FISH and FISHERIES

Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems?

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Abstract
The use of fish aggregating devices (FADs) by purse seine fisheries has come under increasing criticism for its potential deleterious impacts on tuna stocks, for high levels of by-catch and threats to the biodiversity of tropical pelagic ecosystems. Here, we review the current state of scientific knowledge of this fishing technique and current management strategies. Our intent is to encourage objective discussion of the topic and highlight areas worthy of future research. We show that catching juvenile tuna around FADs does not necessarily result in overfishing of stocks, although more selective fishing techniques would likely help obtain higher yield. Levels of non-tuna by-catch are comparable to or less than in other commercial tuna fisheries and are primarily comprised of species that are not considered threatened. Accordingly, to minimize impacts on ecosystem balance, there is merit in considering that all species captured in purse seine fisheries (excluding vulnerable species such as turtles and sharks) should be retained, but the consequences of such a measure should be carefully examined before implementation. The take of vulnerable species could be further reduced by introduction of additional mitigation measures, but their potential benefits would be limited without parallel efforts with other gears. Finally, there is no unequivocal empirical evidence that FADs represent an 'ecological trap' that inherently disrupts tuna biology although further research should focus on this issue. We encourage RFMOs to expand and improve their FAD management plans. Under appropriate management regimes, FAD fishing could be an ecologically and economically sensible fishing method.

Keywords By-catch, ecological trap, FAD, purse seine, tuna

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Introduction

Many species of marine fishes aggregate around floating structures such as drifting logs or palm fronds (Castro *et al.* 2002; Taquet *et al.* 2007). This behaviour was first reported in 200 AD in the Mediterranean, when the Roman author Oppian described the use of floating objects to catch dolphinfish (*Coryphaena hippurus*, Coryphaenidae) (cited in Dempster and Taquet 2004). In the late 1950s, the first tuna (Scombridae) purse seiners operating in the eastern Pacific Ocean found it was feasible to capture schools of tunas associated with natural floating objects such as logs (Hall 1998). Thereafter, industrial tuna purse seiners increasingly focussed on using drifting floating objects to expedite and augment their catches. There are two main reasons for this focus. First, because floating objects are visible at the surface (or their positions are already known – see below), they help fishers reduce the search time required to locate fish schools. Finding and keeping track of floating objects has been further advanced by attaching radio beacons or satellite-linked GPS units. This permits tracking in real time and from great distances. Recently, the practice of attaching satellite-linked echosounder fish finder units to floating objects further improves efficiency by informing fishers as to which ones might have fish underneath and are then worth visiting. Second, floating objects increase the vulnerability of tunas to fishing; sets around floating objects have higher success rates (90%) than those made on free-swimming schools (50%) (Fonteneau *et al.* 2000; Suzuki *et al.* 2003; Miyake *et al.* 2010). Because floating objects provided such a major increase in the catchability of tunas (Marsac *et al.* 2000), fishers started to construct and release artificial fish aggregating devices (FADs). There are two basic categories of FADs – anchored and drifting. Anchored FADs are primarily (although not exclusively) used in small-scale coastal, semi-artisanal and sport fisheries, whereas open ocean drifting FADs are used by industrial purse seine fisheries. This study discusses only the industrial use of drifting FADs. The use of FADs by purse seine fleets started in the 1980s and rapidly expanded throughout the early 1990s. In the remainder of this review, the term 'FAD' refers to any man-made floating object built for the purpose of fishing, whereas the term 'log' refers to any natural object and the term 'floating object' is used when referring to both FADs and logs.

The use of drifting FADs by the purse seine fishery raises the possibility of three potential negative impacts: (i) reduction in yield per recruit of target species (tunas), (ii) increased by-catch and perturbation of pelagic ecosystem balance and (iii) deleterious alteration of the normal movements of the species associated with FADs (Fonteneau *et al.* 2000; Bromhead *et al.* 2003; Morgan 2011).

First, let us address the issue of how FADs might contribute to overfishing of tuna stocks. Although FAD catches are usually mainly comprised of adult skipjack tuna (*Katsuwonus pelamis*, Scombridae), they are also usually characterized by the co-occurrence of small yellowfin (*Thunnus albacares*, Scombridae) and bigeye (*T. obesus*, Scombridae) tuna (although there are large regional and seasonal variations in the co-occurrence of these species). By contrast, purse seine catches on free-swimming schools are typically dominated by large yellowfin tuna and skipjack tuna. Because of the common presence of small bigeye and yellowfin tuna in sets on floating objects, this practice, if not managed, could affect the yield per recruit of these species and could lead to excessive reduction of stocks.

Second, FADs also attract non-tuna species (Hunter and Mitchell 1967), and these species are taken when purse seiners fish on FADs (Hall 1998; Romanov 2002; Amandè *et al.* 2010). Thus, the capture of non-target species associated with floating objects could negatively impact biodiversity either by removing by-catch species in unsustainable quantities or by selective removal of some components of the pelagic ecosystem. In contrast, free-swimming school sets are usually characterized by low amounts of by-catch of non-target species. However, even though by-catch at FADs may be quite small, the fact that fishing on floating objects is a part of the fleet's overall strategy results in an increase in by-catch for the purse seine fishery as a whole (Romanov 2002).

Finally, the release of large numbers of FADs in the ocean could change the natural environment of tunas. The potential effects of such habitat modification on the behaviour and biology of tunas have been grouped under the 'ecological trap' hypothesis (Marsac *et al.* 2000; Hallier and Gaertner 2008). This hypothesis contends that deploying FADs in unnaturally large numbers could either entrain tuna in locations that they might normally leave or, conversely, take them to places to which they would not normally go, thereby impacting negatively their biology (e.g. growth rate or reproductive success).

After reviewing these potential impacts, Fonteneau *et al.* (2000) and Bromhead *et al.* (2003) concluded that, owing to the lack of quantitative data, potential negative long-term effects of FADs on tuna stocks and pelagic ecosystems were difficult to evaluate and remained hypothetical. However, they cautioned that the continuing use of FADs at a large scale could have detrimental effects. As these reviews were published, the use of FADs by purse seiners has increased worldwide (and so have catches of skipjack tuna, the principal target species in this mode of fishing). The Tuna Regional Fishery Management Organizations (the four Tuna RFMOs with a mandate to manage tropical tunas are as follows: The Inter-American Tropical Tuna Commission, IATTC, the International Commission for the Conservation of Atlantic Tunas, ICCAT, the Indian Ocean Tuna Commission, IOTC, and the Western and Central Pacific Fisheries Commission, WCPFC) have implemented several measures to regulate the use of FADs (Table 1), and some research projects dedicated to FADs have been conducted. However, major gaps in knowledge still exist, and there is a need to review what is known about the impacts of FAD fishing and to investigate new management measures.

The objective of this study is to review the current knowledge about tropical tuna purse seine fisheries and the relevant aspects of the biology and behaviour of species that associate with floating objects. More than 60% of the literature on FADs (combining drifting and anchored FADs, Dempster and Taquet 2004) are non-peer-reviewed articles, with a large portion being working documents presented at Tuna RFMOs meetings. A decade after the reviews by Fonteneau *et al.* (2000) and Bromhead *et al.* (2003), we aim to present the scientific and management progress made in this field, providing an evaluation of what is actually known and what is not known. We hope to encourage objective discussion of the good and bad features of fishing on floating objects and highlight the need to better monitor and control the use of FADs. Better management requires both fundamental and applied research. We conclude by reviewing current management practices and identifying the main scientific research priorities that would help decrease the amount of uncertainty and provide better information to fisheries managers.

Table 1 Management measures related to FADs in the four Tuna RFMOs.

Management measure	IOTC	IATTC	ICCAT	WCPFC
Time and area closures[1]	Res 10-01	Res C-11-01	Rec 99-01	CMMs 08-01 and 09-02
Full retention[1]	Rec 10-13[2]	Res C-04-05 REV2		CMM 09-02
FAD monitoring or management plan	Res 10-02	Res C-11-01	Rec 11-01	CMM 08-01
Ban of supply vessels		Res C-99-07		
Measures for oceanic white tip sharks[1]		Res C-11-10	Rec 10-07	
Measures for silky sharks[1]			Rec 11-08	

FAD, fish aggregating devices.

[1]These measures are not restricted to FADs. About measures concerning sharks, we only reported here the ones specifically dedicated to the two main species usually captured by purse seine vessels around FADs.

[2]This measure is not mandatory, but is the only one on full retention on tunas and other species. Full retention measures from the other Tuna RFMOs only concern tuna species (not other species).

