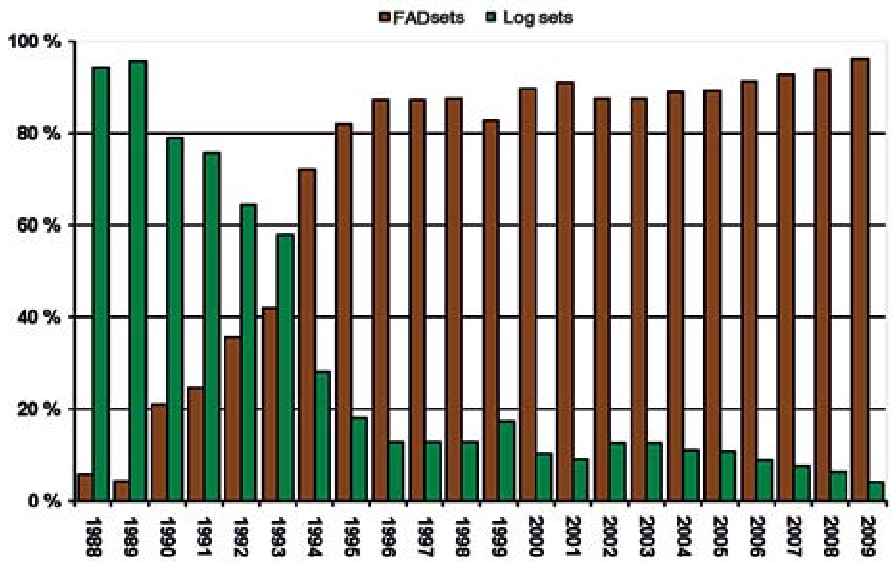
In the early 1990s, these fisheries for tropical tunas on floating objects deployed by the fishers expanded rapidly in all oceans (Fonteneau, 1993; Ariz *et al.*, 1999; Fonteneau *et al.*, 2000; Marsac, Fonteneau and Ménard, 2000; Gillett, McCoy and Itano, 2002). Fonteneau (2010) shows the geographical changes happening during the expansion of the fishery in the Eastern Atlantic. Figure 22 shows the recent growth in numbers of sets on floating objects in the Eastern Pacific, from 2 000 sets in the early 1990s, to more than 6 000 in the period 2006–09.

FIGURE 22
Number of purse seine sets by set type in the Eastern Pacific Ocean, 1987–2009



Note: Vessels > 364 tonnes capacity.

FIGURE 23
FAD sets versus logs, changes in percentage of sets in the Eastern Pacific Ocean



Source: IATTC Observer database.

In the late 1970s and early 1980s, there was a brief peak. Figure 23 shows the steady replacement of sets on logs by sets on FADs.

Figures 24 and 25 show the geographical expansion of the fishery on floating objects in the EPO.

However, FADs are not successful everywhere; areas with fast currents (Figure 26) tend to be the most productive for this way of fishing, and large sections of the ocean do not have the conditions for a FAD fishery.

FIGURE 24
Sets on floating objects: distribution prior to expansion of FAD fishery

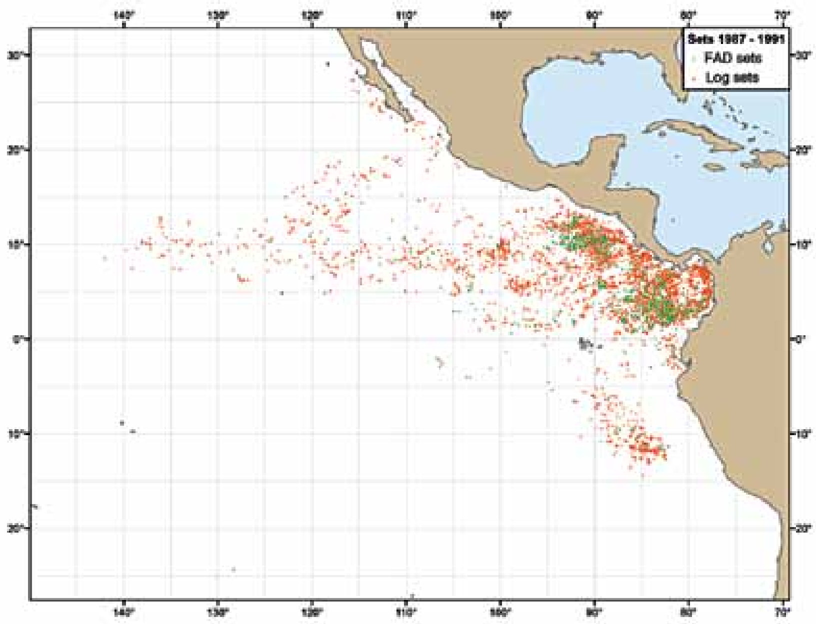


FIGURE 25
Sets on floating objects: Recent distribution

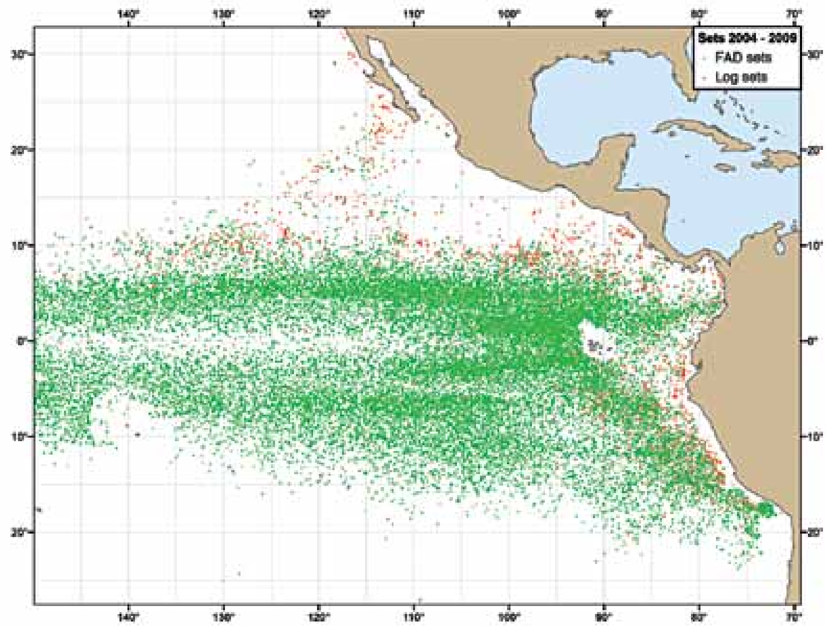
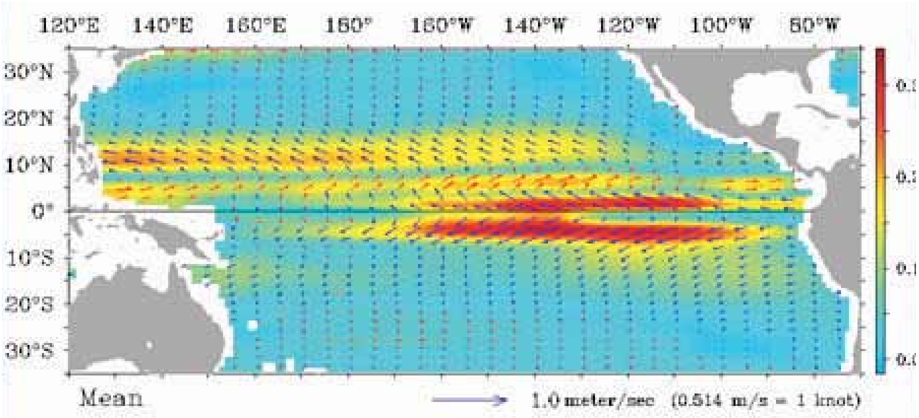


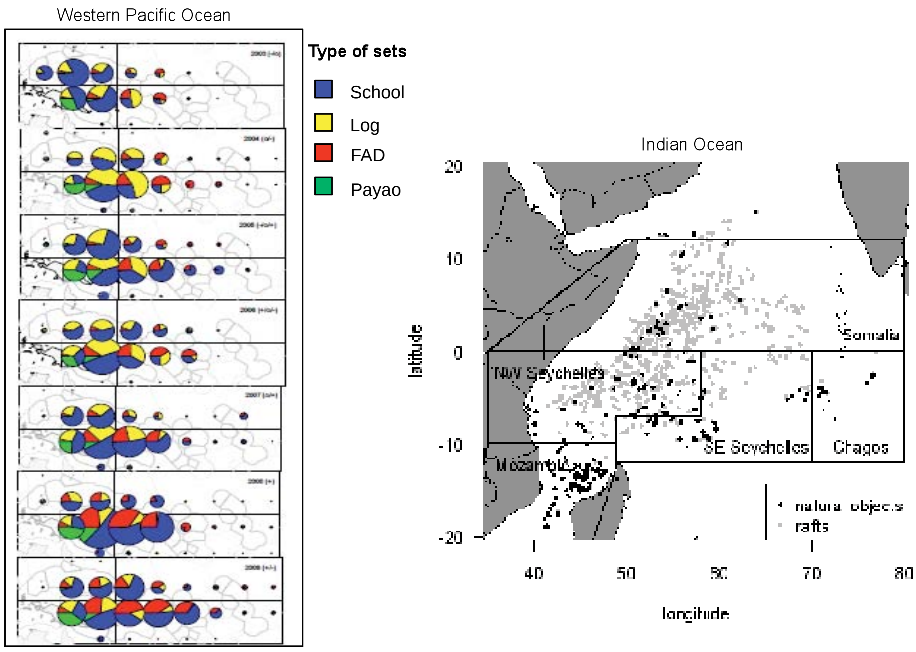
FIGURE 26
Ten-year mean Pacific Ocean surface current speeds, 1993–2002



Source: Bonjean and Lagerloef (2002).

Figure 27 shows the expansion of the fishery in the Western Pacific Ocean (WPO) (Williams and Terawasi, 2009) and in the Indian Ocean (Fauvel *et al.*, 2009). The relationship between current speed and FAD productivity could be a result of faster speeds meaning more distance covered, and more chances for detection of the FAD, or it could simply be that with fast currents the schools are closer to the FAD (Dempster and Kingsford, 2003), so their location and capture is easier. Are there large regions in the oceans where FAD fishing does not succeed, that hold large biomasses of tunas not vulnerable to the purse seine fishery? In general, the addition of FADs could simply increase the density of objects in an area, or it may create new fishing areas, but this expansion is limited by oceanographic conditions. The Western Indian Ocean may be an example of the former (Fauvel *et al.*, 2009), while the EPO could be an example of the latter.

FIGURE 27
Recent expansion of the floating objects fishery in the Western Pacific and Indian Oceans, 2003–09



Source: Williams and Terawasi (2009).

Over the years, the technology to locate the objects has evolved rapidly, and the radio buoys were replaced with self-call buoys, and later with satellite devices. Although the traditional objects have been surface floating objects, they can also be deployed below the surface.

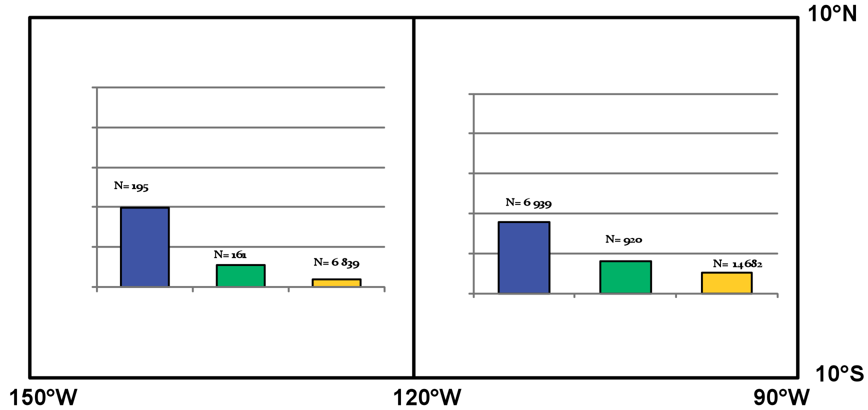
The success of the FAD fisheries is based on:

a. As the schools are "fixed" under the object, the capture process is effective in a very high percentage of the attempts (Figure 28). In the EPO, sets without capture (skunk sets) are 5–8 percent of the sets on FADs, but almost 30 percent of the sets on unassociated schools (Table 4). Skunk sets are less than 5 percent on FADs versus more than 25 percent in school sets for the Spanish fleet in recent years in the Atlantic (Delgado de Molina *et al.*, 2010b). For the Indian Ocean (Pianet *et al.*, 2009), a record of the proportion of skunk sets for 1981–2008 is available. The most recent years (2006–08) show that 8.5 percent of floating object sets are skunk sets, compared with 46 percent of school sets. Therefore, roughly, the odds of failing to capture the school are five times higher when it is not associated with a floating object. An *et al.*, (2009) report 40 percent of school sets as skunk sets for the fleet of the Republic of Korea in the Western Pacific.

