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Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges★

Alain FONTENEAU[1,a], Emmanuel CHASSOT[2] and Nathalie BODIN[2]

[1] Institut de Recherche pour le Développement (IRD), UMR 212 EME "Exploited Marine Ecosystems" (IRD/IFREMER/UM2), 9 Bd Porée, 35400 Saint Malo, France
[2] Institut de Recherche pour le Développement (IRD), UMR 212 EME "Exploited Marine Ecosystems" (IRD/IFREMER/UM2), Seychelles Fishing Authority, BP570, Victoria, Seychelles

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Abstract – This study provides a historical overview of the use of drifting fish aggregating devices (DFADs) in purse seine fisheries since the early 1990s, using global tuna fisheries datasets from the four tuna Regional Fisheries Management Organizations (RFMOs). Tropical tuna purse seine fisheries typically target large yellowfin (*Thunnus albacares*) and bigeye (*Thunnus obesus*) tunas on free-swimming schools and skipjack (*Katsuwonus pelamis*) and juveniles of yellowfin and bigeye associated with drifting objects. DFADs have enabled global skipjack catches to markedly increase, and have also introduced major scientific issues for all tuna-RFMOs. In particular, they have strongly modified the fishing strategies of purse seiners that fish on a combination of free-swimming and DFAD-associated schools. Consequently, the cumulated search time traditionally used to quantify nominal fishing effort to assess the status of tuna stocks is inconsistent and cannot be used to derive time series of abundance indices from catch-per-unit of-effort (CPUE). In addition, the lack of information available on the construction, deployment, and use of DFADs has prevented effective monitoring of the fishing pressure over the last two decades exerted by purse seine fleets using this fishing mode. Juveniles of tropical tunas represent a substantial proportion of purse seine catch on DFADs in the three oceans, which has raised particular concern for some bigeye stocks that have been subject to overfishing in the past. Catches of juvenile tunas by DFAD fishing may also result in a decrease in recruitment for fisheries that target adult tunas such as longliners. In addition, some demographic parameters of tunas and other species associated with DFADs may be affected by the resultant habitat modification arising from the widespread deployment of DFADs. Evidence in the literature and provided by the ratio-estimator method suggest that fishing DFAD-associated schools may result in about 100 000 t of bycatch and discards annually. In addition, there is further potential for ghost fishing related mortality of sensitive species such as marine turtles and pelagic sharks. In this context and following a precautionary approach, we finally discuss the increasing need for all tuna-RFMOs to reduce, or at least monitor and control, the use of DFADs to mitigate their adverse effects not only on yellowfin and bigeye stocks but also on open-ocean ecosystems.

Keywords: Tuna fisheries / FAD / bycatch / purse seine fisheries / *Thunnus albacares, Katsuwonus pelamis, Thunnus obesus*

1 Introduction

Since the early 1990s, tropical tuna purse seine fisheries have globally increased their use of artificial drifting floating objects, i.e. drifting fish aggregating devices (DFADs), to improve catch levels (Hall et al. 1999; Ariz et al. 1999; Fonteneau et al. 2000; Dempster et Taquet 2004; Dagorn et al. 2012). Today, nearly half of all principal market tunas are caught by purse seiners fishing on DFADs. Today, nearly half of all principal market tunas are caught by purse seiners fishing on DFADs, of which an estimated 50 000–100 000 are deployed each year (Baske et al. 2012). This paper aims to review the development over the last two decades of the different purse seine fisheries using DFADs that has occurred in the three oceans, and describe the species and size composition of DFAD-associated catches. We will also examine questions related to the significant and widespread use of DFADs and discuss their potential impact on the provision of scientific advice. This advice may impact the development of management measures required for the sustainable exploitation

★ Supporting information, is only available in electronic form at www.alr-journal.org

[a] Corresponding author: Alain.fonteneau@ird.fr

of the three main tuna species caught on DFADs: yellowfin (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), and bigeye (*Thunnus obesus*). We discuss the potential impacts of DFADs as an "ecological trap" (Marsac et al. 2000; Hallier and Gaertner 2008) and the high magnitude of bycatch and discards that predominate in DFAD fishing relative to fishing on free-swimming (Hall et al. 1999; Amandè et al. 2010). Finally, we also review the management prospects for DFAD fisheries and the opportunities to effectively limit their potentially negative ecological impacts.

2 Materials and methods

We used available nominal catch data, spatially aggregated monthly catch data and size-frequency catch data for the major tropical tuna purse seine fisheries in the three oceans for the time period 1980–2010 (inclusive). Data were obtained from the four tuna Regional Fisheries Management Organizations (RFMOs) in charge of tuna management and conservation in their respective areas of jurisdiction, namely the International Commission for the Conservation of Atlantic Tunas (ICCAT), the Indian Ocean Tuna Commission (IOTC), the Inter American Tropical Tuna Commission (IATTC), and the Western and Central Pacific Fisheries Commission (WCPFC). Data resolution and quality differ between each tuna-RFMO. For instance, confidentiality rules have been developed in the WCPFC and IATTC areas that restrict access to some statistical data (e.g., http://www.wcpfc.int/wcpfc-data-catalogue). Furthermore, the quality of some national statistics (e.g., catch, fishing grounds, and sizes) can be very poor, even for major DFAD fisheries, such as the Philippines and Indonesia (Herrera et al. 2011; Williams and Terawasi 2011). We compiled the best and most recently updated tuna fisheries data from around the world. In cases of missing or incomplete data, additional working hypotheses were made and strata substitutions were used to raise spatially aggregated data to the nominal catch consistently with data processing schemes used in tuna-RFMOs.