Purse seine fishing on floating objects

The main target species of the tropical tuna purse seiners are skipjack, yellowfin and bigeye tuna. Tuna purse seiners (Fig. 1) rely on a variety of strategies for finding tunas. Several of these involve looking for natural and anthropogenic features that tunas are known to associate with in a given region such as herds of dolphins, whale sharks, logs, marine debris (e.g. cargo nets) and oceanic features such as thermal fronts. These phenomena are located using binoculars, bird radars, long-range sonars, helicopters and satellite imagery. The other type of strategy involves fishing in areas that are known to contain artificial drifting floating objects – many of which are equipped with radio or satellite beacons that allow the vessel to track their position. In some regions, the FADs are moored in fixed locations. These anchored FADs are used worldwide by short-distance local fisheries (Dempster and Taquet 2004), but only exploited by purse seiners in the western Pacific Ocean. Purse seining on free-swimming schools or schools associated with floating objects involves similar techniques (see Ben-Yami 1994 and Hall 1998 for details), and the main difference being that object-associated schools are usually less mobile and therefore easier to set on (which explains the higher catch rates on this type of sets, Fonteneau *et al.* 2000; Suzuki *et al.* 2003; Miyake *et al.* 2010). When setting on a drifting FAD, the purse seiner encircles the tuna school and the floating object and then, the floating object is carefully towed out of the circle. When setting on anchored FADs, the school is lured a short distance away from the FAD at night by using lights on the fishing vessel.

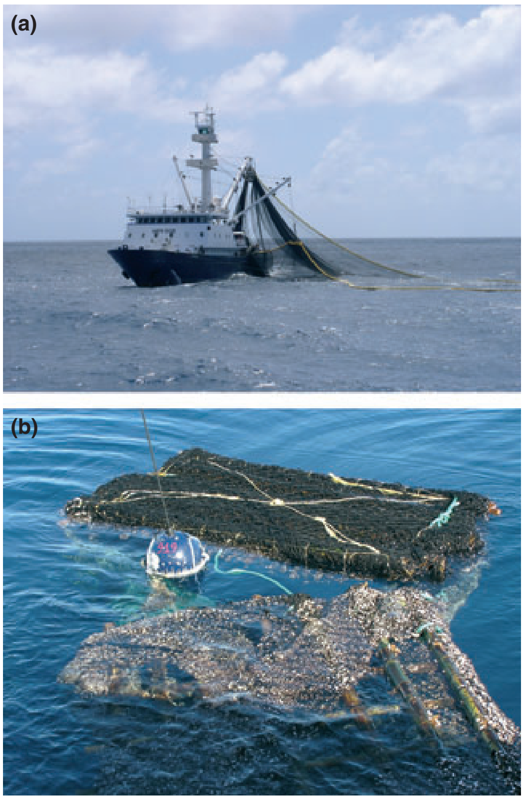

Figure 1 A tuna purse seiner (a) (Copyright: Copyright: FADIO/IRD-Ifremer/D. Itano) and typical drifting fish aggregating devices (b) (Copyright: FADIO/IRD-Ifremer/G. Moreno).

During any given trip, purse seine skippers may use a combination of the two types of strategies to find tuna schools, often relying on an array of instrumented floating objects (mainly FADs) that make it possible for the skipper to plan ahead when and where the sets will be made. During this time, the vessel will also search for natural floating objects and for free-swimming schools. Since the early 1990s, the design of drifting FADs (Fig. 1) has been fairly uniform and constant. Fishers build FADs themselves, using cheap and readily available materials, trying to make them as invisible as possible (to prevent others from setting on the FAD or from stealing it) and to maximize FAD lifespan. A FAD is typically a bamboo raft of 4 to 6 m^2 with old purse seine netting used to cover the top and to hang down beneath the raft. This reduces the chance of it being spotted by other vessels, and the submerged section of net creates an underwater structure that increases the FAD's profile underwater. The submerged section acts as a drogue to keep the raft within the water mass, and many skippers feel that the size of the subsurface component is critical to attracting tuna. The main variation between fleets and oceans is the length of the underwater netting structure, going from 10-15 m for the European fleet in the Indian Ocean up to 100 m for Korean skippers in the Atlantic Ocean.

In the late 1980s, fishers started to attach radio beacons to floating objects (with ranges typically up to 500–1000 nmi and lifetime of about 6 months). Since then, the technology of electronic buoys has been continuously evolving, and most of buoys are currently satellite buoys (no limit in the range) with increased lifespan (e.g.

solar panels). Furthermore, some buoys are now equipped with echosounders that estimate the amount of fish biomass associated with the FAD. This information is transmitted to the vessel through satellite, thus allowing the skipper to plan ahead even more efficiently. The most recent generation of these echosounder satellite buoys is providing biomass estimates of tuna underneath the buoy (by depth layers from 3- to 11-m increments, depending on the brand) with data transmitted at regular time intervals (from 2 h to 1 day, depending on specifications) (Fig. 2). The increasing use of these new buoys will certainly induce major modifications in the behaviour and strategy of fishers. In some oceans (e.g. Atlantic and Indian oceans), supply (auxiliary) vessels are used to build and deploy FADs and to use sonars and echosounders to monitor the amount of fish at the various FADs. This allows the main purse seine vessel more time for actual fishing activities with concomitant reduced overall costs. To reduce fleet efficiency, supply vessels have been prohibited in the eastern Pacific Ocean since 1999 (IATTC Res C-99-07, Table 1).

Impacts on tuna stocks

The increase through time in FAD usage in the tropical tuna purse seine fleet is proof of the efficiency of this method. However, it is noteworthy that the percentage of catches made on floating objects has always been high (around 50% or more) in all oceans even before the substantial increase in use of FADs (Fig. 3). The exception is the eastern Pacific Ocean, where the overall fleet percentage was low (approximately 20%, except in the late 1970s and early 1980s where it was approximately 40%) and only surpassed 50% in the mid-1990s after many purse seiners in this ocean shifted from fishing on tuna schools associated with dolphins to schools associated with floating objects (Hall 1998).

Purse seiners are not the only fisheries catching tropical tunas and there is regional variability in the percentage of the overall catch that is taken by purse seiners fishing on floating objects (Fig. 3). Other major tuna fishing gears are longline and pole and line. In the western and eastern Pacific oceans, catches on floating objects (drifting and anchored) account for about 50% of the overall catch of tunas in these oceans, while they only represent about 25% in the Indian and Atlantic oceans (Fig. 3). The increasing trend in the western and central Pacific oceans (which currently accounts for over 50% of the world tuna production) is quite noticeable. The trend in this region since 1990 is because of an increase in the use of both drifting and anchored FADs (Fig. 3). Globally,

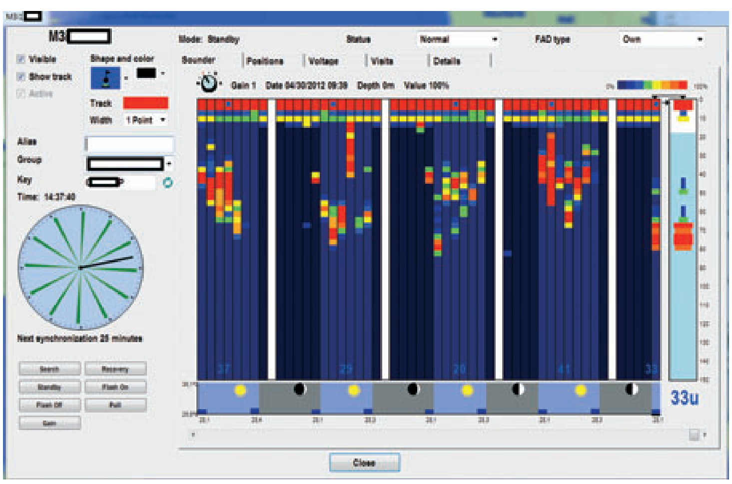

Figure 2 Picture of echosounder readings from the screen of a computer onboard a purse seiner in the Atlantic ocean showing fish biomass underneath a fish aggregating devices (FAD) as observed by an echosounder buoy attached to the FAD (courtesy of Marine Instruments). The image covers 4 days with information provided by the echosounder every 2 h. An aggregation of fish (likely to be tunas) is observed between 20 and 70 m. These data do not allow species discrimination.