b. the average capture per set is much higher under FADs than in school sets (in the EPO: 35–38 tonnes per set versus 20–25 tonnes for unassociated sets, with the comparison based in all sets, including null sets; Figure 29). This difference may result from different school sizes adopting different behaviours, or more probably, by more than one school being captured on FAD sets, from different or from the same species. This difference remains even if the skunk sets from both groups are eliminated, but it is reduced (48 tonnes in FAD sets versus 36 tonnes in school sets). In the Eastern Atlantic, the catch per set is used with only positive sets (i.e. sets with capture > 0), and even with this definition sets on floating objects have higher catches. In the WPO, the CPUE in tonnes/day for skipjack is higher in FAD or log sets than in school sets (Figure 27). In the Indian Ocean, for the French fleet, the CPUE when fishing on floating objects is more than 60 percent higher than when fishing school sets. In the Indian Ocean, there are data for the whole period 1981–2008, and for the main fleets (Pianet *et al.*, 2009): in 2006–08, CPUE in tonnes per searching day on floating objects was about twice the tonnage on school sets. These CPUE figures are not so comparable because the allocation of search effort between set types is far from simple. Catch per positive FAD set is 11 percent higher than in positive school sets. Although the dominant species is usually the skipjack tuna, the proportions of bigeye tuna are quite variable between ocean areas, with a higher abundance of bigeye tuna in FAD sets in the EPO than in the WPO.

c. The use of energy and other costs are greatly reduced as the search process is minimized in time and distance, although some of the FAD sets happen very far offshore from the ports of origin. The use of helicopters is less frequent in vessels fishing on FADs, and this is a major energy expenditure. The use of auxiliary vessels, in support of the FAD fishing operations, also changes the energy use, and it affects the efficiency of the operations (Ariz *et al.*, 1999; Pallarés *et al.*, 2001; Pallarés *et al.*, 2002; Goujon, 2004a; Itano, 2007). These vessels are banned in the EPO because their effectiveness enhanced the overcapacity problem. IATTC Resolution C99-07 reads, "2. Prohibit the use of tender vessels operating in support of vessels fishing on FADs in the EPO, without prejudice to similar activities in other parts of the world…." These vessels are not banned in other ocean areas. The auxiliary vessels could play a role in assessing the bycatch present under FADs, and contributing to better decisions by the fishers. However, perhaps the information provided by acoustics on the FADs may have similar benefits, with lower costs.
d. As the results of a) and b) contribute jointly to increasing the production of FAD sets, this fishery is much more productive than a fishery based solely on school sets. The combination of a much higher proportion of successful sets, where the school did not evade capture and a larger school when the capture is made results in substantial gains. The drawback is that average sizes of tunas caught on floating objects are smaller than in school or dolphin sets, so the bycatch of tunas is higher, and the value of the catch may be lower on a per-tonne basis (Pianet *et al.*, 2009; IATTC, 2010). Moreover, the yield per recruit of yellowfin and bigeye tuna are lowered because of the catches of sizes below the optimal.

FIGURE 28
Proportion of unsuccessful "skunk" sets in two areas in the Eastern Pacific Ocean, 2005–09



Note: Capture = 0 tonnes.

FIGURE 29
Capture per set (tonnes), in two areas in the Eastern Pacific Ocean, 2005–09

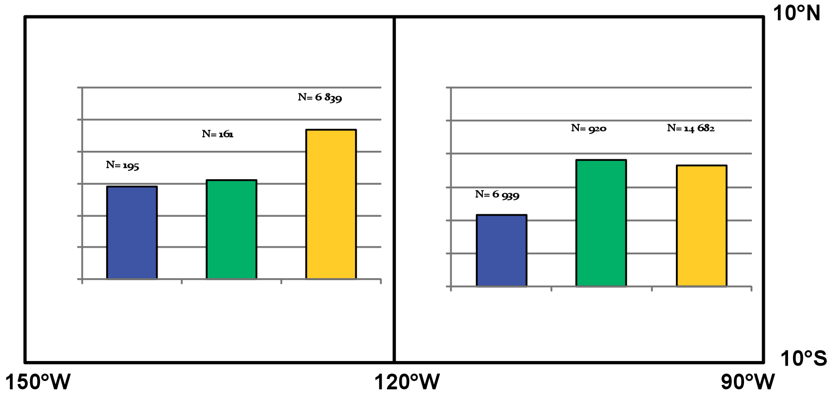


FIGURE 30
CPUE skipjack tonnes/day in the Western Pacific Ocean

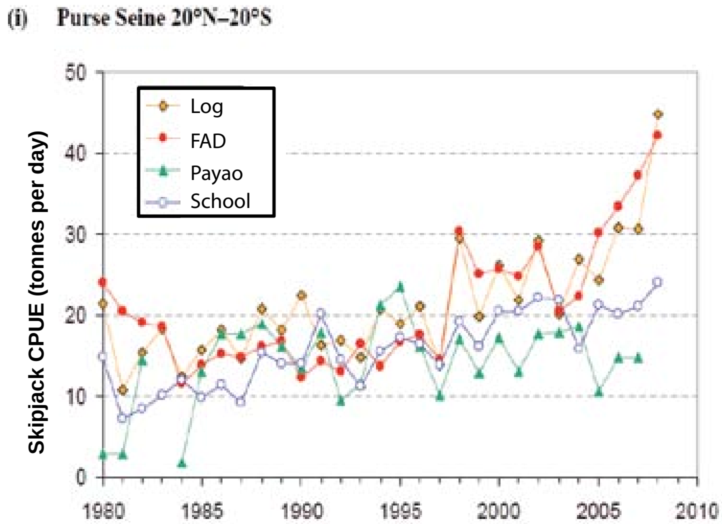


TABLE 4
Percentage of "skunk sets" (sets with zero capture) in the Eastern Pacific Ocean in two periods: 1999–2004 versus 2005–2009 by set type

		Number of sets by type						
Period	Capture/set	Dolphin	FAD	Log	Whale shark	Anch. Buoy	School	Whale
1994-2004	Cps= 0	7 024	2 164	743	5	44	12 554	81
1994-2004	Cps= 0	74 068	37 133	5 280	94	202	26 655	174
% "skunk" sets		**8.7**	5.5	12.3	5.1	17.9	32.0	31.8
Period								
2005-2009	Cps= 0	4 654	2 052	344	35	21	8 213	27
2005-2009	Cps= 0	36 048	25 707	2 111	463	135	20 134	88
% "skunk" sets		**11.4**	**7.4**	**14.0**	**7.0**	**13.5**	**29.0**	**23.5**

Source: IATTC observer database.

FISHING ON FLOATING OBJECTS

FAD characteristics, and operations on FADs

When the fishery on FADs started, there were many different designs of FADs in use, and with time they began to converge in a few models, but the construction and equipment of the FADs is very dynamic, and changes happen in a very short period. The dimensions of FADs are the result of a balance between attraction, which could be related to size (Rountree, 1989), and practical limitation on the seiner to carry them or the materials needed. The number of FADs deployed must also balance the ability of the vessel to track them, the costs of the instruments, current patterns, etc. There is a wide range of strategies in use. In the EPO, the observers were requested to provide more detailed information on the FADs, and since 2004, there has been a significant database on FADs. Some of the findings of the first few years are summarized in Tables 5–10. As most of the characteristics of the FADs, and of the way they are utilized are common to all oceans, the database from IATTC is used to provide the detailed descriptions.

FAD components and evolution

In recent years, the IATTC has started a programme to try to produce a full description of the FADs, as a way to track the changes taking place and their implications for the data collection efforts. In a way, changes in FAD characteristics or equipment may affect the fishing power of a vessel, and they should be tracked. Figure 31 and Plate - 29 shows a diagram of a common FAD from the EPO. Itano *et al.* (2004) provides descriptions off materials and construction of a variety of anchored and drifting FADs from the Western and Central Pacific.

FIGURE 31
FAD components

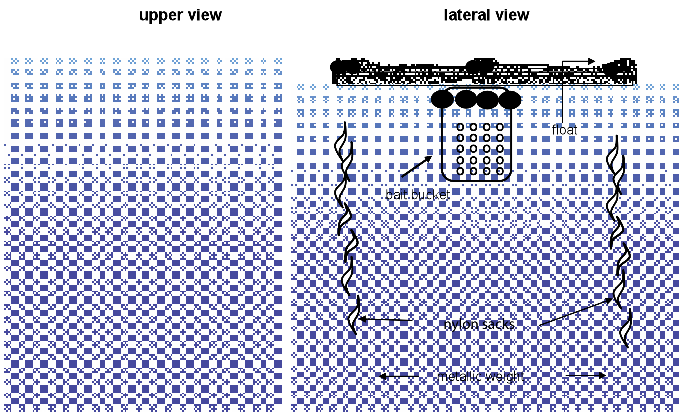


Table 5 shows the origin of the objects being set on. In the period 2005–09, two-thirds of the objects had been planted by the same vessel that was setting on them in the previous trip. Adding those planted by the vessel in a previous trip, and those transferred from another vessel, it results in almost 90 percent of the sets being made in “controlled” FADs, with 2 percent of the sets being made on encountered objects, and almost 10 percent “taken” from another vessel.

Table 6 shows the proportion of sets with the different components and attractive elements. Most FADs contain a common set of basic components: floatation elements (usually bamboo), ropes, netting material, and some weight.

PLATE 2
FADs stac ked on the upper deck

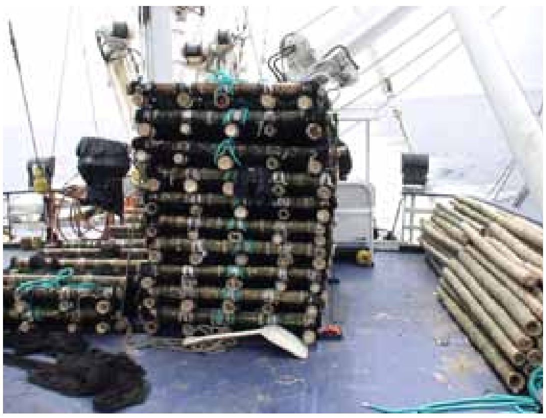


TABLE 5
Percentage of FAD sets by its origin in the Eastern Pacific Ocean (first FAD encounter only)

Floating object origin	2005	2006	2007	2008	2009
Drifting object found	2.3	2.3	2.2	2.1	1.8
Other vessel-no owner consent	10.4	10.9	9.6	10.7	9.6
Other vessel owner consent	18.5	14.9	14.8	16.6	16.6
Your vessel-planted previous trip	59.1	64.8	67.4	65.8	63.4
Your vessel-planted current trip	9.8	7.0	6.0	4.9	8.5

However, the table highlights some constant changes; for example, the use of PVC pipes, in addition to the bamboo frame, more than doubled in the four years of the study, probably reflecting an intention to increase long-term floatability, to prolong the use of the FAD, and to improve the chances of recovering the instruments deployed. FADs are being prepared to last longer, and this may have impacts on catch and bycatch. Plastic sheets, sacks and bags are used to enhance the visibility of the FAD, normally tied to the netting materials, and are included among the basic elements of the FAD in more FADs every year, with a five-fold increase in five years. Lights do not play a major role in attraction in this case. However, there are also opportunistic additions, such as dead animals, trees, etc., which are found and turned into FADs or added to FADs to increase attraction.

Weight is added to the FADs using chain, cables or metal rings in almost 75 percent of the FADs. About 24 percent of the FADs include a bait container hung under the FAD.

Table 7 shows the methods used by the fishers to locate the FADs based on the proportions of FAD sets. Visual markers on the FADs or radar reflectors are no longer important to locate the FADs. The detection of the FADs is now based on satellite systems that are replacing the radio systems used before. More than 90 percent of the sets made on FADs were on FADs that had a satellite system in 2009.

To complete the description, Table 8 shows the information that the instruments attached to the FADs provide to the seiner, which is also changing fast. Directional instruments are decreasing (down from 46 percent to 27 percent in the period of study), while GPS positioning has jumped from 70 percent to 98 percent. Information on tuna quantity and water temperature data doubled in frequency in the period, provided by acoustic and other instruments. Currently, 30 percent of FADs can report the tuna quantity present underneath, a figure double the percentage available four years earlier, saving the fishers from fruitless trips, and increasing the fishing power of the vessels.

Table 9 shows the rapid replacement of radio transmitters by satellite equipment, and the fast spread of instruments providing water temperature.

Finally, Table 10 and Figure 32 show the depth of the netting that the fishers hang under the FAD. This variable may be important to determine the attractiveness of the FAD for deeper species (Minami *et al.*, 2007; Satoh *et al.*, 2007; Lennert-Cody, Roberts and Stephenson, 2008). The vast majority of the FADs carry 10–30 m of netting underneath.