In addition to the nominal and geo-referenced catch data available from the tuna-RFMOs, species composition information of purse seine catches on FSC and DFAD-associated sets during 2000–2009 was also used. The species composition of European purse seine catches has been estimated using a multispecies sampling technique implemented in the Atlantic and Indian Oceans since the early 1980s (Cayré 1984; Pianet 1999). Sampling is carried out during the unloading of purse seiners at port and consists of a two-step approach: (i) the wells are selected from among those containing tunas from homogeneous strata; and (ii) fishes are randomly collected by size category from the selected wells and counted and/or measured. The approach allows estimates of both size and species composition to be undertaken simultaneously. Using species-specific length-weight relationship, fish numbers can then be converted into weight to estimate the sample species composition. De Finetti ternary diagrams (De Finetti 1926), based on sample densities, summarize the percentage of each of the three principal market tuna species in the catch. These were used to compare the purse seine catch between fishing modes and oceans (Fonteneau et al. 2010).

3 Characterisation of purse seine tuna fisheries on DFAD-associated schools

In the early 1960s, fishermen began to show strong interest in the behavior of tunas to aggregate under floating structures. Thus, they significantly increased their fishing effort on associated schools, particularly in the Eastern Pacific and Atlantic Oceans. Initially, fishermen would achieve this by drifting with floating objects and waiting for sufficient tuna to aggregate before setting the net (Greenblatt 1979).

3.1 The emergence of DFAD-associated purse seine fishing

During these early years, purse seine fishing on associated schools mainly occurred in coastal areas using naturally occurring objects, for example, tree logs that washed out to sea during periods of heavy rainfall (Scott et al. 1999). With the development and deployment of large numbers of artificial floating objects, purse seine tuna fisheries were able to extend their activities to offshore fishing zones (Fig. 1).

Hereafter, the term "drifting fish aggregating devices" (DFADs) refers to any type of floating object equipped with satellite-tracked buoys for locating them. It includes natural DFADs (e.g., logs or palm branches), man-made flotsam and jetsam (e.g., wooden pallets, discarded cargo nets, etc.), and purpose-built DFADs, which typically refers to bamboo rafts fixed with an underwater net to reduce drift (Franco et al. 2009). These rafts can quickly and easily be built aboard fishing and supply vessels and recently commercial operations to manufacture DFADs have begun in some locations (e.g., Abidjan, Ivory Coast) to further increase their productivity. Artificial DFADs are deployed at sea by fishers. The number of rafts depends on a range of factors including season, fishing zone and fishing company. Country-specific fleet strategies also have an influence, for example, the Ghanaian fleet fishes almost exclusively on DFADs.

Since the early 1990s, fishing on DFAD-associated schools has steadily increased with annual global purse seine tuna catches reaching almost 2 million t in the last decade (Fig. 2). At present, DFADs represent a substantial percentage of tuna purse seine catches, i.e. an average of 57% during 2000–2009 (Fig. S1).

The percentage of tuna catches taken on DFADs varies between oceans and time periods, but it is substantial across all purse seine fisheries (Fig. S2). Since 2004, the mean annual percentage of DFAD catches is estimated at about 60% with the lowest values (typically <40% of total catch) observed in the Eastern Pacific. The low values observed in 2010 in the Western Pacific (Fig. S1) are due to the strict management measures implemented by the WCPFC to reduce DFAD-associated fishing in this area (Hampton and Williams 2011).

The significant development in the use of DFADs in purse seine fisheries worldwide is primarily due to a combination of three cumulative factors: (i) DFADs are often the only way to exploit tropical tunas, especially skipjack, in offshore areas to complement the periods of spawning aggregations when large yellowfin and bigeye can form large schools; (ii) success rates

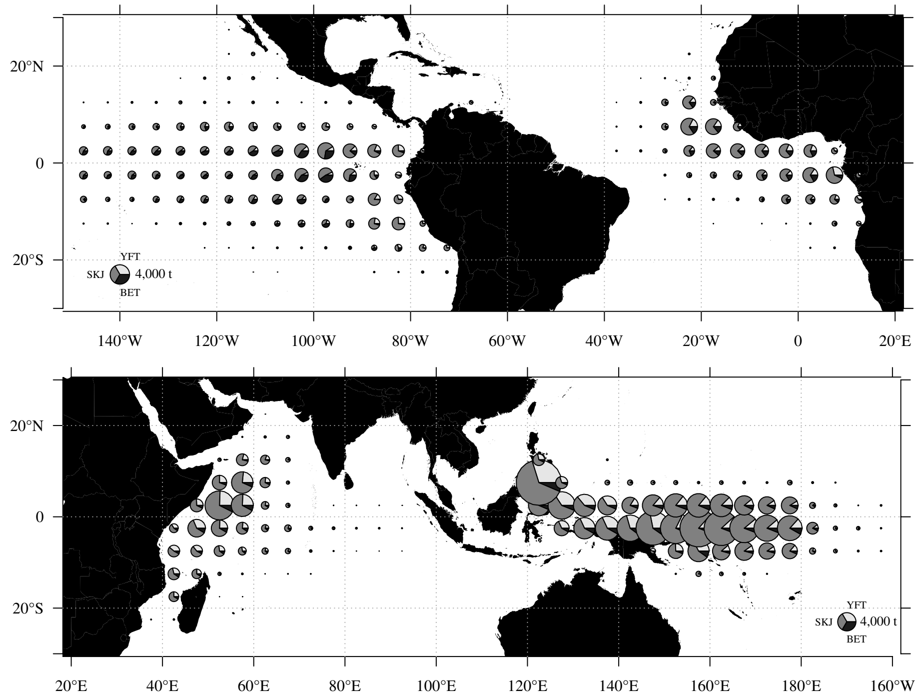

Fig. 1. Fishing zones of purse seine fisheries on drifting fish aggregating devices (DFADs). Mean annual catch by species during 2000–2009. YFT: yellowfin, SKJ: skipjack, BET: bigeye.