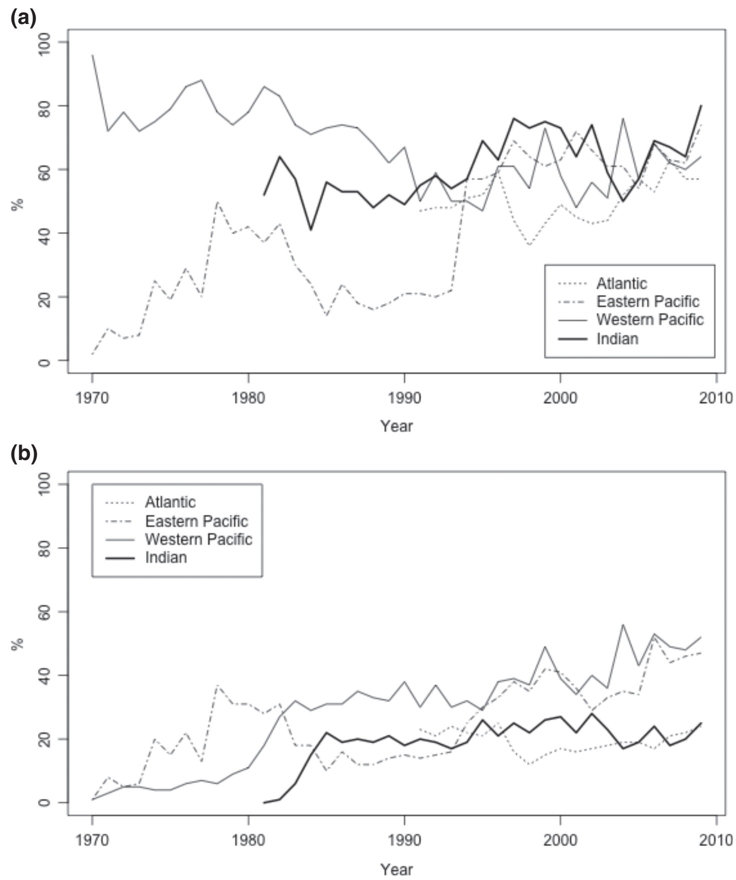

Figure 3 (a) Annual trends in the percentage of the catch of bigeye, yellowfin and skipjack tunas that is made on floating objects fish aggregating devices (FADs and natural logs), by Ocean Region, relative to total catches made by purse seiners. (b) Annual trends in the percentage of the catch of bigeye, yellowfin and skipjack tunas that is made on floating objects (FADs and natural logs), by Ocean Region, relative to all fishing gears. The global trend has been extrapolated without Atlantic Ocean data for 1970–1990 and without Indian Ocean data for 1970–1980. Data are from the Tuna RFMOs, publically available from the respective websites of each Tuna RFMO.

40% of the catch of tropical tunas comes from purse seine sets on floating objects.

The majority of the catch from sets on schools associated with floating objects is made up of skipjack tuna, which is the main target species for today's high-volume-canned tuna market. In 2009, over 2.5 million tonnes of skipjack tuna were caught worldwide (data from ISSF 2011), and about one-half of it from sets made around floating objects. Globally, 75% of the catch of tunas around floating objects is skipjack tuna, followed by yellowfin (16%) and bigeye (9%) tuna (Table 2). In comparison, catches on free-swimming schools have much higher proportions of yellowfin tuna (35%) and lower proportions of bigeye tuna (2%), but with skipjack tuna still being the major species (63%) (Table 2). However, there are important regional differences in the tuna catch composition, and these global estimates hide important regional characteristics. For example, the percentage of bigeye tuna caught under floating objects in the eastern Pacific Ocean is almost one order of magnitude higher than it is in the western Pacific Ocean: 28 vs. 4% (Table 2). While catches on floating objects are dominated by skipjack tuna in all oceans (from 57% in the eastern Pacific Ocean to 82% in the western and central Pacific oceans), composition of catches on free-swimming schools greatly differ across oceans. Catches on free-swimming schools are comprised of approximately 75% of yellowfin tuna in the Atlantic and Indian oceans, while this species represents <50% in the eastern Pacific Ocean and <25% in the western and central Pacific oceans.

Table 2 Per cent composition of the catches of the three tropical tuna species under floating objects (FADs and logs) and in free-swimming schools, by region. The data are averages from the Tuna RFMOs for 2000–2009 (data publically available from respective websites of RFMOs).

	Floating objects			Free-swimming schools		
Ocean	Yellowfin	Skipjack	Bigeye	Yellowfin	Skipjack	Bigeye
Atlantic	17	69	14	76	19	5
Indian	25	67	8	72	22	6
E. Pacific	15	57	28	43	56	1
W. Pacific	14	82	4	22	77	1
Global	16	75	9	35	63	2

FAD, fish aggregating devices.

In the eastern Pacific Ocean, some purse seiners also set on tuna schools (primarily yellowfin tuna) associated with herds of dolphins that are common in this region (Hall 1998).

The large catches of tuna taken from around floating objects can cause two types of impacts on tuna populations (Fonteneau *et al.* 2000): a loss of potential yield (by catching small fish that have the potential to grow to a much larger size if they survive) and a reduction of spawning biomass or stock size (by catching too many fish). The impact that fishing on floating objects (or, for that matter, the impact of fishing with any gear) has on tuna stocks depends on the resiliency characteristics of each stock which, in turn, is shaped by the different life history characteristics of each species.

Table 3 presents the current status of each of the tropical tuna stocks relative to the manage-

Table 3 Latest available estimates (from Tuna RFMOs as of December 2011) of status for bigeye, yellowfin and skipjack tuna stocks. The average 2006–2010 catch is in thousand metric tonnes. Catch composition by major gear types is given in terms of per cent of the total catch ('–' represents very small or nil). F/Fmsy and B/Bmsy measure whether a stock is being overfished (F/Fmsy > 1, in bold) or is overfished (B/Bmsy < 1, in bold) according to the management benchmark levels used by the Tuna RFMOs.

			Per cent catch by gear							
Species	Ocean	Catch 2006–2010	PS-Obj	PS-FS	PS-Dol	LL	PL	GN/OT	F/Fmsy	B/Bmsy
BET	AO	75	21	5	–	56	18	–	0.95	1.01
BET	EPO	100	70	–	–	29	–	–	**1.08**	1.21
BET	IO	105	20	5	–	72	–	–	<1	≥ 1
BET	WCPO	125	38	5	–	51	3	–	**1.46**	1.19
SJK	WCPO	1532	56	30	–	–	8	5	0.37	2.94
SKJ	AO-E	127	62	5	–	–	27	–	<1	>1
SKJ	AO-W	24	9	–	–	–	87	–	<1	>1
SKJ	EPO	237	64	34	–	–	–	–	≤ 1	>1
SKJ	IO	489	31	4	–	–	22	44	<1	2.56
YFT	AO	108	13	50	–	20	11	–	0.86	**0.96**
YFT	EPO	210	17	17	62	3	–	–	0.86	**0.71**
YFT	IO	327	17	17	–	20	5	40	0.84	1.61
YFT	WCPO	496	36	35	–	12	–	15	0.77	1.47

BET, bigeye tuna; YFT, yellowfin tuna; SKJ, skipjack tuna; EPO, Eastern Pacific Ocean; WCPO, Western and Central Pacific oceans; IO, Indian Ocean; AO, Atlantic Ocean (E or W); PS, Purse seine; LL, longline; PJ, Pole and line; GN/OT, Gillnet plus other gears (usually unclassified); Obj, FS and Dol, object-associated, free-swimming school and dolphin-associated purse seine sets.

ment benchmarks used by the pertinent Tuna RFMOs. The table also shows the relative magnitude of the catches made using different gear types during 2006–2010 for each stock. Skipjack tuna is the major species caught around floating objects, and most of skipjack tuna captured are mature. Skipjack tuna is fast-growing, highly fecund species characterized by a high natural mortality rate. To date, these characteristics – and its extremely large habitat – make it resilient to fishing (Fromentin and Fonteneau 2001). However, in the late 1990s, ICCAT determined that Atlantic skipjack tuna stocks were experiencing growth overfishing owing to the active FAD fishery (Fonteneau *et al.* 2000). Nevertheless today, none of the five skipjack tuna stocks (including the Atlantic Ocean one) is currently experiencing overfishing (Table 3). Considering that the use of FADs has increased in the past decade, this situation tends to demonstrate that fishing on floating objects does not *per se* result in overfishing of skipjack stocks. However, concerns still exist that the continuously increasing exploitation rates in areas such as the eastern Pacific Ocean are not sustainable (Maunder 2011), and this expansion is largely attributable to fishing on floating objects.

Most of catches of bigeye and yellowfin tuna around floating objects are comprised of small, immature fish (40–65 cm FL) although larger individuals (100–140 cm FL) are also caught in lower but significant numbers (Fonteneau *et al.* 2000; Bromhead *et al.* 2003). Bigeye and yellowfin tuna are thought to be less resilient to fishing than skipjack tuna, and some of these stocks have been overfished in the past. Currently, bigeye tuna in the eastern and western Pacific oceans, and possibly in the Atlantic Ocean, are experiencing overfishing (Table 3), and their catch by purse seine sets on floating objects is high (close to 70% in the EPO). In contrast, yellowfin tuna in the Atlantic and eastern Pacific oceans are overfished, but their catches by other gear (or set) types are much higher than on objects (Table 3).

Thus, there is no obvious pattern between the relative magnitude of the catch by sets on floating objects and whether a stock is overfished or experiencing overfishing. The same conclusion was reached by a recent workshop (Anonymous 2011) that analysed the status of tuna stocks in relation to whether the fishing mortality on juveniles during the last 10 years (for all gears combined) was higher than the fishing mortality on adults. None of the stocks that have experienced high juvenile fishing mortality are currently below SSB_{MSY} (spawning biomass that would be able to produce the maximum sustainable yield, MSY), and one stock (yellowfin tuna in the Atlantic Ocean) that has experienced high adult fishing mortality is currently below SSB_{MSY} (Anonymous 2011).

Therefore, catching juvenile tunas does not necessarily result in overfishing. The fact is that SSB can be reduced by taking adults as well as by harvesting juveniles. All tropical tuna stocks are exploited by a variety of gears, some of which tend to catch small fish and some of which tend to catch larger fish. For example, more than 50% of the catch of bigeye tuna in the Atlantic, Indian and Western Pacific oceans are caught by longline fisheries that target primarily adults.