The effects of these differences are unknown, but several of them have the potential to affect the attraction characteristics, drifting speed, and duration afloat of the FAD, and in this way they may affect catch and bycatch on them. An example of this is the depth of the netting, and the inference that it may enhance the attraction to deeper swimming bigeye tunas, which has been the subject of several research projects to be discussed later.

The most sophisticated FAD attachments include rapidly improving acoustic systems to send to the vessel data on fish abundance under the FAD, an example of the technological creep that may affect fishing effort estimates (Marchal *et al.*, 2007).

TABLE 6

Percentage of sets with each FAD component in the Eastern Pacific Ocean

Component	2005	2006	2007	2008	2009
Artificial light for actracting fish	0.8	0.9	1.6	0.4	0.3
Bait container / bait	25.0	28.2	23.8	23.9	25.5
Cane / bamboo	84.3	85.0	86.8	87.3	88.5
Chain / cable / rings	83.9	73.2	75.0	80.0	83.4
Cord / rope	92.9	94.4	94.7	96.0	97.3
Dead animal	5.2	5.1	5.5	4.7	4.9
Floats / corks	88.9	82.6	84.6	80.8	81.5
Metal drum / plastic drum	5.5	7.8	5.5	5.9	7.2
Net material	98.0	97.3	98.0	98.8	99.3
Planks / pallets / plywood	8.2	6.9	6.2	5.0	5.9
Plastic sheeting	3.6	7.8	10.0	20.2	31.7
PVC or other plastic tubes	12.8	17.6	16.4	26.9	34.0
Sacks / bags	14.4	19.6	19.6	19.1	21.9
Tree	1.0	1.4	1.3	0.9	0.4

TABLE 7

Location method leading to a FAD set (percentage of sets) in the Eastern Pacific Ocean

Location method	2005	2006	2007	2008	2009
Direction finder	27.9	15.8	6.0	3.2	0.6
Radar	1.1	2.3	1.6	1.9	0.8
Satellite	62.8	72.9	85.0	86.6	91.5
Visual-birds	1.4	1.6	1.3	1.6	1.2
Visual-the object itself	5.9	6.3	5.2	6.0	5.5

TABLE 8

Percentage of FAD set by each transmission capability in the Eastern Pacific Ocean

Transmission capability	2005	2006	2007	2008	2009
Direction to the object	47.4	39.5	35.1	31.5	27.1
GPS	73.5	81.4	93.0	95.3	98.0
Tuna quantity	12.9	14.2	18.5	24.1	29.6
Water temperature	31.8	42.7	56.8	57.1	60.9

TABLE 9

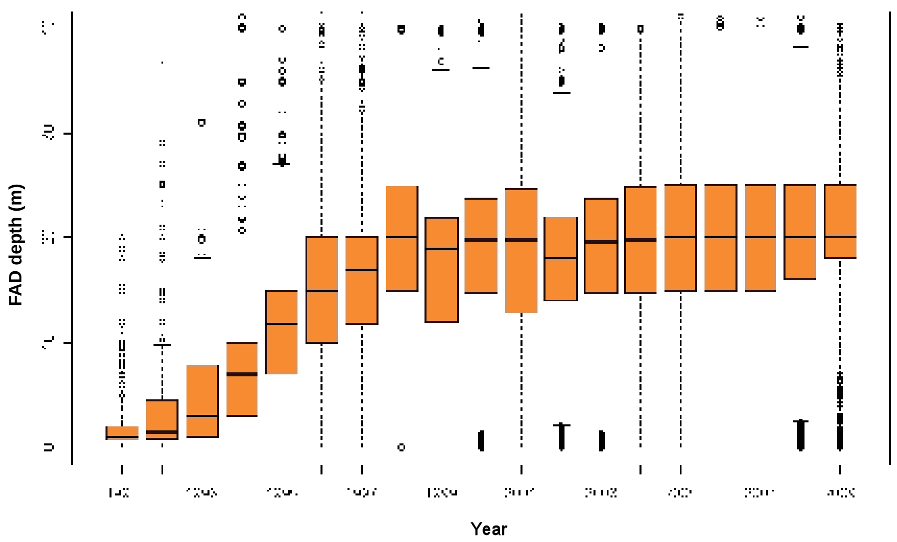
Percentage of FAD sets with each piece of equipment in the Eastern Pacific Ocean

Equipment	2005	2006	2007	2008	2009
Buoy, cork, etc.	7.3	6.7	4.9	3.5	2.6
Flag	4.6	5.8	5.3	4.1	1.5
Lights	7.1	5.7	9.3	5.7	3.5
Radar reflector	0.1	0.3	0.4	0.1	0.1
Radio transmitter / beeper	38.4	24.1	12.4	6.2	1.9
Satellite buoy	74.4	82.4	93.5	96.0	98.7

TABLE 10
Percentage of frequency of depth of net webbing under FADs set on in the Eastern Pacific Ocean

Maximum depth (meters)	2005	2006	2007	2008	2009
<10	7.7	10.5	7.2	7.0	5.5
10-20	36.7	34.4	38.9	37.2	33.7
20-30	46.5	43.0	43.2	43.7	49.0
30-40	8.4	11.5	10.0	10.8	10.3
40-50	0.6	0.6	0.7	1.3	1.2
>= 50	0.1	0.1	0.0	0.1	0.3

FIGURE 32
Depth of netting material hanging from FAD in the Eastern Pacific Ocean



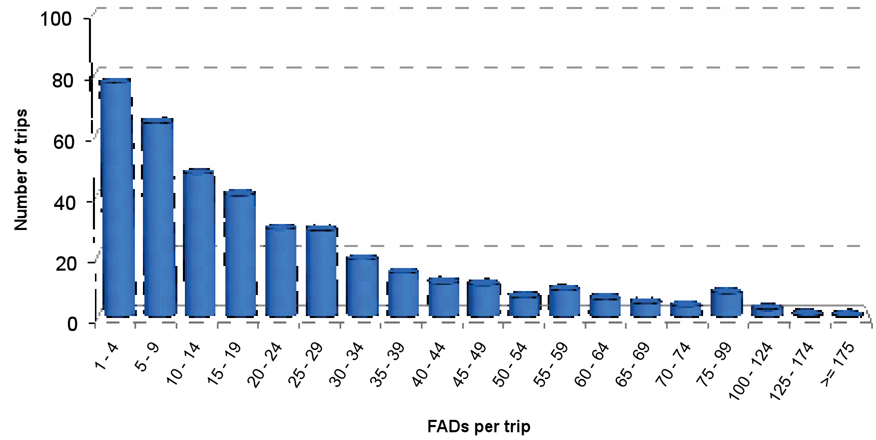
In most cases, the information available from logbooks or observers does not distinguish between sets on logs or FADs. As the IATTC has gathered an extensive database with 100 percent observer coverage from 1993 up to today, the data from this source are available to answer many detailed questions that cannot be answered for the other ocean areas. When the type of object is not specified, or a comparison cannot be made because there is no matching of data, floating object sets is used, as a generic combination of log, FAD, and payao sets.

FAD operations: deployment

Observers collect data on FAD deployment and utilization. The patterns obtained are quite consistent from year to year, with the probable exception of El Niño years. In the EPO, vessels sail to the equator, west of the Galapagos Islands (Ecuador) and deploy a series of FADs at the beginning of a trip. The number of FADs deployed is very variable, ranging from none to more than 170 in a trip. Figure 33 shows the distribution of FADs deployed per trip, for the period 2005–09. There is a long tail, with some vessels deploying more than 100 FADs in a trip, but for all trips the average is about 20 FADs, similar to the average of Mina *et al.* (2002) for operations in the Indian Ocean. Figure 32 illustrates the slowly increasing trend in the numbers deployed per trip.

The currents in the equatorial area take the FADs at a very good speed in a northwest or southwest direction, and the location of the sets suggests that, after some time, they all turn west. Figure 33 shows, as an example, data for 2006. With red symbols, it indicates the points of deployment, generally aligned along the route of the vessel, and with green symbols the locations of sets on those FADs. Based on these data, Figure 36 shows the vectors of movement, as if all the objects had been planted at the centre of the diagram, and a vector connecting the points of deployment and setting. The few deployments outside of this area were omitted. The length of each vector is proportional to the distance covered, and the vector with the scale (600 nautical miles) is shown in the map. There is a clear predominance of drifts towards the quadrant

FIGURE 33
Average of number of FADs deployed per trip in the Eastern Pacific Ocean, 2005–09



	2005	2006	2007	2008	2009
Fads deployed	4 455	8 003	8 390	9 594	100 771
Fads recovered	4 069	6 070	7 457	7 994	8 781

FIGURE 34
FADs seeded by trip in the Eastern Pacific Ocean

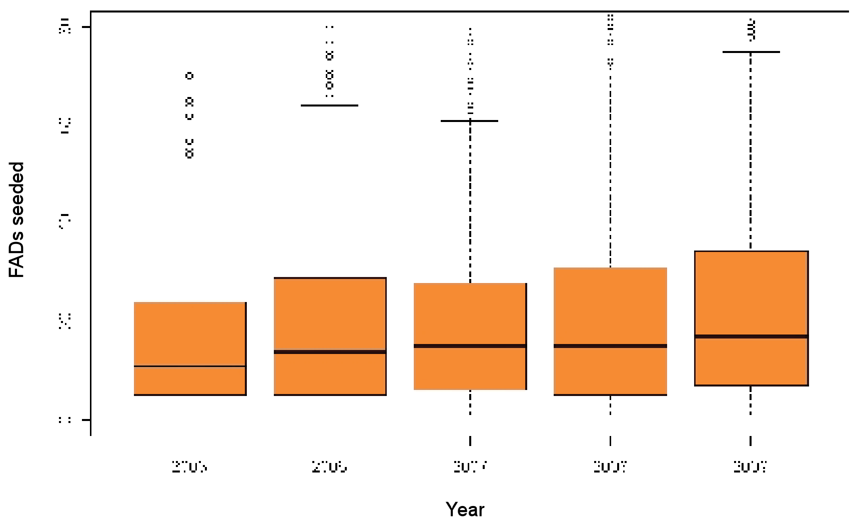


FIGURE 35
Location of deployment of FADs and the subsequent sets, 2006

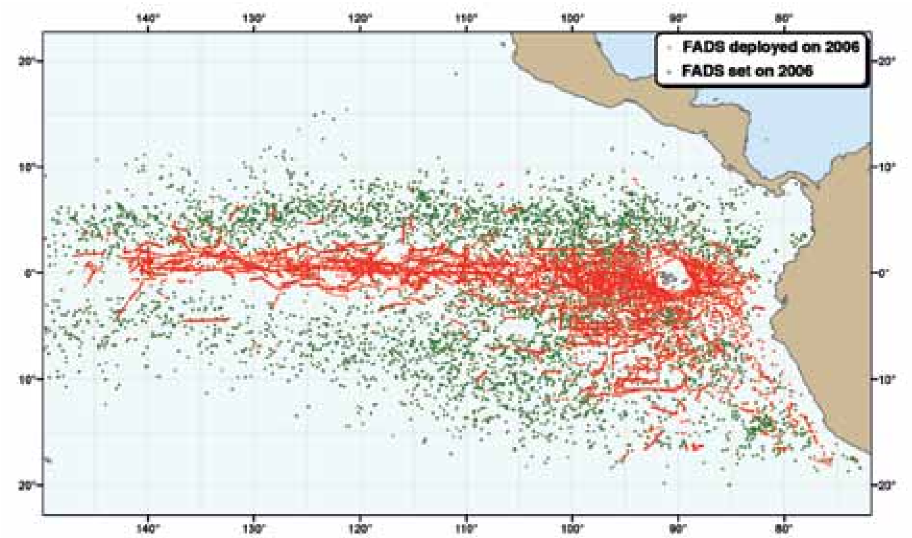
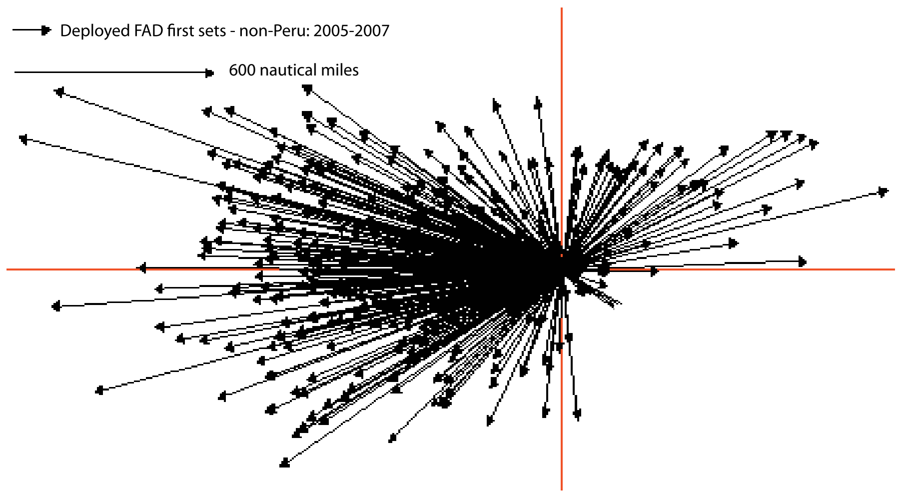