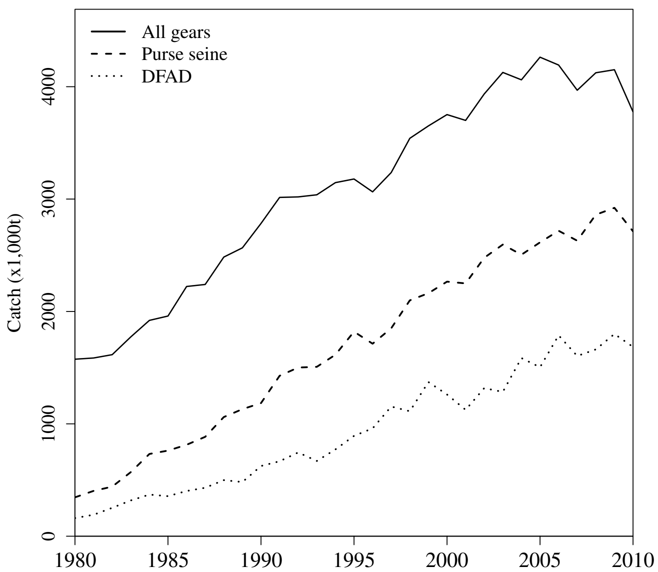

Fig. 2. Annual global catch of the principal market tunas during for all gears (solid line), purse seine (dashed line), and purse seine on drifting fish aggregating devices (DFADs) (dotted line).

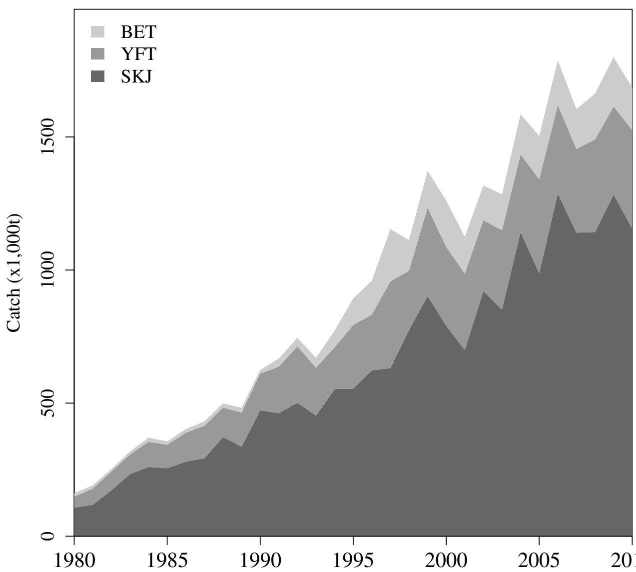

Fig. 3. Annual global catch for purse seine fisheries on drifting fish aggregating devices (DFADs) during 1980–2010. YFT: yellowfin, SKJ: skipjack, BET: bigeye.

for DFAD-associated sets are high and stable (>90%) compared to success rates of free-swimming school (FSC) sets (50–70%; Pianet et al. 2011; Floch et al. 2012); and (iii) the average catch per successful set is often higher for DFAD-associated sets than FSC sets. For instance, between 2000 and 2010, average annual catch values of 32 t set^{-1} and 27 t set^{-1} were observed for European purse-seine fisheries in the Atlantic on DFAD-associated and FSCs, respectively. Similarly, these values were observed at 40 t set^{-1} and 25 t set^{-1}, respectively, in the Eastern Pacific for the same period (Martin Hall, pers. comm.). However, this pattern has not been observed in the Indian Ocean (Floch et al. 2012).

3.2 Species composition of DFAD-associated catches

The species composition of DFAD-associated catches indicates that skipjack has been the main target species for most

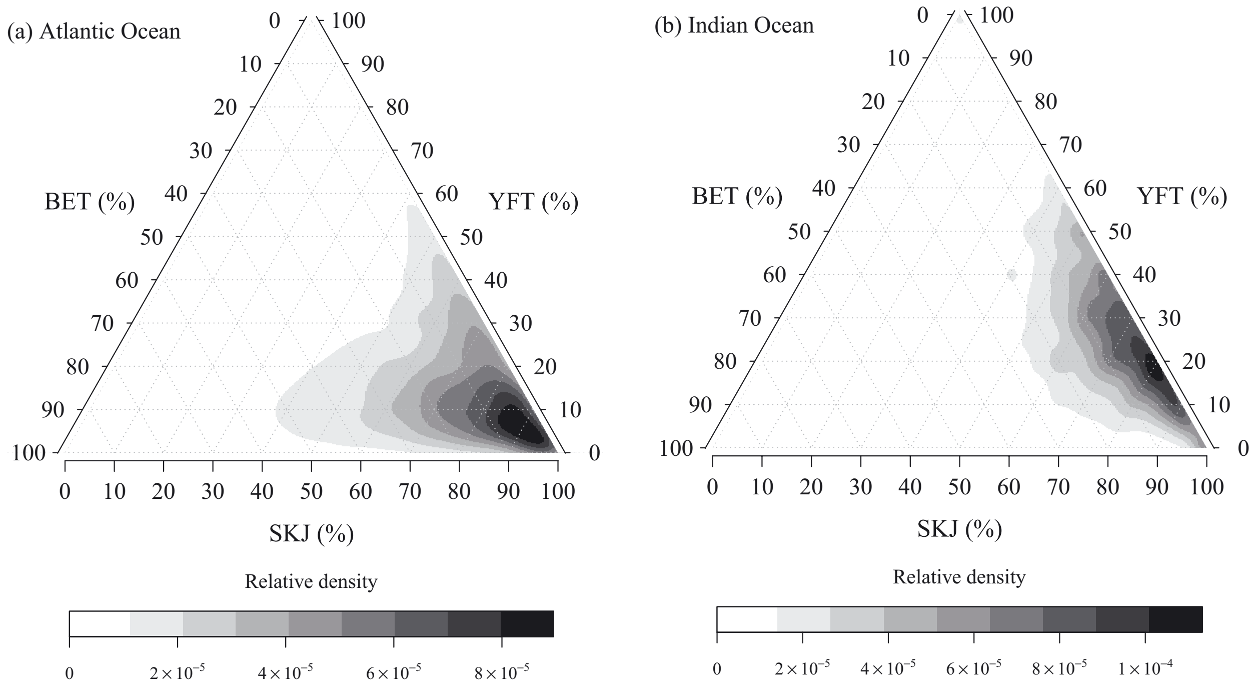

Fig. 4. De Finetti triangle summarizing the species composition (in biomass) of the catch on drifting fish aggregating devices (DFADs) derived from species-specific size samples collected at unloading of purse seiners during 2000–2009 in (a) the Atlantic (n = 5 273) and (b) Indian Ocean (n = 12 900) after Fonteneau et al. (2009).