The other potential type of impact on tuna stocks is a loss in potential yield (lower yield per recruit). Species like yellowfin and bigeye tuna can grow to be quite large – much larger than the size at which they are typically caught around floating objects (average size approximately 50 cm FL). Balancing natural mortality and growth rates to maximize yield would be most pertinent to longline fisheries that catch the larger individuals (average size approximately 100 cm FL), and conceptually, not catching small FAD-associated fish could increase the potential yield. Aires da Silva and Maunder (2011) have calculated that the maximum sustainable yield for the eastern Pacific bigeye tuna stock had already been reduced to one-half of what it was by 1993, when catches were predominantly made with longlines and before large numbers of FADs were introduced. Whether or not the previous higher potential yield can be recovered is receiving considerable attention (see Sun *et al.* 2010) as it is not certain that the additional surviving fish would become available to longline gear (Fonteneau and Ariz 2011).

The evaluation of these potential impacts depends on the rates of growth and natural mortality, and there remains much uncertainty around the estimates of this latter parameter. However, current analyses suggest higher natural mortality for small bigeye, yellowfin and skipjack tuna than previous estimates (Hampton 2000; Fromentin and Fonteneau 2001; Bromhead *et al.* 2003). Consequently, the potential effects of catching large numbers of small fish at FADs may be hardly visible in tuna stocks unless the adult stock is also heavily fished (Fonteneau *et al.* 2000).

Impacts on non-target species: by-catch

All the following data come from scientific observers onboard fishing vessels: French and Spanish observer programmes for European purse seiners in the Indian and Atlantic oceans (Amandè *et al.* 2008, 2010) and observer programmes of the IATTC and WCPFC for the Pacific Ocean (data requested to the respective RFMOs). The accuracy of these data depends on the coverage of the observer programmes in each ocean. Coverage is 100% on large purse seine vessels in the eastern Pacific Ocean (since 1993) but <10% in the Atlantic and Indian oceans. In the western Pacific Ocean, the WCPFC has recently adopted 100% coverage since 1 January 2010 for vessels fishing on the high seas or in several EEZs, but the by-catch data used in the present work for this ocean concern 2005–2010 with coverage from 13 to 21% (Lawson 2011).

After the sustainability of the tuna stocks themselves, the management and mitigation of by-catch are the most pressing issues facing the commercial fishing industry worldwide (Hall 1996; Hall and Mainprize 2005), and this problem has become more evident with the development of the ecosystem approach to fisheries (Pikitch *et al.* 2004). The term 'by-catch' can be used in different ways depending on the context. In the case of tuna purse seine fisheries, some studies considered the discards of small individuals of target species (skipjack, yellowfin and bigeye tuna) as by-catch (Amandè *et al.* 2008, 2010), while others only considered non-tuna species (e.g. Romanov 2002). These types of distinction are important when comparing different studies (and also for comparing various fishing gears). In our opinion, small tunas that are discarded or sold on local markets should not be considered as by-catch but should be included in the available statistics as inputs for stock assessment models of target species (Amandè *et al.* 2010), as it is performed by the IATTC and the ICCAT. For the current discussion, we consider by-catch as the catch of non-target species, which can be either discarded at sea or landed.

For purse seiners, by-catch species are usually divided into six categories: tunas other than target species, miscellaneous bony fishes, billfishes (Istiophoridae, Xiphiidae), sharks (Carcharhinidae), rays (Dasyatidae, Mylionatidae) and sea turtles (Cheloniidae). Purse seine by-catch ratios (by-catch vs. target species) for sets on floating objects vary according to the oceans (Table 4, data expressed in weight): 1.7% in the western Pacific Ocean (0.3% for free-swimming school sets), 2.4% for the eastern Pacific Ocean (0.8% for free-swimming school sets), 3.6% in the Indian Ocean (0.8% for free-swimming school sets) and 8.9% in the Atlan-

Table 4 Observed by-catch composition by weight in each ocean (tonnes by 1000 tonnes of target tunas landed), from Amandè *et al.* (2008) for the Indian Ocean and Amandè *et al.* (2010) for the Atlantic Ocean using EU observers data, and using data provided by IATTC (by September 2011) and by WCPFC (by September 2011) for the Eastern and Western Pacific oceans, respectively. Target tunas are skipjack, yellowfin and bigeye tunas.

	Eastern Pacific		Atlantic		Indian		Western	
	2000–2009		2003–2007		2003–2007		2005–2010	
Species	FSC	FAD	FSC	FAD	FSC	FAD	FSC	FAD
Target tunas[1]	25.3	68.7	0.0	61.0	3.5	17.4		
Other tunas	5.1	10.4	20.8	67.7	5.9	9.2	0.3	2.0
Bony fish	0.7	10.4	0.8	17.0	1.5	19.7	0.8	13.7
Billfish	0.8	1.1	5.1	2.6	0.4	0.7	0.7	0.5
Sharks	1.4	1.9	0.3	1.8	0.3	6.0	0.9	1.1
Rays	0.4	0.0	1.4	0.2	0.2	0.2		
By-catch total (without target tunas)	8.4	23.8	28.4	89.3	8.3	35.8	2.6	17.4
Ratio FAD/FSC		2.8		3.1		4.3		6.7

FAD, fish aggregating devices; WCPFC, Western and Central Pacific Fisheries Commission.
[1]Discards of target tunas.

tic Ocean (2.8% for free-swimming school sets). In three ocean regions (eastern Pacific, Atlantic and Indian), the catch of non-target species around floating objects is three to four times higher than it is on free-swimming schools (Table 4). In the western Pacific Ocean, this ratio goes up to six times higher. The main difference in the Atlantic Ocean comes from the high catches of other tuna species (Amandè *et al.* 2010) and is probably driven by the local market (called 'faux-poisson') in western Africa (Romagny *et al.* 2000).

Data available for comparison of by-catch in different fisheries are quite rare. Comparing the discard rates of various pelagic fisheries (note that by-catch includes discards and non-target species that are retained), Kelleher (2005) found that pelagic longliners have discard ratios (by weight) four to five times higher than purse seiners (about 22% compared to 5%). Pole-and-line fisheries are usually considered to have very low by-catch rates (around 0.1%), but catches of live bait (3.1% of tuna catch, see Gillett 2011) should be added (even though they are not usually taken from the oceanic pelagic ecosystem) bringing the average by-catch ratio of pole and line to 3.2%. This is close to that of purse seiners (note also that some small target tuna are discarded by purse seiners and appear as by-catch in many studies, while the same sizes and species are retained and sold by pole-and-line vessels, therefore considered as catches).

Main non-target tuna species taken by purse seines are kawakawa (*Euthynnus affinis*, Scombridae), little tunny (*E. alleteratus*, Scombridae), frigate tuna (*Auxis thazard*, Scombridae), bullet tuna (*A. rochei*, Scombridae), with variations among oceans, and this category representing from 11 (western Pacific Ocean) to 76% (Atlantic Ocean) of the total by-catch (Table 4). Although up to 55 different bony fish species can be taken from around floating objects (Amandè *et al.* 2008), this category is usually dominated by very few species: oceanic triggerfish (*Canthidermis maculatus*, Balistidae), rainbow runner (*Elagatis bipinnulata*, Carangidae), dolphinfish, wahoo (*Acanthocybium solandri*, Scombridae). Large differences are also observed among oceans, from 19% (Atlantic Ocean) to 79% (western Pacific Ocean) of all by-catch. Species of these two categories (other tuna and bony fish) make up between 81 and 95% of the by-catch and are known to be fast growing and have early sexual maturity and high fecundity (e.g. dolphinfish: Hassler and Hogarth 1977; Oxenford 1999; wahoo: Maki Jenkins and McBride 2009; rainbow runner: Pinheiro *et al.* 2011).

Billfishes captured at floating objects are mainly marlins and spearfishes from the genera Makaira and Tetrapturus. They represent from 2% (Indian Ocean) to 5% (eastern Pacific Ocean) of all by-catch. Some billfishes are of concern because they are thought to be below SSB_{MSY} (e.g. Atlantic marlins), the main fishing gear responsible for their capture being longline (ICCAT 2011).

vvShark by-catch around floating objects is almost exclusively composed by two species: silky sharks (*Carcharhinus falciformis*, Carcharhinidae) that represent up to 90% of shark catches in numbers (Gilman 2011) and oceanic white tip sharks (*C. longimanus*, Carcharhinidae). These days, most captured silky sharks are small (mode around 100 cm total length TL) with large individuals being rare (Amandè *et al.* 2008). It is worth noting the large differences among oceans, in particular when comparing catches of sharks between sets on free-swimming schools and on schools associated with floating objects. For instance, catch rates of sharks are very similar between the two types of sets for the western Pacific Ocean (0.9 tonnes/1000 tonnes of tuna for free-swimming school sets vs. 1.1 tonnes per 1000 tonnes of tuna for associated sets) and the eastern Pacific Ocean (1.4 tonnes per 1000 tonnes of tuna for free-swimming school sets and 1.9 tonnes /1000 tonnes of tuna for associated sets). However, the differences between the two types of sets are bigger in the Indian Ocean (0.3 tonnes /1000 tonnes of tuna for free-swimming school sets vs. 6.0 tonnes /1000 tonnes of tuna for associated sets) and the Atlantic Ocean (0.3 tonnes/1000 tonnes of tuna for free-swimming school sets vs. 1.8 tonnes/1000 tonnes of tuna for associated sets). Sharks and rays combined together represent from 2% (Atlantic Ocean) to 17% (Indian Ocean) of all by-catch. Because they have slow growth, late maturation, low fecundity and long reproductive cycles, sharks in general (and silky and oceanic white tip sharks in particular) are among the least resilient of fish species to intense exploitation (Musick *et al.* 2000; King and McFarlane 2003). IUCN lists silky shark as near threatened or vulnerable depending on the ocean and lists oceanic white tip shark as vulnerable or critically endangered.