FIGURE 36
Vectors of FAD drift, from origin of deployment (centre) to first set – Eastern Pacific Ocean equatorial region, 2005–07

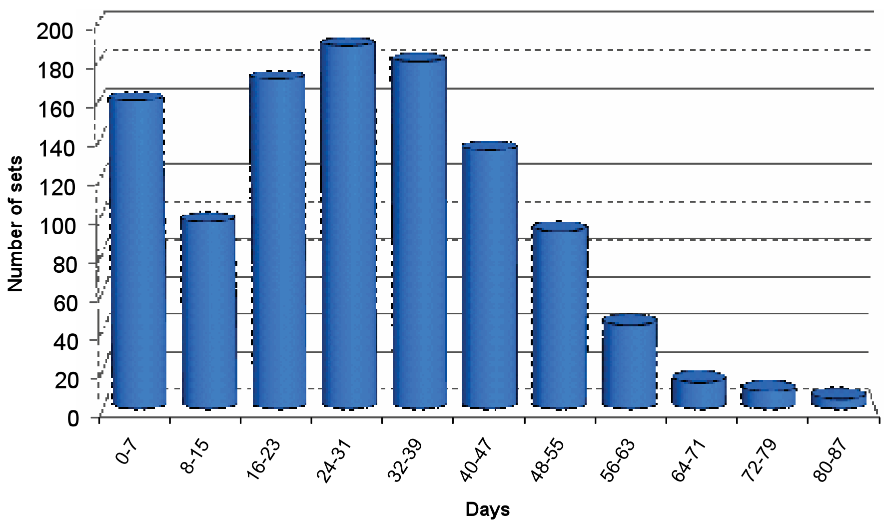


bracketed by the northwest and southwest direction angles (135–225°). The distances covered by the FAD are quite long, showing the speed and persistence of the current system (Figure 26).

FAD "soaking" time

Although some sets are made the day after deployment, most fishers prefer to leave the FADs drifting for some weeks before checking them. The mode is at about 30–40 days (Figure 37), and this choice may reflect practical considerations (such as length of trip, scattering of FADs), and an assessment of the time it takes to form a fully attractive

FIGURE 37
Time in days between FAD seeding and its first set (same trip) in the Eastern Pacific Ocean, 2005–09



community on a new object. There is also a concept that, after fishing a FAD, some time must elapse to renew its population (Cayre and Marsac, 1991).

Time of sets

The vast majority of the sets happen early in the morning, starting before the sun is up (Figure 38 and 39). Combining data from Fonteneau *et al.* (2010a), with data from the EPO, the modes appear either one hour before sunrise or just at sunrise for all fleets. Harley, Williams and Hampton (2009) show the same peak for drifting logs and FADs for the WPO, consistent across all fleets studied. Payaos have the same peak and an additional peak in late afternoon. Although there are suggestions that more sets in daylight hours are being made, the pattern as of today is clear. In the EPO, sets start a bit earlier than in the other regions. Only 5 percent or fewer sets are made 8 hours or more after sunrise. Only species associated with the FAD at this time of the day are going to be caught. In contrast, school sets, are distributed quite evenly during the day, with only a small decline towards the afternoon in the Atlantic and Indian Oceans (Fonteneau *et al.*, 2010a), or a small increase late in the day in the WPO (Harley, Williams and Hampton, 2009).

Duration of sets

The duration of sets is a key element to explore the possibility of releasing individuals from the net or deck. It is very variable, depending on vessel technology, gear characteristics, capture volume, etc. The duration of the sets, a crucial variable for the survival of species to be released, is shown in Figures 40–42 for the EPO. Three periods were used to look at trends. A large proportion of the sets take 2–3 hours to complete. The mode of the most recent period is shifted towards lower values, and the frequency of very long sets is decreasing with time, showing a shortening of the sets, which is clear on the cumulative distribution (Figure 41). The variability of the sets is best appreciated from Figure 42, which shows, for the period 2004–08, the complete distribution of the sets in a “gunshot” view. The vertical structures in the data arise from rounding-off of capture figures. Stretta *et al.* (1997) show very similar distributions for the Atlantic and Indian Oceans, with mode at 2 hours and 20 minutes, and a range of 2–3 h covering the bulk of the distribution. More recently, Delgado de Molina *et al.* (2005a) show for the

FIGURE 38
Percentage of FAD sets by time of day (hours before/after sunrise)

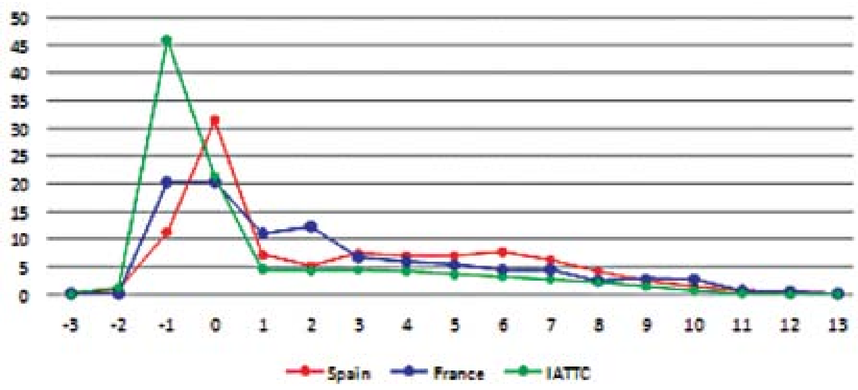
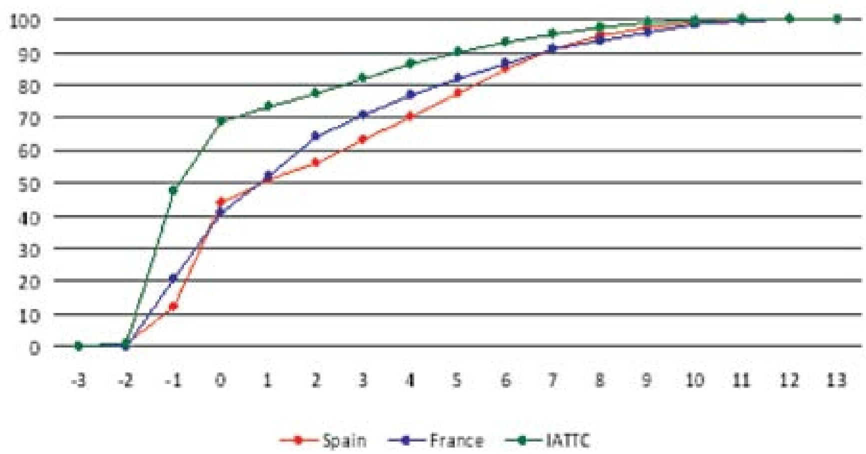


FIGURE 39
Cumulative percentage of FAD sets by time of day (hours before/after sunrise)



Sources: Fonteneau *et al.* (2010) and IATTC.

Spanish fleet in the Indian Ocean that most school sets are completed in 2–3 h (mode at 2–2:30 h), and that FAD sets last longer (2–4 h, with a broad mode from 2–3:30 h). Stretta *et al*. (1997) also offer a scattergram of time versus capture volume for both oceans, and Viera and Pianet (2006) fit regressions to duration of set as a function of capture, and obtain (a) an intercept of 1:30 h and a slope of close to one hour (0.9 h) added for every 100 tonnes in the capture in school sets, and (b) a similar intercept (1:35 h) and a slope of more than 20 minutes per hundred tonnes for FAD sets. In both regressions, the number of points is limited, and there are influential observations at high values that drive the fit, but the FAD regressions have a very low R^2, and their predictive value is poor.

Once a set is started, its duration can vary over a wide range depending on many factors, among them:

- net length and depth (affect speed of net recovery);
- winch power (affect net recovery);
- malfunctions (affect net recovery or brailing time);
- amount and sizes of tuna captured (affect brailing time);
- brailer capacity (affect brailing time);
- abundant bycatch or small tuna discarded delays the set as it is sorted;
- environmental conditions (rough seas).

FIGURE 40
Duration of FAD sets in the Eastern Pacific Ocean – frequency distribution, periods 1994–1998, 1999–2003, 2004–2008

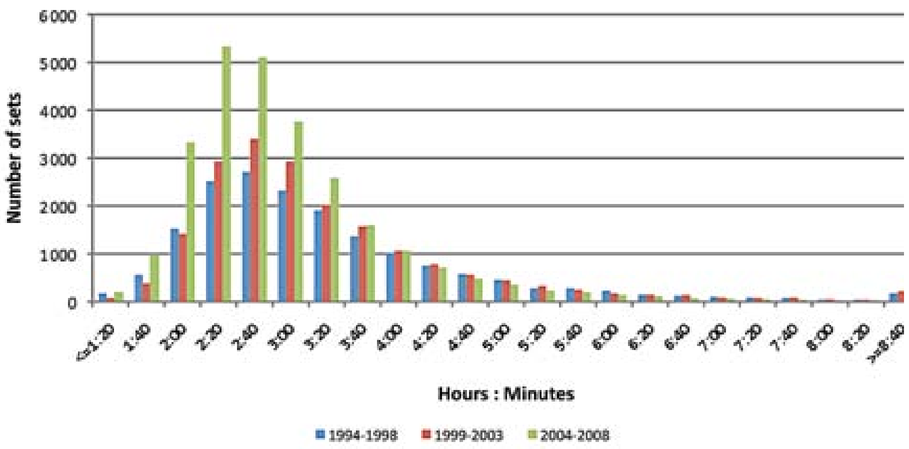


FIGURE 41
Duration of FAD sets in the Eastern Pacific Ocean – cumulative distribution periods: 1994–1998, 1999–2003, 2004–2008

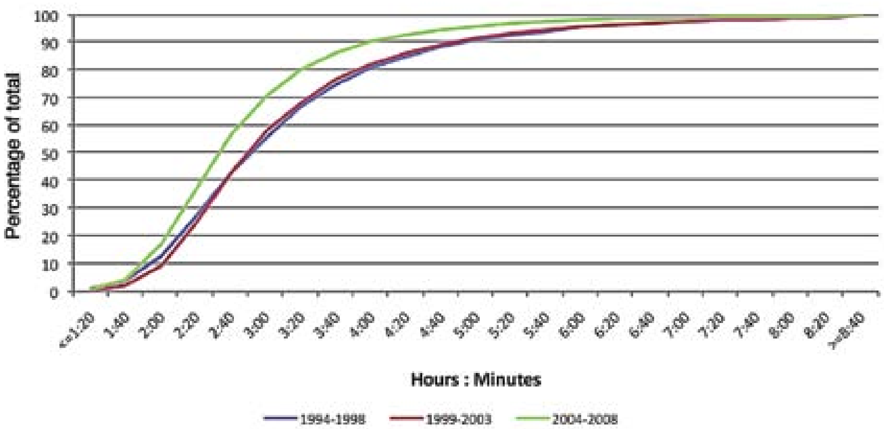
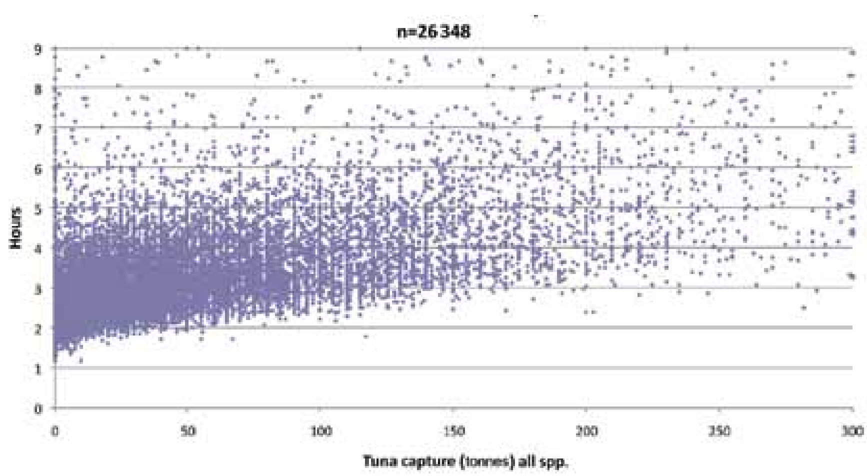


FIGURE 42
Duration of FAD sets as a function of tuna capture in the Eastern Pacific Ocean, 2004–2008

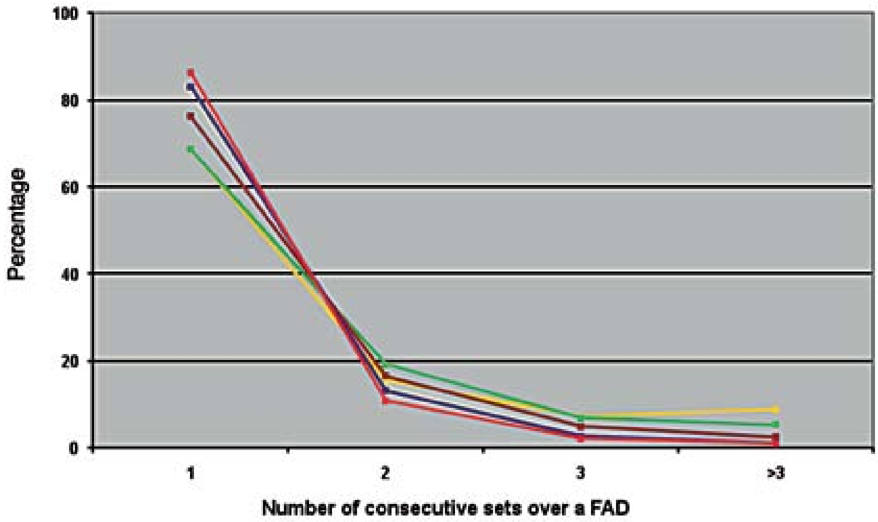


Number of sets made on an object

Many successful sets can be made on the same object. Figure 43 shows the number of repeated sets per FAD in the EPO, in different periods. The tendency is to decrease the number of repeated sets on the same FAD; the mode has always been one set, but the frequency of one-set FADs is growing. Catch and bycatch may change in successive sets, and a few studies have addressed the issue (Ariz *et al.*, 1991; Hall and García, 1992).