DFAD fisheries worldwide. This species represents 60–70% of DFAD-associated catch over the last decade (Fig. 3). In the 2000s, the mean annual species composition of DFAD-associated purse seine catches showed a similar pattern across the four ocean basins: skipjack dominated the catch but was always associated with significant percentages of yellowfin and bigeye (Fig. S3). Regional differences do exist but they could stem partly from the different sampling and data processing schemes used to correct the species composition of DFAD catches (Anonymous 2010).

As most or all skipjack stocks are considered to have been exploited at moderate levels in recent years, the rise in the use of DFADs since the early 1990s has driven significant increases in skipjack catches worldwide (Figs. 2 and 3). The majority of skipjack caught by purse seiners are now taken on DFAD-associated schools (i.e. about 65% during the period 2000–2009; Fig. S4). Significant catches of yellowfin and bigeye are also taken in association with DFADs in all oceans. For the period 2001–2010, DFAD fishing represented 36% and 90% of the purse seine catches of yellowfin and bigeye, respectively. However, there are still uncertainties in the species composition of tuna for DFAD-associated catches, especially for bigeye. Juveniles of yellowfin and bigeye (<2 kg) are difficult to identify and fishers and canneries often classify them as skipjack as they hold a similar market value (Fonteneau 1976; Itano 1998). To estimate the species-specific catch of tunas for scientific and management purposes, the species composition of DFAD-associated catches and the true level of small bigeye caught in association with DFADs have been routinely monitored and estimated. This evaluation is based on species-specific sampling schemes that rely on observers or port samplers; and are known to differ between ocean basins (Anonymous 2010). In some regions and fisheries, sampling schemes have been insufficient which has introduced uncertainties in the historical catch records of DFAD-associated bigeye. For example, time series of bigeye catch from the Western-Central Pacific has recently been revised and updated based on a new sampling scheme, resulting in much higher numbers of bigeye detected in DFAD-associated catches (Williams and Terawasi 2011).

The regular and rigorous sampling of purse seine catches conducted in the Atlantic and Indian Oceans over the last 30 years indicates that DFAD-associated tuna schools are generally comprised of multiple tuna species (Fig. 4). While the species composition of the Atlantic appear to be dominated by skipjack (up to 80–90% of the catch), yellowfin and bigeye account for more than 60% and 50%, respectively, in some samples. By contrast, FSCs are typically monospecific. Monospecific schools represented 38% of the Atlantic and 44% of the Indian Ocean purse-seine samples gathered for FSCs over the last decade.

Detailed multispecies sampling data from the Pacific Ocean are not publically available. However, it can be hypothesized that the typical species compositions that are observed for DFAD-associated sets in the Indian and Atlantic Oceans are also observed in the Pacific Ocean.

3.3 Size composition of DFAD-associated catches

The data indicates that skipjack are mostly caught at similar sizes, irrespective of whether they are from FSC or DFAD-associated schools. In contrast, the majority of yellowfin

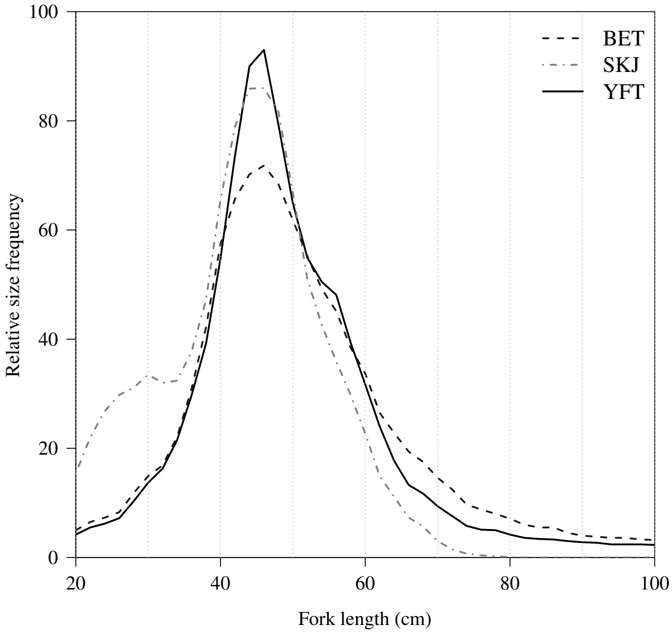

Fig. 5. Relative size-frequency distributions (in numbers) of yellowfin, skipjack, and bigeye tunas caught by purse seine fisheries on drifting fish aggregating devices (DFADs) during 2000–2009.

and bigeye caught on DFADs are small (<60 cm) and immature as compared with those caught in FSCs (Fig. 5). The size-frequency distributions of the three species caught on DFADs show similar patterns, i.e. a modal size of around 45 cm (~2 kg) with tunas larger than 70 cm being caught infrequently. Individuals of yellowfin and bigeye <40 cm are essentially absent from DFAD-associated catches, while small skipjack (20–40 cm) are found more frequently.

An inter-specific comparison of the mean annual weight and size distribution of catch in each ocean basin provides insight of the differences in fishing patterns and the underlying ecosystem productivity between oceans (Figs. 6 and S5). The mean annual weights of skipjack caught on DFADs during the 2000s were larger in the Indian and Eastern Pacific Oceans (2–3 kg) than in the Atlantic and Western-Central acific Oceans due to a higher proportion of larger individuals (Fig. 6a). The lowest mean annual weights were observed in the Western-Central Pacific Ocean (~1.5 kg) driven by the large quantities of small skipjack that were caught on DFADs in the Philippines and Indonesian fisheries. The Atlantic Ocean shows intermediate and stable mean annual weights of ~2 kg.