The ratio of catches of sharks per landed catches of target tuna for purse seiners fishing on floating objects is very low (<1%), when compared to other fisheries such as pelagic longline (Gilman *et al.* 2008). Longline fisheries have quite variable ratios of shark catches depending on their strategy (target species), but sharks correspond up to a quarter of total catches (Gilman 2011), even in fisheries which do not target sharks (some longline fisheries actually target blue sharks, *Prionace glauca*, Carcharhinidae, which is thought to be more resilient to fishing than other shark species – Gilman *et al.* 2008). In the western Pacific Ocean, considering all sharks caught by longliners and purse seiners, only 9% of them come from purse seiners (Lawson 2011). In the same ocean, Oshitani (2000) estimated that purse seiners caught an order of magnitude fewer silky sharks than longliners in the 1990s.

Sea turtles are caught in small numbers by purse seiners and are released alive relatively easily. Of the estimated 5–200 caught per year per ocean, 95% were released alive (Gilman 2011). In the Atlantic Ocean, Amandè *et al.* (2010) reported only 40 individuals observed taken by purse seines over the 2003–2007 period, with almost equal share between object-associated sets and free-swimming school sets. Almost all turtles (98%) were seen being released alive by the crew. Over the same period in the Indian Ocean, 74 turtles were observed, mainly on associated sets (95%), and nearly 90% of them were released alive. Turtles, however, can get entangled in the underwater netting or in the nets covering the bamboo rafts that form the FAD float. Mortality of this type is usually not estimated (Amandè *et al.* 2008). It is clear that turtle entanglement in FADs should be reported and assessed, and priority should be placed on adopting FAD designs that would eliminate such mortality (Franco *et al.* 2009; see section 'The route towards sustainable use of drifting FADs'). Sea turtle by-catch in longline fishery was estimated as 10 000s to 100 000s caught each year in each ocean (Gilman 2011).

Impacts on habitats and ecological consequences

Whereas logs and other floating natural debris have always been a component of the world's oceanic ecosystems, FADs are now a major new component of this surface habitat. The change represented by FADs could be of two types: (i) FADs are deployed in areas where no natural floating objects would normally occur and (ii) FADs increase the total density of floating objects in areas where logs already occur. Using data from observers on board European purse seiners in the Indian Ocean, Fauvel *et al.* (2009) concluded that in this region FADs did not create new 'floating object areas', but considerably increased the existing density of floating objects in some areas, mainly north of 7° S (e.g. up to 40 times in the Somalia area), while having almost no effect on the density in southern areas (e.g. increase of only 10% in the Mozambique Channel as there was already a high density of natural floating objects).

In the absence of similar studies in the other oceans, we used log book data to determine the spatial distribution of logs and FADs from fishing sets in the Atlantic, eastern Pacific and western Pacific oceans. We first examined whether contours of areas of log sets match the contours of areas of FADs (regardless of densities of sets of each type), and then, we looked at the densities of these two set types in these areas. For oceans other than the eastern Indian Ocean (see maps in Marsac *et al.* 2000; Coan and Crone 2003, and maps provided by M. Hall, personal communication), it appears that the overall spatial distribution of FADs and logs is similar; the main difference being the densities of floating objects. This is a result of the deployment of FADs in some areas where very few logs are found naturally. It therefore appears that the major change in the environment caused by FADs is an increase in the densities of floating objects where logs naturally occur. In other words, FADs are not fished in areas completely free of logs. However, one should bear in mind that logs and FADs might drift into areas where purse seiners do not go (and therefore, cannot be reported by observers). For instance, it is known that many logs and FADs drift from the western to the eastern Indian Ocean, but purse seiners do not usually go to the East as tuna are not abundant enough for them.

Thus, it seems that FADs modify the habitats by increasing the densities of floating objects in some areas. Some authors have postulated that, because tuna seem to have such a strong attraction to floating objects, such a change (increased density of floating objects) could significantly and deleteriously modify the behaviour and biology of tunas by establishing an 'ecological trap' (Marsac *et al.*

2000; Hallier and Gaertner 2008). The ecological trap hypothesis is a concept that was first advanced 40 years ago (Dwernychuk and Boag 1972). It results from animals selecting habitats that previously conferred an evolutionary advantage but which have become maladaptive owing to recent changes in the environment. These changes are often because of anthropogenic influences. Ecological traps have recently received a lot of theoretical and experimental attention but are mainly focussed on terrestrial species (see reviews in Schlaepfer *et al.* 2002; Battin 2004; Robertson and Hutto 2006), with few studies on marine species (Marsac *et al.* 2000; Hallier and Gaertner 2008; Dempster *et al.* 2011). It is worthy to note, however, that Robertson and Hutto (2006) could only find five studies of 45 providing strong evidence for the existence of such traps. Investigating the existence of an ecological trap first requires knowledge of the original circumstances and the role of a particular cue under those conditions. This background then allows evaluation of the use of the same behavioural cues in an altered environment.

Fréon and Dagorn (2000) reviewed a total of 16 different hypotheses that attempt to explain why some species associate with floating objects. For tunas, two of these hypotheses are considered to be the most credible: the meeting point (Dagorn and Fréon 1999) and the indicator-log (Hall 1992) hypotheses. The meeting point hypothesis posits that fish gather around floating objects to facilitate or enhance schooling behaviour, which is considered to provide several advantages to members of the school (see Pitcher and Parrish 1993 for a review). Soria *et al.* (2009) recently demonstrated that FADs act as meeting points for a small pelagic fish species, the bigeye scad (*Selar crumenophthalmus*, Carangidae). Associating with floating objects would therefore help tuna to form schools (or to increase the sizes of their schools). Simulation studies (Dagorn and Fréon 1999) demonstrated that the addition of floating objects (FADs) to an area could either result in positive effects on school size (if larger numbers of floating objects facilitate encounters of schools in the area) or negative ones (by providing too many competitive sites for aggregation). Consequently, negative impacts would only occur if too many floating objects in an area results in under-optimal school sizes and if suboptimal sizes of schools have a deleterious influence on the animal such as increased predation vulnerability or preventing the animal from selecting more appropriate habitats. These impacts have not yet been empirically studied (Dagorn *et al.* 2010). However, it is noteworthy that some areas display high densities of natural occurring logs (e.g. Mozambique Channel in the western Indian Ocean) that are comparable to current high densities of FADs (e.g. Somali region in the western Indian Ocean, see Fauvel *et al.* 2009). Tunas occupied these areas of naturally occurring high log densities and so it can be argued that this speaks against high densities of floating objects alone having an inherently deleterious impact on tuna biology. Of course, under the primordial conditions in which the associative behaviour evolved, tuna populations were certainly larger than they are today.

The indicator-log hypothesis (Hall 1992) stipulates that natural floating objects are often located in productive areas because most natural objects originate from areas that inject nutrients into the ocean (e.g. river mouths, mangrove swamps) and logs remain within these rich bodies of water as they drift offshore. Thus, after an appropriate length of time, the nutrient-rich waters generate plankton blooms, which in turn support higher trophic level organisms that are food for tunas. Additionally, even after they move offshore, logs may become entrained in frontal zones where currents meet and thereby indicate regions of enhanced forage. Under both scenarios, the hypothesis proposes that tunas would use floating objects to find or stay in contact with rich areas. An important implicit statement of this hypothesis, however, is that tuna can more easily detect floating objects than prey, which has not been demonstrated yet (Fréon and Dagorn 2000).

Recent studies investigating the possibility that FADs are ecological traps focussed specifically on the indicator-log hypothesis. We review these studies by distinguishing between behavioural (e.g. movements) and biological (e.g. feeding behaviour, fitness indices) aspects (Table 5). In this review, we discuss information from both drifting and anchored FADs because Dagorn *et al.* (2010) have shown that there is no scientific evidence that the behavioural processes driving the association of tunas with FADs are different for drifting or anchored objects. Table 5 clearly shows the conflicting interpretations that can be found in the scientific literature on both the behavioural and biological aspects. At this point, no conclusion can

Table 5 Studies reporting results related to the ecological trap hypothesis, distinguishing interpretations (made by authors) in favour or not in favour of an ecological trap. Interpretations in italics did not appear as such in original papers and correspond to our interpretation.