FIGURE 43

Proportion of number of consecutive sets on a FAD in different periods in the Eastern Pacific Ocean



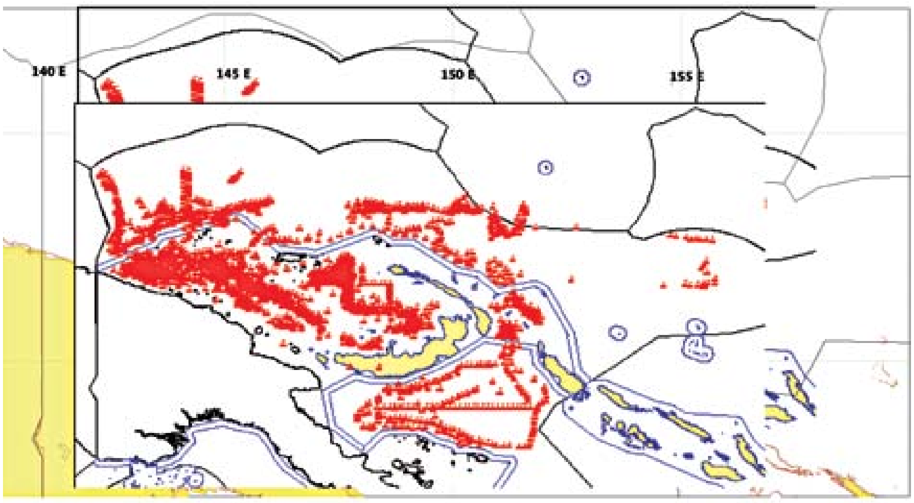
These types of data could be used to model survival of released species, when observer data are not available, and improve the mortality estimates. They also inform physiologists and others of the duration of the stressful conditions in the net, which may suggest which species may survive the capture process.

Fishing on payaos (anchored FADs)

Predating this use of drifting objects by several centuries, coastal fishers, many in island countries, had started deploying anchored objects to attract fishes (Désurmont and Chapman, 2001). In the Philippines, a type of anchored object using palm leaves to provide an attractive structure, called "payaos" has been used since the 1970s or even earlier (Greenblatt, 1979; Kihara, 1981; Matsumoto, Kazama and Aasted, 1981; De San, 1982; Brock, 1985a, 1985b). They are especially important in Papua New Guinea, where the deployment of FADs increased significantly in the mid-1990s (Figure 44–45; Leroy *et al.*, 2010) and in the Philippines, where they were blamed for reductions in tuna production in the early 1980s because of the higher vulnerability of very small tunas (Floyd and Pauly, 1984). There were about 2 000 payaos by 1981, some inshore, and some in deep water.

They are extensively used for tuna fishing in many locations in the WPO (Bromhead *et al.*, 2000; Itano, Fukofuka and Brogan, 2004; Kumoru and Koren, 2007; Sokimi, 2008, 2009), and also in the Caribbean, and to a much lesser extent in the Indian and Atlantic Oceans (Matsumoto, Kazama and Aasted, 1981; Preston, 1982; Boy and Smith, 1984;

FIGURE 44
Network of payaos around Papua New Guinea



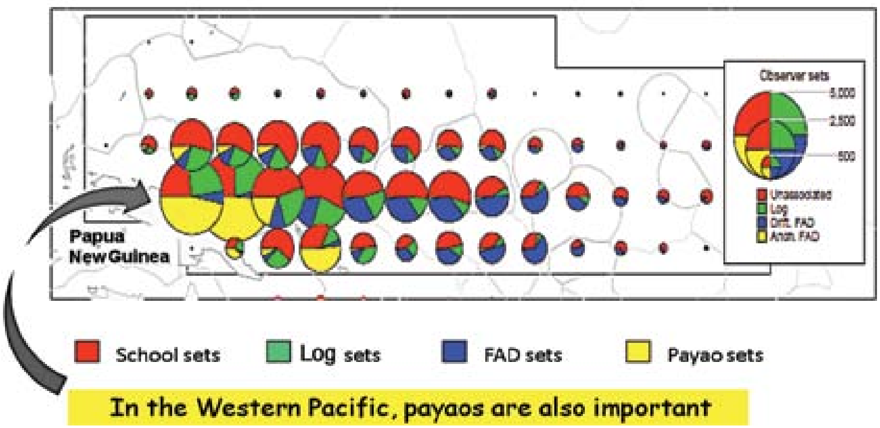
Note: 800 active ones.
Source: Kumoru (2002).

Frusher, 1986; references in Le Gall, Cayré and Taquet [2000b]; Taquet [2004]). They are not used in the EPO.

They were initially placed in coastal, shallow waters, and mainly utilized by small-scale artisanal vessels, but in some cases they have expanded into deeper, farther offshore locations, and they are been used by vessels of a wide range of sizes. The technology has evolved into more complex mooring systems (Désurmont and Chapman, 2001), with the support of the Secretariat of the Pacific Community through their technical assistance programmes (Anderson and Gates, 1996; Gates, Cusack and Watt, 1996; Gates, Preston and Chapman, 1998). The targets in these fisheries include tunas, but also a variety of other species. In general, the purse seine targets include mostly smaller sizes than the fisheries on unassociated schools, or drifting FADs (Babaran, 2006). Only in the WPO is a substantial part of the purse seine effort directed to payaos.

Besides these payaos, deployed with the goal of attracting fishes, there is another group of anchored structures deployed for scientific purposes. Oceanographic buoys

FIGURE 45
Distribution of floating objects in the Western Pacific Ocean



organized in arrays, or isolated, are also present in the fishing grounds of the tuna fleets. One example of these is the Tropical Atmosphere Ocean Project – Tropical Ocean Global Atmosphere Project with 70 buoys deployed in the Pacific Ocean (www.pmel.noaa.gov/tao/). Sets on these buoys are not enough for detailed analysis. A recent resolution (IATTC C-10-03) aims to discourage this practice, which may have negative impacts on research programmes that spend significant amounts of money to create these networks of data-collecting buoys. Similar networks are present in the Indian Ocean (www.pmel.noaa.gov/tao/doc/RAMA_BAMS.pdf) and in the Atlantic (www.pmel.noaa.gov/pirata/PIRATA_2008.pdf).

Payaos are deployed and maintained by fishers, or by local or national government agencies (e.g. the state of Hawaii, the United States of America www.hawaii.edu/HIMB/FADS/) for use by commercial and recreational fishers.

There are also other fisheries that utilize anchored FADs to attract other species but that may occasionally catch some tunas. An example is the fishery using “kannizzatti” or “cannizzi” in the Mediterranean (Sacchi, 2008), focused mainly on mahi-mahi (*Coryphaena hippurus*).

The name of payaos is used in this paper for anchored FADs of all types.

Within the group of anchored objects, there may also be differences in construction, materials, etc. Besides these, there are at least two variables that could affect the composition of catch and bycatch: (i) distance to the coast (island or continent); and (ii) depth where it is anchored. These two variables may affect potential sources of recruitment to the payao. Coastal, demersal or even benthic species may be attracted to the payao if the object is close enough to be detected by these species that may be absent in FADs drifting offshore, or in very deep waters. As the mooring technology advanced, they could be placed in deeper waters. Ideally, a 2 × 2 matrix, coastal vs offshore, shallow vs deep would allow for all comparisons if there were enough data.

When all these categories, logs, FADs, and payaos, are lumped together, or when there is no clear description of which type is been used, the name “floating object sets” is used in this paper, implying that data for FADs, logs and payaos have been pooled together, or that there is no specific identification to separate the data into categories. Hence:

- Floating object sets = log sets + fad sets + payao sets
- Occasionally, some authors may separate:
- drifting objects = logs + FADs (or dFADs for drifting FADs)
- anchored object = payaos (or aFADs for anchored FADs)

It is important to complete the research needed to conclude, on solid statistical grounds, whether this pooling is an adequate description of the heterogeneity of the data, and decide on the level of discrimination needed. Not enough stratification and too much stratification are both problems to be avoided. As the majority of the data available from all t-RFMOs are aggregated, most analyses will have to be based on aggregate data to allow for comparison, but some discussion on the possible sources of differentiation between logs, FADs and payaos will be useful in order to explore the reasons.

A classification of floating object sets

Anchored versus drifting objects

It is not known if the mechanisms of attraction and the behaviour of the different species around anchored objects is the same as in drifting ones, but environmental conditions around anchored and drifting objects may be quite different because:

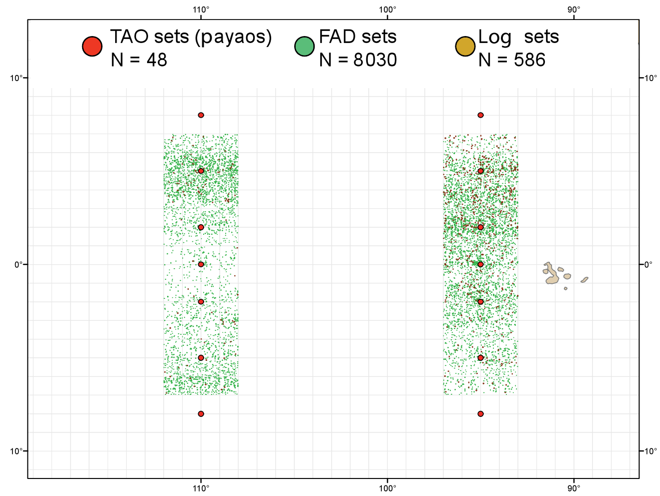
- The resistance of the anchoring system to the currents may create oceanographic structures in the water column, absent or different in a drifting FAD.

- The anchoring system may bring up tunas from deeper layers to the FAD (e.g. more bigeye tuna attracted to anchor FADs).
- The drift over a long track may allow more species and more schools to encounter a drifting object than an anchored one.
- The movement of the anchoring system caused by the passage of waves, and the currents may create sounds and vibrations that may affect the ability of tunas and other species to detect the structures or their attraction (e.g. Babaran et al., 2008).
- The colonization of the anchor system and of a FAD by marine species, including those growing on the structure, and those more closely associated with it, may be quite different, and that may affect the attraction of the objects.
- The structures hung by the fishers under drifting FADs (netting, bait buckets, etc.) may be different from those more commonly used under anchored FAD (e.g. palm fronds under payaos, or instruments in oceanographic buoys).
- The anchored objects may tend to have a more coastal, or shallow distribution, and the drifting objects may be set on much farther offshore.
- The demersal species or benthic species that may associate with anchored objects especially with shallow ones may not have any contact with drifting objects.
- These differences may affect the species, and size composition of the communities associated with the objects, their temporal persistence, or the diel patterns of their association (Dempster, 2004; Perkol-Finkel et al., 2008), and the diets of the species (Brock, 1985b).
- Logs versus FADs
- Are there structural differences between logs ("encountered objects") and drifting FADs ("deployed objects built for this purpose") that may affect their attractiveness for tunas, or their retention?
- FADs are built with underwater components to enhance their visibility, and perhaps also their attractiveness to tunas (netting, bait buckets, etc.). Some logs may have significant underwater profiles (e.g. trees with many branches, trees that may float vertically, dead whales) but in most cases the underwater profiles will be absent, or less deep, than in the case of FADs.
- FADs also have components to add floatability (buoys, floats, PVC tubes) that may result in longer periods floating.
- The transmitting devices that facilitate relocation are usually tethered to the FAD, so FADs have two components, and logs usually only one. As a result of the presence of the transmitting devices, FADs will be set more frequently than logs. If repeated sets on an object, especially when repeated over a short time span, have differences in species composition or abundance (e.g. lower abundances because of shorter time to renew the biomass removed), then FADs will show these differences.
- The prevalent FAD design (a bamboo raft) sits quite flat on the water, partially submerged; logs may also be flat (e.g. a tree trunk, a seaweed patty, a pallet), but there are some with significant aerial components (e.g. full trees, large boxes).
- The drift patterns and the drifting speed may be affected by both the underwater and the above-water components.