Except for the Eastern Pacific Ocean, the mean annual weights of yellowfin and bigeye caught on DFADs showed similar values and temporal trends for each ocean basin over the last decade (Figs. 6b, c). The mean annual weights of yellowfin and bigeye were generally low (i.e. 3–4 kg), with the notable exception in the Eastern Pacific Ocean where medium-sized bigeye were caught on DFADs during 2000–2001 (mean weight <10 kg). Yellowfin caught on DFADs in the Indian Ocean were slightly larger, i.e. with a mean annual weight of ~5 kg during the mid-2000s (Fig. 6b). In recent years, the mean weight of yellowfin decreased to less than 3 kg in the Western-Central Pacific Ocean due to small individuals (<30 cm) caught by the Philippines and Indonesian DFAD fisheries (Fig. S5).

4 Problems introduced by DFAD fisheries

4.1 Targeted species and complexity in the CPUE-biomass relationship

Standardized indices of catch per unit of effort (CPUEs) of purse seine fisheries that exploit FSCs can be used, at least to some extent, to provide historical representations of stock densities and biomass. However, DFAD fisheries have introduced major changes to the efficiency and selectivity of purse seiners. These changes have made it difficult to properly define effective effort, thus introducing major biases and uncertainties to the CPUE-biomass relationship. Consequently, search time (i.e., the time devoted to the searching of tuna concentrations), the metric traditionally used to reflect nominal effort, is no longer useful. Presently, search time represents: (i) time periods when the vessels directly target satellite-tracked DFADs; and (ii) time periods associated with spatial search patterns using radars and binoculars to detect FSCs and/or DFADs belonging to other vessels.

The mixture of search and cruising times when targeting a combination of free-swimming schools and DFAD-associated schools have resulted in large increases in CPUEs of purse seiners worldwide (e.g., Floch et al. 2012). Furthermore, the positive effects of DFADs on purse seiners' efficiency have become permanent with the advent of technological improvements such as: (i) enhanced geo-location and monitoring capabilities, both at night and day and at increasing distances; (ii) increased robustness of DFADs; (iii) increasingly powerful bird radars that detect bird flocks associated with DFADs 10–15 nautical miles away; (iv) a generalization of echo-sounders on DFADs that helps to identify rafts with a higher probability of associated tunas; and (v) improved long distance sonar that enables more efficient fishing on both FSCs and DFADs (Gaertner and Pallarés 2002; ISSF 2012; Torres-Irineo et al. pers.comm.). In addition to these technological changes, the number of DFADs deployed at-sea by supply vessels and larger purse seiners has increased as has the active use of supply vessels in the Indian and Atlantic Oceans.

In such a changing context, the mean catch-per-set on DFADs may be a better index of local tuna abundance than the traditional CPUE based on search time. However, as catch-per-set is likely to be highly dependent on the density of DFADs, it could only be used if the number of active DFADs at-sea were well estimated. Currently, this requirement is far from being met. Presently, all tuna-RFMOs are developing DFAD management plans that will collect detailed information on DFAD dynamics, including deployment and use by purse seiners (e.g., Res. 12/08 of the IOTC). However, the amount of data currently available remains very limited. Recently, quarterly information on the number of DFADs deployed by supply vessels and purse seiners has begun to be collected in the Indian Ocean (Res. 10/02) and French purse seiners have begun to share trajectory information of their DFADs with French scientists. If this program can be broadened to include all purse-seiners globally, new types of DFAD stock assessment models