Citation	Focal species, ocean	Method	Findings	Interpretation in favour of the ecological trap hypothesis	Interpretation against the ecological trap hypothesis
Behaviour					
Kleiber and Hampton 1994	Skipjack tuna, Pacific	Conventional tagging	Four to five anchored FADs in a 50*50 km area can reduce the propensity of skipjack to leave the area by 50%, but additional FADs do not increase this propensity	FADs increase the time residency of skipjack in a meso-scale area	Above a certain threshold of FAD density, there is no additional effect
Dagorn *et al.* 2007	Yellowfin and bigeye tuna, central Pacific	Acoustic tagging	The majority of tagged fish tend to leave the area completely without visiting other FADs or only briefly visiting nearby adjacent FADs		The island effect is more likely than the FADs to be responsible for the presence of fish around the island
Hallier and Gaertner 2008	Skipjack and yellowfin tuna, eastern Atlantic	Conventional tagging	Different migratory directional preferences and displacement rates for fish recaptured associated with FADs or in free-swimming schools	FADs modify the natural migratory patterns of tuna	
Schaefer and Fuller 2010	Bigeye tuna, eastern Pacific	Archival tagging	Fish spend about 95% of their time in a relatively restricted area, while FADs are known to drift westward through this area		If bigeye tuna were trapped in these arrays of westward drifting FADs, one would have expected to observe bigeye tuna moving westward, which is not observed

Table 5 Continued.

Citation	Focal species, ocean	Method	Findings	Interpretation in favour of the ecological trap hypothesis	Interpretation against the ecological trap hypothesis
Stehfest and Dagorn 2010	Skipjack, yellowfin and bigeye tuna, western Indian	Conventional tagging	Different displacement rates and movement angles between tuna associated with FADs or in free-swimming schools Spatial and temporal overlap between recaptures at FADs or in free-swimming schools Movement characteristics did not differ between fish tagged during periods of high and those tagged during periods of low FAD density		The observed difference is not necessarily an indication of a FAD effect on tuna movement, but might be an artefact of the non-uniform distribution of FAD fishing effort Either only a part of individuals are affected by ecological trap, or there is no ecological trap effect and fish movement is determined by environmental cues or natural migratory pathways This might indicate the absence of an ecological trap effect
Biology					
Gaertner *et al.* 1999	Skipjack, yellowfin and bigeye tuna, eastern Atlantic	Biometric data on frozen tuna	No difference between fish associated with floating objects and in free-swimming schools		No effect of FADs
Marsac *et al.* 2000	Skipjack tuna, eastern Atlantic	Biometric data on frozen tuna (same data set than Gaertner *et al.* 1999), but limited to north of 5° N	Conditions (thorax girth vs. fork length) of fish associated with floating objects are lower than those in free-swimming schools	FADs have detrimental effects on tuna biology	

Table 5 Continued.

Citation	Focal species, ocean	Method	Findings	Interpretation in favour of the ecological trap hypothesis	Interpretation against the ecological trap hypothesis
Ménard *et al.* 2000	Skipjack, yellowfin and bigeye tuna, eastern Atlantic	Stomach fullness	Small fish do not feed when associated with FADs, but large tuna do feed		Tuna are likely to feed during their daytime excursions away from FADs, before coming back to FADs. Large tuna benefit from the association with FADs
Hallier and Gaertner 2008	Skipjack and yellowfin tuna, eastern Atlantic	Stomach fullness, condition factors (plumpness), growth	Tuna associated with floating objects have more empty stomachs, are in poorer condition and grow slower than fish caught in free-swimming schools	Negative impacts of FADs on the biology of tuna	
Jaquemet *et al.* 2011	Skipjack and yellowfin, western Indian	Stomach fullness	No difference in the diet of tuna between drifting floating objects and free-swimming schools in a rich-food area, but skipjack and small yellowfin tuna associated with drifting FADs in a poor-food area have more empty stomachs than individuals associated with drifting FADs Large yellowfin tuna do not show any difference between the two areas, and in the poor-food area, they are similar to individuals caught by longliners	Drifting FADs can impact negatively skipjack and small yellowfin by trapping them in poor-food area (but small yellowfin are more efficient when foraging in such a context than skipjack)	Minor impact of FADs on large yellowfin

Table 5 Continued.

Citation	Focal species, ocean	Method	Findings	Interpretation in favour of the ecological trap hypothesis	Interpretation against the ecological trap hypothesis
Robert *et al.* 2010	Skipjack, western Indian	Condition factors (plumpness, bioelectrical impedance)	In an area poorly modified by the addition of FADs – i.e. dominated by logs – fish around logs are in a poorer condition than skipjack in free-swimming schools		The lower condition of tuna around floating objects vs. free-swimming schools is natural and normal and is not induced by the habitat changes because of FADs

FAD, fish aggregating devices.

be made on this hypothesis. It is noteworthy, however, that none of these studies included data collection protocols specifically designed to test the ecological trap hypothesis. The only exception is the study conducted by Robert *et al.* (2010) who tested the hypothesis that if associating with logs confers a feeding advantage, log-associated fish found in areas of high density of natural logs (only slightly modified by FADs) should exhibit body conditions equal or even superior to fish in free-swimming schools. Results rejected the hypothesis, which led the authors to caution against concluding that a difference in condition indices of associated and non-associated fish demonstrates a negative consequence of the introduction of FADs. The role of logs and FADs in the ecology of tunas – especially their feeding ecology – requires a greatly expanded data base and should be a research priority.

If some species stay associated with floating objects (or arrays of floating objects) for long periods, floating objects may modify their dispersal patterns. This might result in deleterious consequences. Dispersal of sessile marine animals attached to marine debris has been documented for several years (Highsmith 1985; Gregory 2009) and has been viewed as facilitating the invasion of non-native species and therefore, a potential threat for the biodiversity (Barnes 2002; Barnes and Milner 2005). On the other hand, in metapopulation theory, dispersal can serve to reduce extinction risk through the colonization of empty habitat (Bowler and Benton 2005) and is also considered to counteract the negative effect of disturbances on local populations in the metacommunity concept (Venail *et al.* 2008; Altermatt *et al.* 2011). Neither of these hypotheses has been tested regarding sessile organisms that colonize FADs, nor on fish species which associate with FADs. There is insufficient knowledge of the 'normal' behaviour, and distribution patterns of tunas and other fish species to be able to judge whether the current situation of higher FAD density has altered their behaviour.

Fish aggregating devices can also impact coastal ecosystems when they end up on reefs or beaches. Bamboos (which are used to fabricate FADs) are biodegradable materials, but might cause some physical damages on corals when they are washed by the waves, similar to what natural objects such as logs or other solid debris can also cause. In addition, electronic buoys (which are not biodegradable) attached to FADs can also end on reefs and beaches, as nets equipping FADs which might then be responsible for ghost fishing on reef-associated species when stuck on reefs or beaches. Although surveys are conducted to assess the amount of man-made debris (e.g. plastic) stranding on beaches in the world (Barnes 2002), there is currently no estimate of the numbers of FADs ending on reefs or beaches and it is therefore not possible to assess the relative importance of such impact.

The route towards sustainable use of drifting FADs

Although banning the use of FADs has been proposed by some NGOs (e.g. http://www.greenpeace.org/international/en/press/releases/Greenpeace-Calls-for-Urgent-Ban-on-FAD-Fishing-to-Save-Pacific-Tuna/), it is very unlikely that industry will willingly abandon this efficient fishing tool. Such a move would first result in a drastic decrease in tuna catch (especially skipjack tuna) with the direct consequence of a shortage of canned tuna – one of the major source of affordable natural proteins in the world (1.7 million tonnes of canned tuna in 2006, Miyake *et al.* 2010). Moreover, such a measure could have unexpected negative consequences as any type of fishing invariably impacts an ecosystem. It is worth remembering that the reduction of fishing on dolphin herds in the eastern Pacific Ocean in response to campaigns of environmental groups contributed to more fishing on logs and FADs, bringing new conservation issues (Hall 1998). Reducing the number of sets on floating objects would almost certainly result in an increase in the numbers of sets on free-swimming schools. A recent study in the Indian Ocean has shown that a 1% decrease in the number of sets on floating objects would decrease the catches of skipjack tuna by 1.3% but increase those of large yellowfin tuna by 1.7% (Guillotreau *et al.* 2011) as a result of redirecting fishing effort. In cases like the Indian Ocean, where it would be inappropriate to increase catches of yellowfin tuna beyond the current level, an assessment of the effects of a ban of FAD fishing on the yellowfin tuna stock should be carefully investigated before any decision is taken.

The purpose of this section is to list the measures investigated or implemented by the RFMOs and to identify which new measures and practices, based on the best available science, could be proposed and what future research could improve the sustainable use of FADs.