To make statistical comparisons between all these types of sets, logs, FADs and payaos, there are very few datasets with the sample sizes needed. The number of payaos is only sufficient in the WPO, and, even there, there is a whole array of depths, and distances to land masses that may make even the payao data heterogeneous. FADs and logs in some cases are set on in different areas or seasons, with a confounding effect on the figures.

A simplistic examination of two areas of the EPO (Figure 46) where there are a few anchored oceanographic buoys that receive some sets showed similarities and differences shown in Figures 47 and 48. With very close to 100 percent observer

FIGURE 46
Area for comparative study between floating object types in the Eastern Pacific Ocean

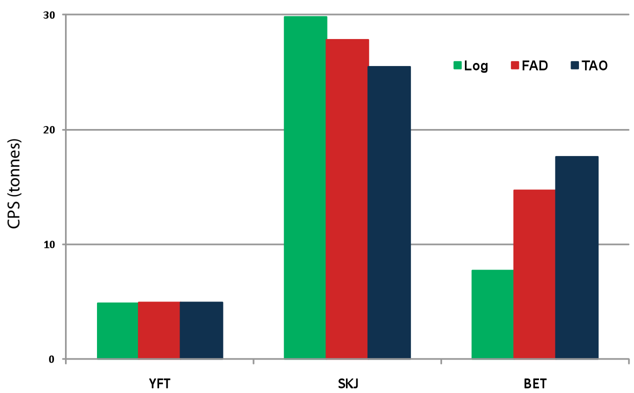


coverage, the observer estimates may have some errors because of misidentification of species, or inaccurate estimates of numbers or weights, but they are not expected to be significant, so the observed differences reflect the total number of sets in those areas. Comparisons of different years show similar patterns.

For the main tuna species, the results are quite different (Figure 47). Yellowfin tuna, the least abundant under objects, shows no differences in the captures in the three types of sets. Skipjack tuna increases from payao to FAD to log, with a maximum change of 15 percent (higher on logs than on payaos). Bigeye tuna capture per set is almost double in payaos than on logs (17.5 tonnes vs 7.7 tonnes per set), the most striking difference. FADs (14.7 tonnes/set) are closer to payaos. What payaos and FADs have in common is that the vertical dimension of the object is generally much longer than in logs. The vast majority of logs have are only from a few inches to a couple of metres in vertical profile, as opposed to 25–35 m in FADs, and much more on these payaos, anchored in depths of thousands of metres of water. As a result of this, it is possible that FADs and payaos may attract the deeper swimming bigeye tuna more effectively than the shallower logs. Another possible explanation for the difference is that the residence time of the bigeye tuna may be longer at anchored objects, so more schools are aggregated under payaos over time.

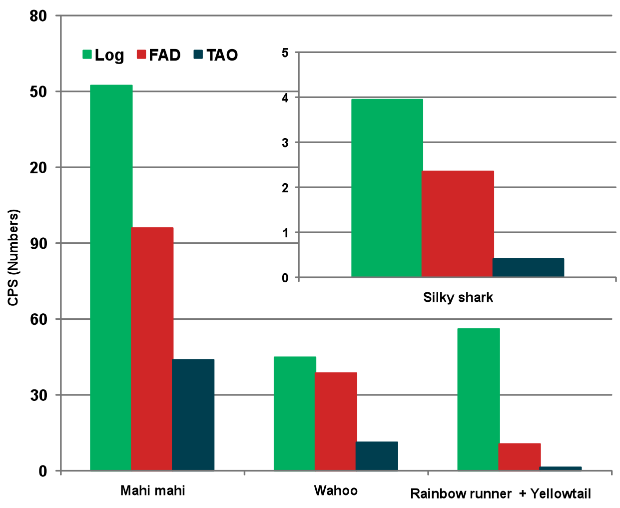
Figure 48 shows the weight per set (WPS) (capture per set [CPS] in tonnes) for a few other species that may be part of the catch or bycatch. For these, the differences are much higher. Payaos have very little associated fauna, compared with FADs, and logs are much higher than the other two. For these species, there are very large differences. Logs have many more silky sharks, mahi-mahi, and rainbow runners than FADs, and both are much higher in the density of all species than the anchored buoys. The question is whether these differences are real, or: (i) an artefact of the changes in the fishing operation required by the presence of the mooring, which may cause the loss of some fish from the payao set; or (ii) a result of the fact that many of these moored oceanographic buoys are in a less-productive water mass (warmer, and flowing to the east) than the FADs or logs that could be

FIGURE 47
Capture per set of major tuna species by type of floating object in the Eastern Pacific Ocean



TAO are anchored buoys (payaos)

FIGURE 48
Capture per set of silky shark and pelagic fishes by floating object type in the Eastern Pacific Ocean



spatially near, but in a different oceanographic setting. A finer analysis is required. These differences may be the result of different modalities for fishing on anchored versus other objects (Itano *et al.*, 2004), but they are not valid reasons for the FAD–log disparities. Some possible reasons are that FADs are set more frequently because they are being tracked, and this reduces the associated fauna by depletion, or that logs may come from areas where the initial colonization is more important. The drift speed of FADs and logs may result in differences. In any case, the extrapolation of data from anchored to drifting and from logs to FADs or vice versa should be handled with great caution.

Kumoru (2007) found very few differences between the catch and bycatch comparing anchored with drifting objects, in a small sample off Papua New Guinea. The tuna species present, and most of the species associated, were in similar proportions, and of similar size compositions. An exception was the silky sharks, with large individuals prevailing in anchored objects and smaller ones under drifting objects. However, the location of the payaos or FADs makes a difference (e.g. Kumasi *et al.*, 2010).

Sets on slow-moving species (whale sharks and whales) are sometimes included as log sets, (EPO), sometimes as school sets (whale sets in the Atlantic and Indian Oceans). In this review, they are not considered in detail because: (i) they are uncommon in most oceans, and the databases are too limited to compare their characteristics with the others; and (ii) as they may vary in depth and speed depending on the species, and on their behaviour, it is not obvious that they should be pooled into a single group. Therefore, it is hard to decide whether they are just another "drifting" object, or whether they belong in a separate group, or in several groups. Dead animals are included in the log group.

Nomenclature of floating object sets

When the fishery started modifying objects and adding radios to them in the EPO, the IATTC adopted an operational definition to separate them from the natural floating objects, encountered by chance. Fish Aggregating Devices (FADs) were then defined as: "Objects constructed and deployed, or encountered and modified by the fishers, to attract fish, and to facilitate their aggregation and capture, outfitted, in most cases, with a system to aid in their relocation. They can be anchored or drifting."

The Conservation and Management Measures Nos. 2008-01, and 2009-02 from the Western and Central Pacific Fisheries Commission (WCPFC; e.g. in its Sixth Regular Session, Papeete, 2009), defined FADs as:

"The definition of a FAD in footnote 1 to CMM 2008-01 [For the purposes of these measures, the term Fish Aggregation Device (FAD) means any man-made device, or natural floating object, whether anchored or not, that is capable of aggregating fish.] shall be interpreted as including:

"any object or group of objects, of any size, that has or has not been deployed, that is living or non-living, including but not limited to buoys, floats, netting, webbing, plastics, bamboo, logs and whale sharks floating on or near the surface of the water that fish may associate with."

The main differences with the definition proposed here are that logs, FADs and payaos are all lumped together, and that living organisms are also defined as FADs. There is a linguistic issue in that a tangle of floating seaweed, a tree trunk carried to the ocean by a river, or a whale shark are not devices as such, i.e. a piece of equipment or a mechanism designed to serve a special purpose or perform a special function.

From the point of view of management, there are enough differences in the species composition and sizes that associate with the different types of attractors that a separation in these types will help pinpoint the targets for management actions.

This paper uses a simplified nomenclature, recognizing the historic origin of each type of floating object. All objects are classified as FADs, logs or payaos (Table 11).

TABLE 11
Simplified nomenclature of floating object sets

	Anchored	Drifting
Encountered	n.a.	log
Deployed	Payao (= anchored FAD)	FAD

Note: n.a. = not applicable.

The major categories are anchored versus drifting objects. Most scientists agree that the behaviour of many species around anchored objects is not the same as around drifting objects, and these differences were the basis for the separation. These were discussed at length at workshops in La Jolla (Scott *et al.*, 1999) and Martinique (Le Gall, Cayré and Taquet, 2000a). This stratification of anchored versus drifting is expected to have some impact in the Western and Central Pacific where sets on payaos are very important in a section of the fishery. In the other oceans, the proportion is much lower, to the point of being negligible.

Beyond this, the level of stratification needed to separate meaningful units has not been demonstrated. Do catch and bycatch under FADs and logs made in the same area, and roughly at the same time, differ? Not all FADs are equal, although the designs seem to be converging. Not all logs are equal. Are objects with netting hanging underneath, equivalent to objects without it (e.g. Lennert-Cody, Roberts and Stephenson, 2008)? Which characteristics of FADs and logs make a difference?

Although encountered drifting objects have been used for many years (Stretta and Slepoukha, 1983; Ariz *et al.*, 1999; Hall *et al.*, 1999b), the introduction of the drifting FAD fishery had a major impact on the production of the tuna fisheries in all oceans of the world within a relatively short period (Fonteneau *et al.*, 2000). Figure 23 shows, for the EPO, the switch in predominance from "encountered" objects, to deployed objects; by 1994, the deployed objects had become the prevailing way of fishing on floating objects.

As the fishery on deployed drifting objects (FADs) has substantially replaced the fishery on encountered objects, the more recent information is dominated by the former in most oceans of the world. Differentiating a set on a floating object from a set on a school of tunas that happened to be close to an object is not always obvious, because some objects may be submerged. For regulatory reasons, sets on objects have been defined as sets within 500–1 000 m from an object by some t-RFMOs that needed the definition in order to enforce some recommendation. However, in practice, as the vast majority of the sets on floating objects happen early in the morning, and the vessel has approached the object before setting, and without searching, it is not so problematic to determine the type of set in those cases (Harley, Williams and Hampton, 2009).

The fishers had to find the right areas for FAD deployment and drift, and when that was determined, the scale of the harvest grew consistently. There are also areas where drifting FADs have been deployed, and they have not produced profitable catches. Hence, only a portion of the range of the tropical tunas is being fished with FAD. The areas where FADs are effective do not always coincide with the areas where encountered object sets were important prior to the increase in the FAD fisheries; thus, a major geographical shift in fishing effort has happened in some ocean areas.

This review distinguishes, where possible, between anchored and drifting objects. Drifting objects (encountered or deployed) are today the most common technique to catch tropical tunas in all oceans of the world. In many cases, the information available does not distinguish between these types. As the IATTC has gathered an extensive database with 100 percent observer coverage from 1993 up to today, the data from this source are available to answer many detailed questions that cannot be answered for the other ocean areas.

Another issue that has some scientific interest is the classification of fishes into associated with or aggregated under a FAD (Castro, Santiago and Santana-Ortega, 2002). From the point of view of this review, the significant fact that separates groups is whether they are captured in the set or not, rather than the motivation to be close to the FAD.

HYPOTHESES ON THE ASSOCIATIONS OF DIFFERENT SPECIES WITH FLOATING OBJECTS

Some marine species are attracted to floating objects, and associate with them for varying amounts of time. Some spend a few hours; others are associated for prolonged periods. Some species are very close to the object, while others are more loosely associated. Parin and Fedoryako (1999) have described, and given names to, these communities associated with objects, based on their proximity to the object. There is a very high level of similarity in the composition of those communities in all oceans of the world. They call the components of the community living in very close contact with the object the "intranatant", those present within 2 m of the object the "extranatant", and those outside this radius and up to 10 m the "circumnatant".