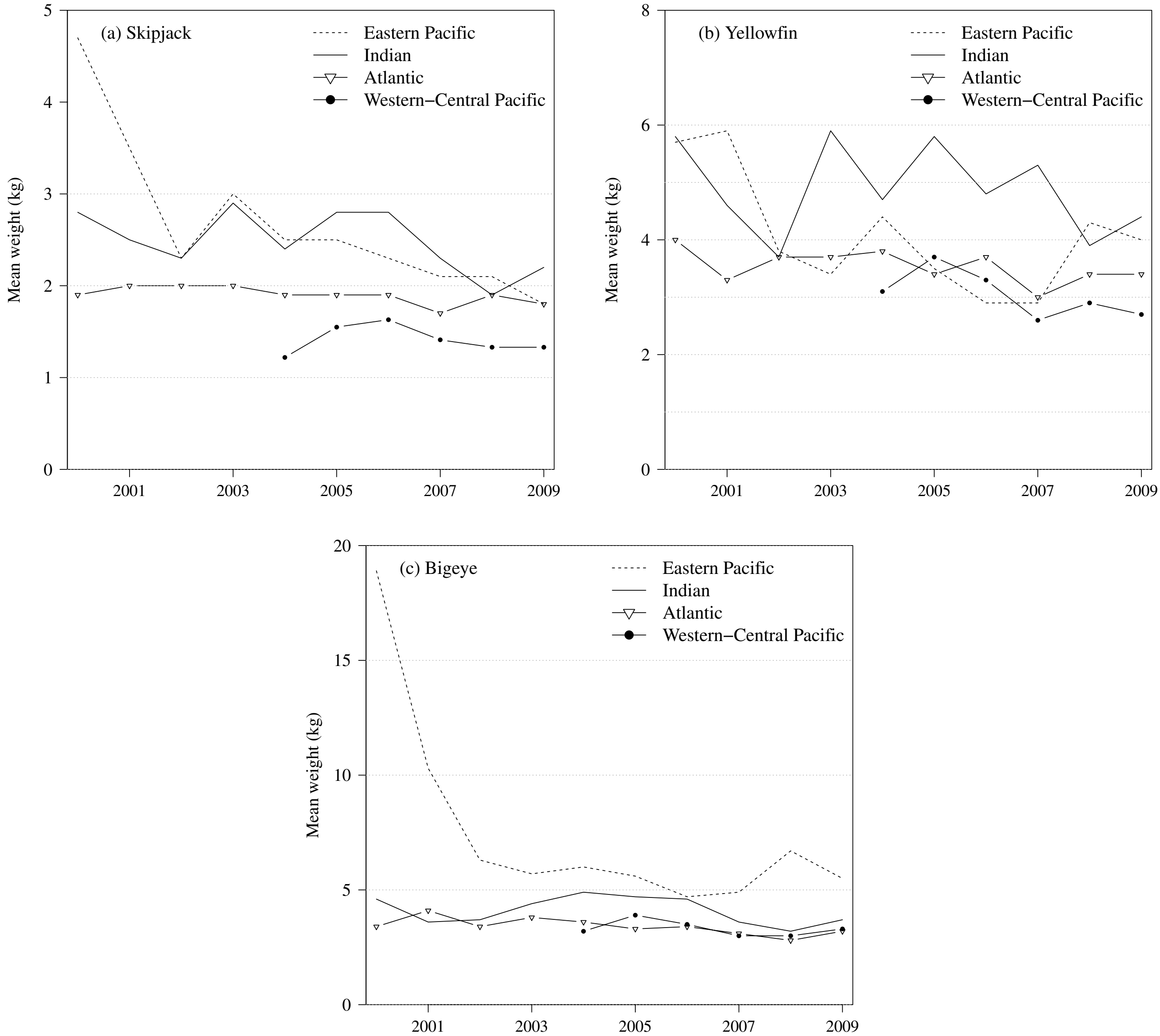

Fig. 6. Yearly average weight (kg) of (a) skipjack (b) yellowfin and (c) bigeye caught by purse seine fisheries on drifting fish aggregating devices (DFADs) during 2000–2009 for each oceanic basin.

could be developed to estimate the dynamics and impact of DFADs in purse seine fishing strategies. A primary action would be to register and monitor all DFADs deployed at sea by fishermen, consistent with the FAO "Code of Conduct for Responsible Fisheries" (Article 8.2.4, FAO 1995). The implementation of electronic logbooks aboard European purse seiners in 2013 should address these needs by including mandatory information on the type and origin of DFADs, as well as the number of visits, transfers, and modifications to the DFADs.

When information becomes available, models of DFAD dynamics will provide estimates of the number and density of DFADs by estimating "demographic" parameters, such as recruitment (i.e. the number of DFADs deployed each month and the number of natural logs equipped by fishermen), natural mortality (i.e. the rate of DFADs stolen, sunk, stranded on beaches or lost outside fishing zones), lifespan (including the rates of stolen DFADs), and movements and migrations (e.g., do they follow oceanic surface currents or do they accumulate in frontal areas and convergence zones?). In addition to DFAD dynamics, operational data of DFAD attributes should be collected and used to improve their geo-location (i.e. the distance and precision of DFAD positions) and aggregative features (e.g., net size and depth). These metrics will allow changes in DFAD catchability to be quantified over time. Finally, logbook and vessel-monitoring system (VMS) data of supply vessels should be made available to improve our understanding of their role in increasing the effective effort of DFAD fishing.

Full collaboration between the fishing industry and scientists appears to be a major prerequisite for the continuous collection of good-quality data on DFAD fishing. However, information on past practices (i.e. from the mid-1990s to

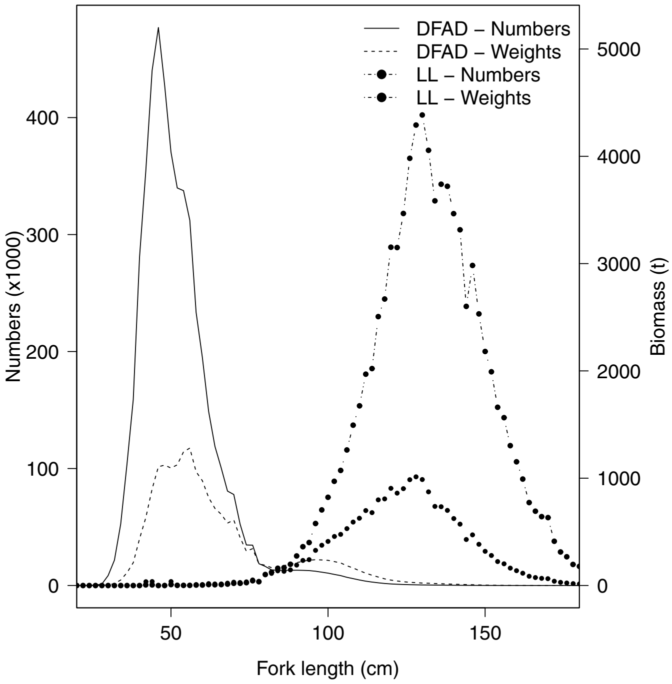

Fig. 7. Size-frequency distributions of bigeye on longliners and DFAD purse seiners.

the late 2000s) remains critically important for deriving long CPUE time-series. The incorporation of detailed parameters, data and knowledge of DFADs obtained by tuna-RMFOs into stock assessment models will likely facilitate better estimates of exploited tuna biomass by purse seine fisheries.

4.2 Yield-per-recruit interactions between purse seiners and longliners in the global exploitation of bigeye tuna

The massive global expansion in the use of DFADs by purse seiners since the early 1990s has widely changed the exploitation levels and fishing patterns of skipjack, yellowfin, and bigeye. In particular, bigeye tuna is the most heavily-impacted species by DFAD fishing (Harley et al. 2005). Longline fleets are also increasingly targeting bigeye due to its high value on the sashimi market. As a result, during the time when DFAD fishers were experiencing large increases in immature bigeye catches ($\leqslant$5 kg), longliners were catching increasing quantities of mature bigeye (about 40 kg). As observed in the Indian Ocean, there was no significant overlap between the sizes of tuna caught by the two gear types (Fig. 7).

The mean size ranges of bigeye taken by longliners and purse seiners on DFADs are very similar worldwide. As such, potential technical interactions on the yield-per-recruit between both fisheries are expected to occur in the three oceans, with a time-lag of 2–5 years. This lag corresponds with the delay needed to observe the negative effects of increased DFAD catches of immature bigeye in the longline fisheries.

However, it should be noted that in recent years, some observed declines in the CPUE of bigeye longline fisheries have been slight. This suggests that potential declines in the adult biomass have frequently been masked by increased targeting of bigeye and a hidden increase in longline fishing power (Ward 2008). During the time DFAD fishing increased, most longline fisheries were increasing their fishing effort on bigeye and associated bigeye catches. The reasons for such changes in longline CPUEs remain unclear. These moderate CPUE declines may be due to a combination of factors, including (i) the effects of increased catches on DFADs which produce a subsequent decline in adult biomass; (ii) the effects of increased catches by longliners which reduce the adult biomass; and (iii) the effects of increasing fishing power and changes in selectivity of longliners that may mask the declines in abundance.