Monitoring the numbers of electronic buoys and numbers of FADs (FAD management plans)

Fish aggregating devices (and supply vessels when they exist) are a major part of the fishing effort of this fishery and will probably remain so. Because FADs are very efficient fishing aids, it is urgent that they must be monitored like any other type of fishing effort. This is necessary to quantitatively assess the impact induced by the use of FADs. Fishing effort of purse seiners is usually estimated through numbers of fishing days and types of sets (although this latter is not really an index of effort), but never using the numbers of FADs or electronic buoys. A major part of the 'FAD effort' of a purse seiner comes from its use of electronic buoys, and this more or less determines the average number of floating objects monitored at any given day of the year. Because almost all electronic buoys are now linked via satellite, it is technically possible for RFMOs to require a copy of all pertinent satellite signals. This would not only serve as a measure of the number and location of FADs deployed in an area, but by linking the locations of these FADs to locations derived from vessel monitoring systems (VMS), it would be possible to monitor exactly which FADs that are fished. This would not only measure FAD fishing effort but would also give insight into the biology of the fish by determining how they are distributed within the FAD array. One such scheme has just been implemented by ORTHONGEL, the French association of tropical tuna purse seiners. They record the daily positions of all active buoys of all their purse seiners and transfer them to a French research institute (IRD, Institut de Recherche pour le Développement). To ensure neutrality and anonymity regarding fishing strategies, the data are not made available until after a delay of several months.

In addition, all floating objects of the ocean (natural objects, FADs deployed by the purse seiner and FADs deployed by other purse seiners) represent potential aids to a purse seiner. It is therefore essential to not only count the numbers of active electronic buoys but to get a better estimate of total FADs in the water (including those no transmitters or with dead batteries), we should know the number of FADs that are built and deployed by each purse seiner every year. Monitoring the number of FADs is also key to quantifying the changes of the habitat they induce and assessing if FADs act as ecological traps. Counting the number of FADs has been an objective of all RFMOs. Marking FADs to help observers to identify individual FADs has been investigated by the IATTC and WCPFC (WCPFC 2009). Such a measure would allow tracking of the numbers of FADs deployed. Despite the fact that each RFMO currently has or is starting a FAD monitoring or management plan (Table 1), information on the numbers of FADs is still lacking, at least on some oceans. The only available estimates come from the IATTC (with 9,813 FAD deployments recorded by observers onboard fishing vessels in 2008, WCPFC 2009) or from research projects (e.g. Moreno *et al.* 2007). Current FAD monitoring plans could be improved with more mandatory requirements (it is only mandatory for ICCAT and IOTC to report numbers of deployed FADs to the respective RFMOs, while for IATTC and WCPFC, vessels report to their country flags) and better compliance. Currently, there is no FAD management plan in place, but each RFMO is under the process of asking each country to develop such a plan.

Reducing fishing mortality of juvenile bigeye and yellowfin tuna

Although it is necessary to conduct research (e.g. through the use of conventional tagging) to improve scientific knowledge of the growth and natural mortality of juvenile tunas, there is no current scientific evidence that demonstrates that the catches of small bigeye and yellowfin tuna around floating objects put these stocks at risk of collapse. Decision-makers need to look at all sources of fishing mortality and reduce it where necessary. These decisions are often difficult because they can influence the way in which catches are allocated among different users/fleets. For example, an analysis by SPC/OFP (2010) shows that the necessary reduction in the overall fishing mortality of bigeye tuna in the western Pacific Ocean can be achieved through various combinations of substantial catch reductions in at least two of three major fleets (floating object fisheries, longline fisheries, and domestic Indonesian and Philippines fleets using a mix of gears). The multispecies nature of all fisheries, including today's floating object fisheries, needs to be taken into consideration. In general, skipjack tuna stocks are healthy (in better situations than yellowfin and bigeye tuna stocks) and FAD fishing does represent an efficient fishing method to target this species. However, as sets on floating objects also catch important quantities of bigeye and yellowfin tuna, an increase in catches of skipjack tuna by this method is not possible today without also capturing of these other species. This could impact the status of these stocks. Purse seine sets on floating objects do account for an important part of the overall catches of all of these stocks, and therefore, controlling them can have an important direct impact on their exploitation. Several Tuna RFMOs have adopted measures to limit the catch of small tunas (Table 1). Two main techniques are currently used: (1) moratorium of FAD fishing in some areas at certain times (ICCAT Rec 1999-01) or full time-area closures in areas where FAD fishing is the main fishing strategy (IOTC Res 10-01, IATTC Res C-11-01), and (2) retention of all tunas of all sizes (Resolution for IATTC C-04-05 REV2 and WCPFC 2009 -02 and recommendation for IOTC 10-13), with an exemption for catches that are deemed to be unfit for human consumption. The efficiency of time-area closures to reduce the fishing mortality on juvenile tunas has often been counterbalanced by redistribution of fishing effort or non-compliance by non-participating fleets (Bromhead *et al.* 2003). Harley and Suter (2007) modelled the effects of time-area closures on the fishing mortality of bigeye tuna. They concluded that only very large or long closures would have significant impacts, and therefore, they concluded that emphasis should preferably focus on gear technology methods.

Restricting the numbers of sets on floating objects was investigated in the western and eastern Pacific oceans (IATTC Res C-99-07, WCPFC 2004, 2009) but was considered difficult to monitor and was never implemented. However, as FADs and electronic buoys have become increasingly crucial components of the fishing effort of purse seiners, they could be used to monitor and regulate fishing effort. Restricting the number of FADs per vessel was investigated in the western Pacific Ocean (WCPFC 2004) but not adopted as a management measure. However, restricting the number of electronic buoys could be a better method to limit the effort on FADs. As mentioned previously, an automatic link of any signal from a satellite buoy to a RFMO would ensure a relatively easy compliance. The French association ORTHONGEL has just set a limit of all their purse seiners to 150 active electronic buoys at any given time, and a total of 200 new electronic buoys purchased per year. Such precautionary initiative places the onus onto scientists to assess what numbers of monitored FADs would be sustainable. Such a study was requested by the IATTC but no scientific report yet exists. The lack of monitoring of electronic buoys and FADs has so far precluded scientists from estimating the effects of changes of the numbers of buoys or FADs on catches. This reinforces the urgent need for RFMOs to monitor these variables and is a pre-requisite to assessing if restricting the numbers of buoys or FADs would have a significant effect on the fishing mortality of juvenile tunas.

Reducing the fishery-induced mortality of by-catch

Mitigation measures currently in use in FAD purse seine fisheries are few and only recently enacted (Table 1). The main reason for this late effort is because of the very low proportions of by-catch generated by this gear when compared to other gears such as longlining. Consequently, longlining has received most attention in terms of developing mitigation techniques. An exception is the Ecuadorian purse seine fleet, which is mandated to carry sorting grids to let by-catch species of small body size out of the net. Although this technique is mandatory in Ecuador, no scientific assessment of its success has been completed (an assessment is currently being undertaken). Sorting grids are based on size sorting of individuals. However, the main issue is that juvenile bigeye and yellowfin tuna around FADs are usually of the same sizes as skipjack tuna (e.g. fish that should be kept), while other by-catch species are either smaller or larger than skipjack tuna. However, if the species to be released can be separated from the species to be kept (skipjack tuna) through behavioural manipulations (such as constraining them to specific area of the net – see Hasegawa *et al.* 2010), such grids (or any other system allowing an opening of the net, such as the ones used in the Mediterranean bluefin tuna, *T. thynnus*, Scombridae, fishery) could potentially contribute to reducing the mortality of some species.

Priorities should be set to determine the species on which fishing mortalities must be reduced. It is noteworthy that many key biological parameters of most of by-catch species are poorly known (or even sometimes completely unknown), which makes it difficult to fully assess the risk for each species. Moreover, no stock assessments are conducted on by-catch species. The ecosystem approach to fisheries (Pikitch *et al.* 2004) requires assessment of the effects of fishing on all components of the catches, and more research efforts should be encouraged on the most common by-catch species, such as oceanic triggerfish or rainbow runners. The fact is that most (81–95%) purse seine by-catch is comprised of small tuna species (other than target species) and other bony fishes, and the current knowledge or assumptions are that those populations are not considered to be under threat. Consequently, it can be argued that the most appropriate current approach is to avoid waste and to promote use (full retention) of this by-catch as it is carried out in other fisheries (Salomon 2009). However, careful socio-economic studies should be developed before implementing such a procedure as it can affect some local markets. Currently, a full retention measure is already in place for tunas managed by IATTC and WCPFC (C-04-05 REV2 and CMM 2009-02), but no measure concerns by-catch species. Any full retention measure requires 100% observer to be enforced. Usually, full retention measures motivate fishers to avoid catching by-catch (Salomon 2009). However, if a market for by-catch is created, fishers can sometimes fish for by-catch when target species are rare. It is noteworthy that the Atlantic Ocean, where a large market for by-catch exists (Romagny *et al.* 2000), is the ocean with the highest by-catch ratio. If fishers get paid on by-catch, they might begin to target some of these species. Another approach is to not pay fishers for by-catch even though it must be retained and utilized.