Various reasons have been proposed to explain the association of some fish species with floating objects, and it is probable that different species or sizes of fish associate for different reasons. There are several competing hypotheses on the subject, and some excellent reviews are available (Dagorn and Fréon, 1999; Fréon and Dagorn, 2000; Castro, Santiago and Santana-Ortega, 2002; Dempster and Taquet, 2004; Dempster, 2005). Many of the hypotheses suggested do not apply to tuna schools (e.g. spawning substrate, cleaning stations, protection from predators, and substitute of the sea bed). The stomach contents of payao-associated or FAD-associated tunas usually have less food than those of tunas caught in school sets (Brock, 1985b; Batalyants, 1993; Buckley and Miller, 1994; Ménard *et al.*, 2000a; R. Olson, personal communication, 2010). Thus, food does not appear to be part of the attraction mechanism for tuna schools. As the association appears to be mostly nocturnal for tunas around drifting FADs, visual stimulus or shade attractions do not seem likely. Some authors believe FADs operate as a nursery habitat for some species (Castro, Santiago and Santana-Ortega, 2002; Andaloro *et al.*, 2007). For small individuals, the floating objects can provide some protection from predators (Gooding and Magnuson, 1967; Hunter and Mitchell, 1967; Mitchell and Hunter, 1970; Rountree, 1989), although predators of small fishes are also associated with FADs.

This leaves a few hypotheses, the main ones being that the object is a meeting point to re-form schools (Soria and Dagorn, 1992; Freon and Misund, 1999; Soria *et al.*, 2009), or that the object is an indicator of a productive water mass (Hall, 1992).

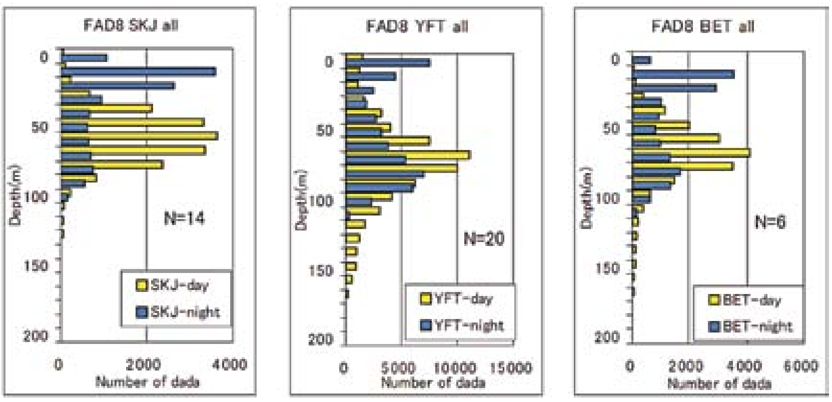
According to the first one, tuna schools spend time foraging, and in the process the schools may become smaller than optimal, or individuals may become separated from the school; after a day or days of foraging, the schools seek floating objects, and re-aggregate into larger schools (Dagorn, 1994; Fréon and Dagorn, 2000). Simulation studies support this hypothesis, and show its evolutionary advantages (Dagorn and Fréon, 1999), and some experimental evidence agrees with the predictions (Soria *et al.*, 2009).

According to the second one, when tunas encounter floating objects in the oceans, their presence is an indicator of a productive water mass (e.g. because of terrestrial contributions, currents aggregating materials), and by associating with the object during the night, they make sure that they do not swim away from the productive area, as could happen if they swam randomly during the night. Natural floating objects originate in, are retained in, and in some cases may also drift to, areas of high productivity. The retention of floating objects in some coastal regions may not only keep small individuals in a productive area, but also may keep them away from predators.

As the association of tunas with objects began millennia before humans introduced debris in many areas, it is possible to see that the main areas of the natural floating objects fisheries coincide with areas of major continental inputs to the coastal zone. The characteristics of these areas include: abundant coastal vegetation, well-marked dry and rainy seasons, and significant freshwater flows to the oceans (large or many rivers) to transport materials (Hall *et al.*, 1999b; Scott *et al.*, 1999).

Most of the sets on FADs are made very early in the morning (Stretta *et al.*, 1997; Goujon, 2004a; Fonteneau *et al.*, 2009; Harley, Williams and Hampton, 2009), because the fishers believe that the largest numbers of tunas are aggregated under the objects at that time, and research supports this (Figure 49). This supports the idea that the association is mostly nocturnal, although observations and sets confirm that there are some schools under FADs during daylight hours (e.g. 17 percent of successful sets in the Indian Ocean [Hallier and Parajua, 1999]). For payaos in the WPO, there is also a sunrise peak and a much smaller secondary peak in the frequency of sets at sundown (Hampton and Bailey, 1999; Harley, Williams and Hampton, 2009). Other species present at the time will be taken, regardless of whether they are permanent residents on the FADs or transient. Some of the species may be associated with other species, and not directly with the object itself.

FIGURE 49
Vertical distribution of three tuna species around drifting FADs



Source: Matsumoto, Okamoto and Toyonaga (2006).

Tunas do not associate with objects to find food – their stomachs are generally empty when they are caught in sets on objects (Hallier and Gaertner, 2008). As is known from other areas where objects are not present, tunas do not need to associate with objects. Therefore, for the behaviour to develop, there must be some evolutionary advantage in doing so. However, the distribution of the FADs is not the same as that of the natural objects, and it is possible that the behaviour has turned maladaptive (ecological trap hypothesis), or at least lost the original adaptive value.

There are no controlled sets to compare the fauna that could be captured in sets in open waters but in the vicinity of drifting FADs. School sets made in the same region as where the FAD fisheries are operating are only made after detection of some activity of the tuna school, so it is not the result of a random process. Not all tuna species and sizes associate with floating objects. Large yellowfin and bigeye are not common under objects in the Pacific (Kumasi *et al.*, 2010; IATTC, 2010), but larger sizes of yellowfin and bigeye are found under FADs in the Atlantic and Indian Oceans (Fonteneau *et al.*, 2005). It is not known whether this lack of association reflects the fact that the objects are found in a habitat unsuitable for these individuals (because of temperature, oxygen, prey availability, etc.), or if the objects are not detected by the schools (e.g. fishes are in deeper water), or are not attractive to them, or if they are associated, but at a distance that prevents their capture in the sets.

BEHAVIOUR OF DIFFERENT SPECIES AROUND FLOATING OBJECTS

The behaviour and ecology of different species around anchored or drifting objects have been the focus of several research projects in recent years. The studies of rafting ecology were reviewed by (Thiel and Gutow, 2005a, 2005b), and cover most groups of marine organisms.

The behaviour of large pelagic fishes around floating objects has also generated much interest. Following the initial studies of Hunter and Mitchell (1968), and Gooding and Magnuson (1967) using visual means, ultrasonic telemetry has been used to describe the behaviour of the larger species (Holland, Brill and Chang, 1990; Cayre, 1991; Klimley and Holloway, 1999; Dagorn, Josse and Bach, 2000; Schaefer and Fuller, 2002; Girard, Benhamou and Dagorn, 2004), and there are a few studies of small individuals of the larger species, e.g. Babaran *et al.* (2009) tracking 22–26 cm yellowfin tunas that spent all their time in the upper 25 m of the water column.

However, most of these studies describe the behaviour around anchored objects, and it is not likely that those results can be extrapolated to drifting objects, although some authors believe much is to be gained from studies on anchored objects (Dagorn, Holland and Filmalter, 2010). Studies on drifting FADs are very limited (Schaefer and Fuller, 2002; Taquet *et al.*, 2007a; Taquet *et al.*, 2007b; Dagorn *et al.*, 2007; Marianne, Dagorn and Jean-Louis, 2010). The residence times of tunas on FADs appear to be a few days at a time, about 3–10 days. For example, Babaran *et al.* (2009) tracked small yellowfin that spent up to 60 hours under the same payao. However, the sample sizes in drifting object settings is still very low, given the spatial heterogeneities of the fishing areas (current speed, bathymetry, etc.). Interesting approaches are being tested, such as comparing condition indices of fishes captured on FADs and schools (Marianne, Dagorn and Jean-Louis, 2010). Ignorance of the behaviour of most species under logs and FADs is a major gap in knowledge, as most of the tuna purse seine fishing effort is directed towards floating objects.

Around payaos, the average residence time of yellowfin and bigeye tunas was estimated at 5–8 days, with a maximum of more than 2 months; there was also some site fidelity, with tunas tending to return to the original FAD where they were released (Dagorn, Holland and Itano, 2007). They are capable of finding their orientation from up to 10 km (Girard, Benhamou and Dagorn, 2004). The tuna schools are shallower at night than during the day in most studies carried out with anchored FADs (Holland, Brill and Chang, 1990; Cayre, 1991; Josse, Bach and Dagorn, 1998; Brill *et al.*, 1999; Babaran *et al.*, 2009). Moreover, there is a considerable vertical overlap among the different species during the night and early morning, which is the preferred time for setting (Leroy *et al.*, 2010). Yellowfin and skipjack spend most of their time in the mixed layer (Brill *et al.*, 2005; Dagorn *et al.*, 2006a), with bigeye staying deeper but foraging on the deep scattering layer when it rises (Leroy *et al.*, 2010). Bigeye tuna spends more time in shallow water during the new moon, while skipjack behaviour is the opposite (Langley, 2004).

The studies have also covered individual objects, or networks of objects (e.g. Marsac and Cayre, 1998). The empirical knowledge of the fishers is that the maximum catch can be obtained very close to sunrise, hence, sets start just before sunrise, as discussed above, and this has determined the daily rhythm of the fishery. It appears that most tunas move to shallower waters at night, and their peak abundance happens at or close to sunrise (Brill *et al.*, 1999).

Despite the scientific interest of these studies, and their value to improve stock assessments, they have not yet offered much information that is valuable to reduce bycatch. If during the day the tuna schools become less vulnerable or if average school size decreases, then it would be difficult to switch the fishing operations to those alternative conditions. If experiments of this type are continued, care must be taken to perform them in well-specified conditions; the communities associated to logs, FADs, and payaos are quite heterogeneous in both composition and biomass, so conclusions on behavioural patterns across them cannot be extrapolated.

Payaos can range from modest in size to very large (Ohta, Kakuma and Kanashiro, 2001; Ohta and Kakuma, 2005), and the impact of the fishing operations on them may reflect these differences. Locations with different current or productivity conditions may translate into different behaviours. It is believed that when there are FADs in an area, some species such as bigeye tuna become shallower (Leroy *et al.*, 2010). The behaviour of tunas on anchored objects is likely to differ from the behaviour around drifting objects; for example, yellowfin and bigeye tunas associate with anchored FADs in Hawaii during the day (Holland, Brill and Chang, 1990). Residence times around FADs have shown a very large variability in different experiments, but they have almost all been performed on anchored FADs (Holland, Brill and Chang, 1990; Cayré and Marsac, 1993; Brill *et al.*, 1999; Klimley and Holloway, 1999; Dagorn, Josse and Bach, 2000; Ohta, Kakuma and Kanashiro, 2001; Schaefer and Fuller, 2002, 2005; Girard, Benhamou and Dagorn, 2004; Ohta and Kakuma, 2005). The composition of the diet and stomach fullness is different for payaos and drifting FADs (Jaquemet, Potier and Menard, 2011).

The association of tunas with payaos in the Bismarck Sea is of very short duration, perhaps because of the high density of payaos (Leroy *et al.*, 2010), while other studies show much longer residence times (Ohta and Kakuma, 2005; Dagorn, Holland and Itano, 2007). Studies tracking individuals from different species from the same FAD show simultaneous departures in some cases, indicating the multispecies school structure (Leroy *et al.*, 2010).

There is a concept termed the "effective range of influence" of an object (Fréon and Dagorn, 2000). The concept can be applied to anchored or drifting objects, and it defines an area of influence, based on the detection and/or orientation abilities of the species. For tunas around anchored objects, it appears to be in the range of 5–7 nautical miles (Cayre and Chabanne, 1986; Holland, Brill and Chang, 1990; Cayre, 1991). Experiments are needed for drifting objects, and for other species to complete the picture.

Perhaps the most interesting studies for bycatch reduction would be those centring on the behaviour and physiological conditions of the different species inside the purse seine, and during the whole operation. If there is stratification inside the net by size or by species, then it could be used to devise escape procedures. If there is differential mortality, it will also provide an opportunity. If hypoxia or anoxia is a significant factor for mortality, then the conditions in the net can be modified. This is another significant gap in the understanding of the processes leading to mortality of individuals that are to be discarded.

FLOATING OBJECT OPERATIONS

The dominance of FADs, whose construction seems to be converging to a successful model in the EPO, is making the extrapolation simpler. It seems that the stratification between anchored and drifting FADs should be a default, on the basis of their differences, unless statistical evidence supports the pooling. This issue is only relevant in the Western and Central Pacific, where payaos receive a significant proportion of the sets. Oceanographic buoys, another type of anchored object (although anchored for another purpose than to serve as a FAD) do not receive significant effort to make a comparison.

To maintain the review within reasonable limits, the focus is on the association of tunas with drifting floating objects, with an emphasis on those deployed by the fishers because it is the prevailing way of fishing tunas in the world today. Although sets on logs and on FADs may happen at the same location, and time, the transition from a log-fishery to a FAD-fishery has resulted in clear changes. To begin with, the number of sets on floating objects, not depending on encounters, has expanded by a large factor (Figures 22 and 23; Fauvel *et al.*, 2009).