The negative impacts of DFADs on the yield-per-recruit of bigeye stocks have been tentatively estimated by all tuna-RFMOs, but changes in the yield-per-recruit are difficult to estimate. This is because they are strongly dependent on natural mortality-at-age values, a biological parameter that remains widely uncertain. The rates of natural mortality for adult and juvenile bigeye are still very poorly estimated today; though it is thought to have a low mean natural mortality due to its slow growth rates and longevity (>12 years; Farley et al. 2006). Similar uncertainty exists for yellowfin. Based on a universal biological rule (Lorenzen 1996), natural mortality in bigeye should be much higher for juveniles than adults, as illustrated by estimates developed from tagged individuals of the three tropical tuna species in the Western-Central Pacific Ocean (Hampton 2000). Preliminary estimates of natural mortality for bigeye from large-scale mark-recapture experiments conducted in the Indian Ocean (2005–2012) also indicate higher mortality rates for juveniles (Bousquet et al. 2012).

Overall, the current uncertainties in the relative levels of juvenile and adult natural mortality are so high that the yield-per-recruit interactions between DFAD and longline fisheries remain difficult to estimate. The same difficulties are faced when estimating the effects of increased juvenile yellowfin and bigeye catches by DFAD fisheries or the implementation of time-area closures on the spawning stock biomass.

4.3 DFADs and the "ecological trap hypothesis"?

Marsac et al. (2000) proposed the hypothesis that DFADs may act as "ecological traps" for tunas and other associated species, e.g., mahi mahi (*Coryphaenus hippurus*). In this hypothesis, the large numbers of DFADs deployed worldwide could affect tuna biology in a range of ways, including (i) modifying movement patterns and unintentionally displacing individuals towards ecologically poor and unsuitable areas (Hall et al. 1999; Hallier and Gaertner 2008); (ii) modifying growth rates due to reduced food availability (Ménard et al. 2000; Jaquemet et al. 2011), which may increase the slow growth stanza observed between 40–60 cm for yellowfin and bigeye (Gascuel et al. 1992; Fonteneau and Gascuel 2008); (iii) potentially increasing natural mortality rates due to reduced nutrition, poor individual condition and/or higher predation by adult tunas and billfishes (Hallier and Gaertner 2008, Jaquemet et al. 2011; Hunsicker et al. 2012); (iv) potentially reducing natural mortality rates due to enhanced protection from predation brought about by the large schools associated with

Table 1. Annual discards (in t) of the global purse seine fishery on drifting fish aggregating devices by ocean and taxonomic group, estimated from the literature (average period 2000–2009).

Tuna category	Tropical tunas	Minor tunas	Bony fishes	Sharks	Billfishes	Total
Indian Ocean	3 700	2 000	4 300	1 300	100	11 400
Atlantic Ocean	5 700	3 000	6 500	2 000	200	17 500
Eastern Pacific	18 500	2 100	1 200	600	100	22 400
Western-Central Pacific	35 200	8 800	6 700	1 000	1 100	52 700
Total	63 100	15 900	18 700	4 800	1 500	104 000

DFADs; and finally, (v) increasing the reproductive potential of skipjack by increasing encounter rates between spawning adults.

The potential effects of DFADs on tuna biology and movements are likely to be significantly dependent on the fidelity of tuna to DFADs, but this fidelity remains very difficult to evaluate. Archival tags from the Eastern Pacific Ocean indicate that bigeye only stay under offshore DFADs for a few days at the most (Schaefer and Fuller 2005, 2010). However, there remains significant uncertainty of the stay duration when DFADs occur in dense networks. The hypothesis that a massive increase in the use of DFADs has modified the biology and movement patterns of associated species remains open to discussion and further investigation.

4.4 Increased bycatch due to DFAD fishing?

It has been known for some time that bycatch in purse seine fisheries is higher for fishing associated with DFADs than for fishing associated with FSCs (Anonymous 1993; Sabadach and Hallier 1993; Stretta et al. 1998; Arenas et al. 1999; Delgado de Molina et al. 2000). Consequently, the massive increase in the use of DFADs over the last two decades is expected to have resulted in substantial increases in bycatch. Global bycatch levels discarded at sea by fishers, and the proportions which originate from DFAD-associated sets, are difficult to estimate as they are based on frequently limited observer data. An exception to this is the IATTC area that is characterized by 100% observer coverage due to the problem with tuna-dolphin associations (Hall 1998, IATTC Res. C-99-07). In general, however, tuna-RFMOs do not maintain publicly accessible datasets on fisheries' bycatch and discards, as they do for landing statistics. At a global scale, the order of magnitude of DFAD-associated bycatch can be tentatively estimated by taxonomic group, based on the literature available in each ocean and the simple ratio-estimator method (Amandè et al. 2010, 2012; Gaertner et al. 2002; Kelleher 2005; Romanov 2002, 2008) (Table 1). These estimates are based on a series of strong hypotheses but they should only be considered as provisional indications of the potential order of magnitude.

Total bycatch rates for DFAD fishing have been estimated to be significant and in the range of 5–10% of the retained tuna catch. The mean global biomass of bycatch for DFAD fishing can be estimated at just over 100 000 t y^{-1} (Table 1). The species composition of bycatch discarded at sea appears quite similar across the four ocean basins. Small tuna are most common (~60%) and can be classified into two groups: (1) small-sized principal market tunas (<40 cm) dominated by skipjack (>80%); and (2) minor tuna species such as *Auxis* spp., *Sarda* spp., and *Euthynnus* spp., which cannot be sold to canneries but can be sold in some local markets (e.g., Abidjan). The overall biomass of the discarded principal market tuna appears low in comparison to the magnitude of their landings. Similarly, the total estimates for mixed minor tuna that are discarded (approximately 20 000 t y^{-1}) are assumed to be negligible relative to their biomass (probably millions of metric tons). Thus, although tuna discards in association with DFAD fishing certainly plays a minor role in the management of tropical tuna resources, it enables the monitoring of the catches of very small tunas (early age-class 0) that are indicative of recruitment trends. These values can help quantify the full effects of purse seine fishing on open-sea ecosystems.