Priority research should focus on species that are known to be more vulnerable, such as sharks and turtles, even if the catch rate of sharks (<1%) is very low as compared to other fisheries. Tuna RFMOs recommend the release of live sharks, but the numbers released and the percentage of these that survive in purse seine fisheries are not currently known (Clarke 2011; but see Poisson *et al.* 2011 for a first estimate). The anti-fining measure implemented in all RFMOs (Clarke 2011) is mainly addressing longliners, not purse seiners. Recently, the ICCAT and IATTC prohibited the landing, storing and selling of the oceanic white tip shark in the Atlantic and eastern Pacific oceans (ICCAT Rec 10-07, IATTC Res C-11-10), but the efficacy of this measure to reduce catches of this species has still to be tested as this does not preclude fishers from catching and discarding this species. The successful efforts to virtually eliminate dolphin by-catch in the eastern Pacific Ocean purse seine fishery indicate that innovation and legislation can result in significant reduction in the take of large marine species (Hall 1998). Similar advances may be possible for sharks and turtles. However, this must be accompanied by parallel efforts to reduce mortalities of sharks and turtles by other fisheries, for example longlines, as purse seiners are only responsible for a small portion of the fishing mortality of these species (Gilman 2011; Lawson 2011).

Measures must also be developed to reduce shark and turtle entanglement in the FAD structures themselves, and some attempts have been made to test new FAD designs (Delgado de Molina *et al.* 2007), but no conclusive results were found because of the small number of tests. Recently, Franco *et al.* (2009) proposed different designs of ecologically friendly FADs that used only biodegradable materials. Moving from traditional to environmentally safe (and, if possible, biodegradable), FADs appear to be a necessary and appropriate step for reducing the ecological impact of FADs, and some efforts are currently being undertaken in the Indian and Atlantic oceans by the French and Spanish fleets. We recommend that RFMOs should only allow FADs on which animals cannot get entangled. To respect the MARPOL convention and reduce the impacts on coastal habitats, FADs should be made of only biodegradable materials. Limiting the lifetime of FADs has been investigated in the eastern Pacific Ocean (see: self-destructing FADs – IATTC 2008) and could also result in reducing fishing effort.

Managing fisheries with an 'ecosystem approach' is still very much a 'work in progress'. In the mid 1990s, Hall (1996) wondered if a selective (or, 'targeted') fishery is better than a non-selective one in terms of ecosystem stability. In more recent discussion of the concept of the proportional removal of all species/components from an ecosystem (except vulnerable ones such as turtles, sharks), it has been argued that very selective fishing might not always be the best way to achieve the objectives of the ecosystem approach to fisheries (Zhou *et al.* 2010; Garcia *et al.* 2012). Continued effort should be made to understand what balance of species can be taken from the pelagic ecosystem and the role of FADs in that strategy. Methods quantifying the ecosystem impacts of fisheries, through the consideration of the absolute removals incurred during the fishing operation, should be encouraged. Such methods provide a useful tool for drawing comparisons between various fisheries or fishing modes (Gerrodette *et al.* 2012). Models used to manage fisheries were first developed by population dynamists with concepts based on single species (Hall *et al.* 2000). The multispecies nature of catches of most fisheries (including the tropical tuna purse seine fishery), as well as indirect impacts of fishing on ecosystems, led to the emergence of the ecosystem approach to fisheries (Pikitch *et al.* 2004). This new approach has brought more ecologists to fisheries science, but determining how to harvest an ecosystem in accordance with ecological concepts is still very much in the research phase (Hall *et al.* 2000).

Fish aggregating devices have increased the numbers of floating objects in the ocean. And, even though the change seems to be one of intensity within pre-existing regions rather than the introduction of completely novel components, FAD use should be monitored (numbers, types, trajectories, etc.) to measure the evolution of these anthropogenic changes and their impact on the pelagic ecosystem. In the same way that we monitor oceanographic variables (for example, through remote sensing), it would be advantageous to monitor the density and distribution of floating objects at sea, as this appears not only to be a key part of the fishing effort, but also a key factor in understanding the dynamics of tunas and other associated species. It is conceivable that the density of floating objects affects the movement of tunas and other species and, like sea surface temperature or other oceanographic parameters, FAD densities should be factored in when trying to determine which factors drive the movements and distribution of pelagic animals.

Tuna RFMOs cannot ignore the possible effects of FADs on the ecology of fishes. If some effects are demonstrated, then some limits on the numbers of FADs deployed should be established. We have seen, however, that analyses to determine whether FADs act as ecological traps for tunas (or other species) gave contradictory results. More research is clearly needed. Designing experiments to determine the existence of ecological traps is not trivial (Robertson and Hutto 2006). Investigating whether the existing level of FAD deployments represents an ecological trap requires dedicated research with data collection protocols designed specifically to test this hypothesis. At a minimum, this requires establishing some reference points (in terms of both behavioural and other biological aspects) against which to measure the effects of FADs. Ideally, reference points would correspond to indices describing the behaviour and biology of species before FADs were invented. Because such data do not exist, reference points should be estimated under current conditions. Robert *et al.* (2010) approach was to identify an area with natural occurring logs and only a minor number of FADs. This allowed the assumption that the behaviour and conditions of fishes in this area were similar to what could have been observed before the use of FADs. We recommend this approach be used in other oceans where similar circumstances exist. A complementary approach would be to start a time series data base of some key behavioural and biological indices referenced to the densities of floating objects, proportion of FADs vs. logs, and key oceanographic parameters (already performed through remote sensing). This would allow assessment of whether changes of behavioural and biological indices could be linked with changes of densities of FADs or environmental factors. Determining the best indices is itself a part of that research. Adult survival and reproductive success, classically used in terrestrial ecology to investigate the existence of an ecological trap (Robertson and Hutto 2006), should obviously be estimated for tunas or other species at regular time intervals. This is usually carried out through conventional tagging projects and large-scale biological programmes which, unfortunately, are not so frequent because of their high costs. In addition, we also recommend identifying complementary indices that could reflect changes in the conditions or behaviour of fishes. Condition indices could come from morphometrics measurements (for instance, the commonly used plumpness indices) but also using bioelectrical (e.g. Willis and Hobday 2008) and biochemical approaches (e.g. Fraser 1989). When collecting such indices, it is essential to collect detailed information on not only the location and time, but also the type of schools sampled (free-swimming schools, schools associated with logs or FADs) and the FAD-to-log ratio in the area. In terms of behaviour, we would recommend starting to collect regular information on the timing and duration of residency at FADs in regions with different densities of FADs and different environmental parameters. This can be done through regular acoustic and archival tagging. The regular collection of such indices will not only help assess the effects of FADs on the ecology of fishes, but will help understand why tunas and other fishes associate with floating objects.

Conclusion

After reviewing what we know and do not know about the impacts of the use of FADs on tuna populations and habitat or on the biodiversity and viability of the ocean pelagic ecosystem, we aim at providing a framework for the objective scientific analysis of the use of FADs. Although Tuna RFMOs have started to implement measures primarily to limit the effort on FADs, the efficiency of these measures is not yet demonstrated. We believe that it is urgent that Tuna RFMOs collect accurate data on the numbers of active electronic buoys used by purse seiners. Some RFMOs do collect data on the numbers of FADs deployed, but still, very few reliable estimates exist. More must be carried out to quantify the phenomenon. Such monitoring will facilitate a real understanding of the role of FADs as a component of the fishing effort. This is an essential pre-requisite to assessing the effects of management measures that would limit the numbers of buoys or FADs in the fishery.

In terms of by-catch, although purse seining on FADs is not responsible for the major fishing mortality of silky and oceanic white tip sharks (Gilman 2011), urgent research is required to develop methods to limit fishing mortality of these species in purse seine fisheries. The existing resolutions on the oceanic white tip sharks (ICCAT Rec 10-07, IATTC C-11-10) and on the silky sharks (ICCAT Rec 11-08) will have almost no effect on by-catch by purse seiners. Finally, there is no reason that all fleets should not adopt FAD designs that would not cause any entanglements. RFMOs have initiated the Kobe process to structure and harmonize their efforts on various topics because it is recognized that each RFMO will benefit from a strong collaboration (Anonymous 2007). Some FAD issues were part of this Kobe process (e.g. by-catch), but we recommend an additional international group that could coordinate research on FADs with an eye to paving the way towards the sustainable use of FADs. The groundwork for such a body has been laid by three symposia held on FADs in 1992 (San Diego), 1999 (Martinique) and recently in late 2011 (Tahiti).

Fish aggregating devices are not necessarily bad. They are efficient fishing gears that must be monitored and managed. Used correctly, they can reduce the fuel costs and 'carbon footprint' of the fleet without jeopardizing either the viability of the target species or the integrity of the pelagic ecosystem. Management of FAD fishing should be conducted in conjunction with the management of other gears catching the same species. We feel the review presented in this article is a critical tool for informing future decisions that must be made by fisheries managers and research funding agencies to achieve the objectives of ecological-based fishery management and the sustainable and cost-effective harvest of pelagic marine resources. We point out future research directions for assessing the effects of FADs on the ecology of fishes, the results of which would directly benefit our understanding of ecological function of the aggregations of fishes at FADs and also benefit the fisheries exploiting this behaviour.

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