The geographical changes resulting from the development of the FAD fishery for the Eastern Atlantic and for the EPO are a westward shift of the fishery (Figures 24 and 25; Ariz *et al.*, 1999; Hallier and Gaertner, 2008). From a coastal fishery, the effort has switched to an offshore fishery. There have also been changes in seasonality, with the log fishery being prevalent in May–July, while FADs are available most of the year (Figure 50). This triple switch in geography, season, and type of object, makes it very difficult to compare the characteristics of log and FAD sets, and even school sets and floating object sets predominate in different areas (Figure 51); there is a basic confounding that limits the statistical analyses, even when the databases are very complete.

On the other hand, Fauvel *et al.* (2009), show much less dramatic changes in the spatial distribution of the fishery after the increase in the number of FAD sets for the Atlantic and Indian Oceans. In earlier years, Fonteneau *et al.* (2002) showed the northward expansion of the Indian Ocean fishery as a result of increased FAD utilization. The major impact of the FAD introduction appears to be an increase in the number of floating objects, and the change in geographical distribution is less marked.

FIGURE 50
Seasonal distribution of effort in the Eastern Pacific Ocean

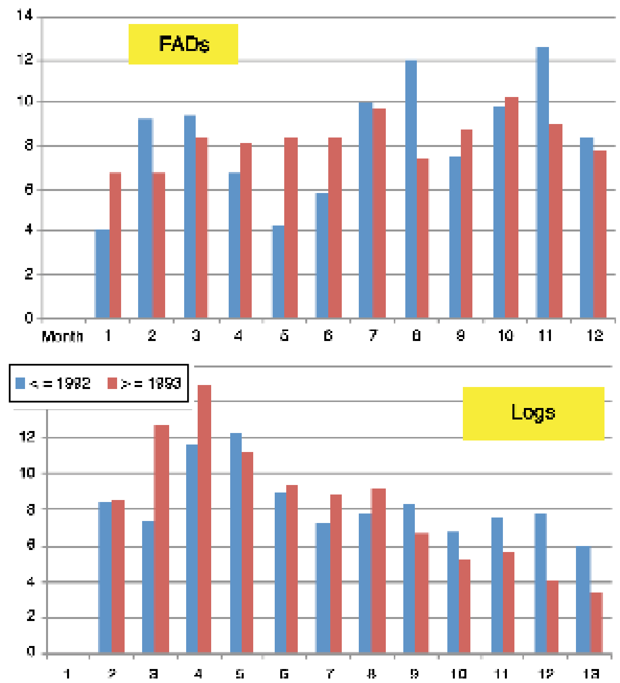
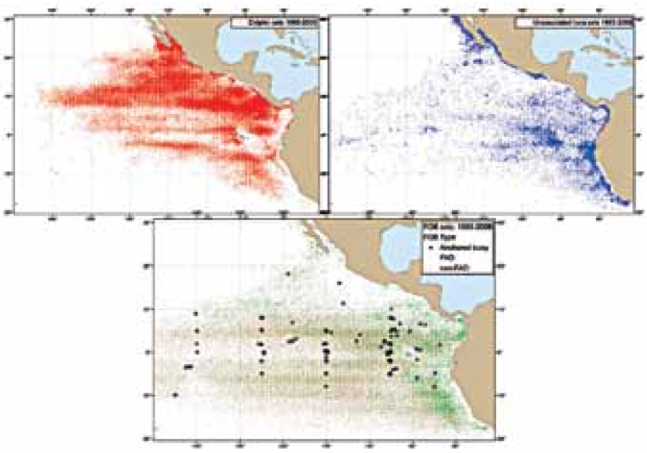


FIGURE 51
Distribution of sets by type in the Eastern Pacific Ocean



Fishing operations on logs, FADs and payaos

The fishery on drifting objects has several characteristics that need to be reviewed in order to understand what they have in common, and in what they differ from payaos, and the influence of the type of drifting object and payao on the catch and bycatch (Itano, 2007). A purse seiner leaving port on a fishing trip will select the area to search based on: information from other vessels; climatic (e.g. storms) and oceanographic (e.g. satellite information on water temperature, productivity, location of fronts) information; economic factors (fish prices, fuel costs, etc.); legal limitations (permits, spatial or temporal closures); and previous results and activities from the vessel and from other vessels from the same or associated companies. Some characteristics of the vessels will influence their operations (Arrizabalaga *et al.*, 2001; Gaertner and Pallares, 2002; Reales, 2002; Itano, 2002, 2004, 2007), and the collection of information at the level of detail needed is critical (Matsumoto *et al.*, 2000). Examples of forms describing the purse seine, the electronics and other equipment from the vessels, and which can be used to help in the standardization work, are available from the IATTC Web site (www.iattc.org Downloads/Gear descriptions). All the issues relevant to the standardization of fishing effort for CPUE studies apply directly to the bycatch estimation (Coan and Itano, 2003).Vessels planning a trip on logs will search in the well-defined areas and seasons where tunas are frequently associated with floating objects. Vessels planning a trip on FADs have several options. They know: the position of FADs deployed by them in previous trips; the position of FADs deployed by other vessels that share that information (e.g. from the same company); and the position for deployment, and expected drift of the FADs that the vessels carry and are going to plant. The drift of the FADs described before, results in two strips running east–west, where most of the fishing takes place. Both are only a few degrees wide, north and south of the Galapagos Islands. The drift of the FADs in most oceans is "predictable" with a reasonable error, and the satellite will bring the vessel to the precise location. Difficulties may arise if the FADs scatter to a point that the search becomes onerous.

Some FADs have acoustic systems to detect and transmit information on the biomass underneath, and the seiner may decide which FAD to visit based on that. In other cases, where that information is not available, the vessel approaches a FAD the previous day or a few hours before sunrise, and tries to assess (using the acoustic devices of the seiner) whether it is worthwhile making a set, or whether it is better to continue searching for another FAD. The purse seining operations usually start before the sun is up (Figure 38; Hall *et al.*, 1999a; Hallier and Parajua, 1999; Hampton and Bailey, 1999; Fonteneau *et al.*, 2010b).

In sets on payaos, manoeuvres have been developed to avoid encircling and entangling the mooring lines, but besides that, the operation is very similar to sets on drifting objects (Bromhead *et al.*, 2000). An excellent review of operations on and characteristics of payaos in the WPO is available (Itano, Fukofuka and Brogan, 2004). Fishing operations on payaos may happen throughout the day, but are prevalent during daylight periods (e.g. recreational fishing, trolling). Purse seiner sets have a major peak before sunrise, and a secondary peak at much lower level close to sunset (Harley, Williams and Hampton, 2009).

Duration of fishing trips

The duration of fishing trips depends on many variables, including the type of fishing, fishing success, location of fishing grounds, weather, vessel capacity, and vessel speed. As a generalization, it is possible to use a modal value of about 45–50 days, with a broad range of from less than a week to more than 5 months (Figures 52 and 53). For the Indian Ocean, Sarralde, Delgado de Molina and Ariz (2006) report trip lengths of 18–60 days, with modes of about 30–40 days.

The development of the FAD fisheries, shown here in the last two histograms, has resulted in a shortening of trips with respect to the initial distribution. Fewer sets are needed to fill the vessels, as the production in FAD sets is higher than in the other types of sets.

FIGURE 52
Duration of observed tuna purse seine trips in the Eastern Pacific Ocean, 1979–2010

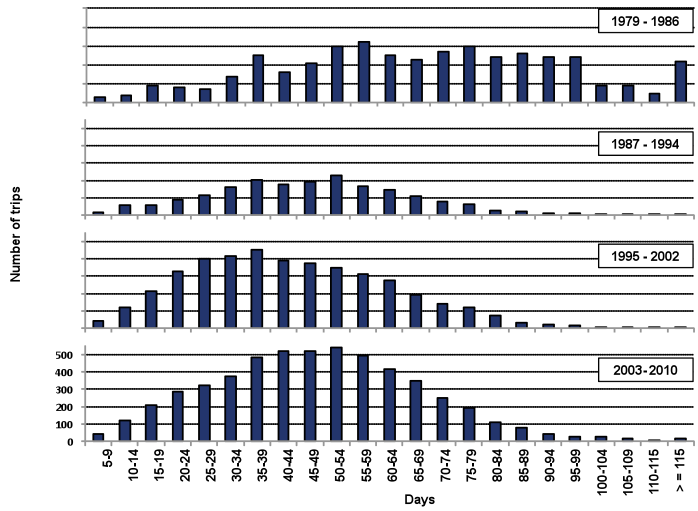
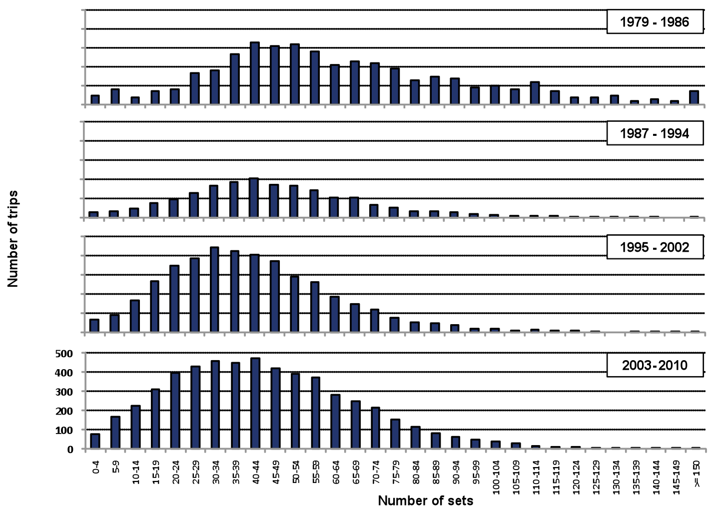


FIGURE 53
Number of sets made on observed tuna purse seine trips in the Eastern Pacific Ocean



5. Conditions during the capture process that may cause mortality

Given the large dimensions of the purse seines used in the fishery, most of the individuals or schools have enough space to move freely at the beginning of the set. The description of the sets begins with chaotic movements inside the net.

As the purse cable is closed, the shallowing of the net brings up schools that may have been in deeper water. In areas with deep thermoclines, this may be a stressor working on the deeper swimming species (e.g. bigeye tuna).

According to the observations from tuna skippers, they frequently see chaotic movement at the beginning of the set, and then things settle down. There are no observations of what happens inside the net with the different species and sizes. Are they stratified vertically? Do they interact with one another? This type of information may prove critical in attempts to release some individuals from the net, but it is a gap in the current knowledge.

As the net is retrieved, the volume inside shrinks, and different stressors may begin to have an impact. Temperature is likely to rise, given the restricted water circulation, and the shallowing of everything as the set progresses. In the tropical locations where this fishery takes place, the temperature may by itself cause some mortality, especially in prolonged sets.

Oxygen inside the net may be reduced during the set, given the large biomass consuming it. As the movement of the schools is restricted, their possibilities for ventilation decrease. Hypoxia, or even anoxia, may be an important stressor acting on the capture.

Physical contacts between individuals or with the net may result in injuries and abrasions that may prove lethal for some species (Misund and Beltestad, 2000; Suuronen and Erickson, 2010).

The next stage of the set is the brailing process. Large scoop nets (usually capable of lifting 2–4 tonnes of fish, but some can lift 8 tonnes) are used to bring the fish on board the seiner. The fish then go a large tray on the main deck (called a hopper) to be sorted out. In this case, the bycatch is tossed aside on the deck of the boat, and in general it is left there until the end of the set. Alternatively, the fish go to the well deck through an opening in the main deck. In this case, the fish fall onto a conveyor belt that distributes the catch to the wells (Plate 1). The species and individuals to be discarded are still mixed on the conveyor belt, and the crews sort them out from the belt. In some vessels, again, the individuals to be discarded are tossed aside until the set is over. In other vessels, there is another conveyor belt with the specific purpose of taking the bycatch out of the vessel.

The amount of time spent out of the water by an individual that is to be discarded depends on the duration of the set, the type of brailing operation, the system the vessel uses to return the bycatch to the water, and the way the crew handles the return process. Moreover, as this time may affect the survival of the individual, it is necessary to understand the process, and perhaps modify some components to improve survival. Taking a precautionary approach, and lacking evidence that individuals or species can survive the encirclement, brailing, and handling on board, it is assumed that all the capture that undergoes the full process is dead or dying when returned to the sea. Some shark experts believe that this may not be the case for some shark species. When research evidence shows survival, and allows a rate to be estimated, then the data should incorporate this correction. Reviews of the survival of fish escaping from different gear types are found in Chopin and Arimoto (1995), Chopin, Arimoto and Inoue (1996), Davis (2002), Suuronen (2005), and He (2010).

In all cases, the best way to reduce bycatch is by avoiding the capture of the unwanted individuals.