Worldwide, sharks are commonly caught on DFADs and discarded. The silky shark (*Carcharhinus falciformis*) and whitetip shark (*Carcharhinus longimanus*) are the main species caught. Rays are seldom caught. Global levels of shark bycatch levels on DFADs are estimated at about 5 000 t y^{-1} (Table 1), which appears low compared to the 900 000 t of shark officially landed (FAO 2012). This is particularly true as the official landing value is certainly being underestimated (Clarke et al. 2006). As the CPUEs of silky and whitetip sharks have been showing major declines across various DFAD fisheries (Aires Da Silva et al. 2012), the bycatch of these pelagic sharks is now an issue of increasing concern for all tuna-RFMOs. Recently reported observations of silky sharks becoming entangled in the nets hanging under DFADs (Filmalter et al. 2012) may indicate that ghost fishing is causing additional mortality. The use of non-entangling DFAD designs recently tested by the European purse seine fleet in the Indian Ocean may reduce this effect (Franco et al. 2009).

Various bony fish species such as rainbow runner (*Elagatis bipinnulata*), mahi mahi (*Coryphaena hippurus*), triggerfish (*Balistes* spp.), wahoo (*Acanthocybium solandri*), yellowtail (*Seriola* spp.) and billfish (marlin and sailfish) are also caught on DFADs by purse seiners. These fish are often, but not always discarded (Gaertner et al. 2002; Romanov 2002, 2008). However, during recent years, many of these species have increasingly been retained and sold, particularly on the local markets in Madagascar and the Ivory Coast (Chavance et al. 2011).

Observer programs conducted between 1991 and 2011 aboard European purse seiners in the Atlantic and Indian Oceans indicate that marine turtle bycatch rates are low and highly variable in space and time (Clermont et al. 2012). While rates appear to be higher on DFAD-associated sets than FSC sets in the Indian Ocean, rates between the two fishing modes were very similar in the Atlantic Ocean. Overall, total estimates for all marine turtle species caught in the European DFAD purse seine fishery, based on simple raising methods and survival rate observations following release (Atlantic: >90% and Indian: >75%), suggest that a few dozen individuals may die each year. However, as with sharks, it appears that entanglement in the nets on DFADs may cause significant ghost fishing mortality. Mortality from this source has been observed by fishermen and observers (Anderson et al. 2009) but never quantitatively estimated. Even at low levels, this is a potential conservation issue, especially for endangered species (e.g., green turtle (*Chelonia mydas*) or Kemp's ridley turtle (*Lepidochelys kempii*)) or compromised populations. Consequently, this mortality source should be reduced as much as possible, for example, through the global uptake of ecological DFADs built without nets (Gilman 2011). The use of these ecological DFADs is now actively being studied by fishermen and scientists (Delgado et al. 2005; Franco et al. 2009).

It should be kept in mind that other fishing gear types like longline and gillnet are also responsible for large levels of bycatch (Kelleher 2005; Mejuto et al. 2006). In most cases, estimating these rates remains very difficult due to the scarcity of observer data. Bycatch ratios observed in some fisheries suggest that globally, the bycatch by longlines of bony fish and shark species is much higher than by DFAD purse seine fisheries (Stevens 1992; Harrington et al. 2005; Kelleher 2005; Mejuto et al. 2006). While the potential ecological dangers arising from the use of DFADs in purse seine fisheries are more visible because of observer programs implemented in all tuna-RFMOs, they are surely much lower than the environmental risks exerted by longliners (Arrizabalaga et al. 2011). The same conclusion stands for some unobserved fisheries, such as the large-scale driftnet fisheries of the Indian Ocean that annually catch ~500 000 t of tuna and likely produce large undeclared bycatch of sharks, turtles, and marine mammals (IOTC 2012).

5 Management prospects for DFAD purse seine fisheries

5.1 Any effect of increased DFAD catches on tuna stocks?

All analytical stock assessment models used by the tuna-RFMOs allow the effects of DFAD fisheries to be estimated on each of the target species (yellowfin, skipjack, and bigeye). The results of these analyses suggest that DFAD fisheries had a positive impact on skipjack catches and yield-per-recruit, but negative impacts on yellowfin and bigeye stocks due to the small sizes of these species that were caught on DFADs. The yellowfin and bigeye caught on DFADs were substantially under the "ideal" mean weight that maximizes the yield-per-recruit, thus reducing the maximum sustainable yield (MSY) for these two species. However, the negative effects from an increase in DFAD fisheries are still difficult to estimate, primarily due to the substantial uncertainties in the natural mortality of all small-sized tuna. Uncertainties in catch-at-size data also hinder accurate estimates. Comparative in-depth analyses examining the DFAD-driven changes occurring in the world's oceans are seldom carried out, but they would facilitate a better evaluation of the full effects of DFADs on tuna stocks.

5.2 How to limit the negative impacts of DFADs?

There is increasing international pressure to monitor and reduce the use of DFADs by purse seiners worldwide. Clearly, the use of DFADs has very efficiently increased the fishing power of purse seiners. Their use has also resulted in a major increase in skipjack catch; the most productive of the tuna stocks, which are not currently considered overfished. However, DFADs have had potentially negative impacts on the exploitation of yellowfin and bigeye, and this should be reduced as much as possible into the future. Furthermore, DFAD-associated bycatch levels are higher than with other purse seine fishing modes, sometimes resulting in the undeclared catch of some highly sensitive species (Arrizabalaga et al. 2011). Consequently, in line with the precautionary approach, there is an increasing need to reduce, or at least to fully control, the use of DFADs. These steps will enhance the sustainable management and conservation of yellowfin and bigeye stocks and reduce bycatch. A reduction in purse seine bycatch could also be obtained by investing in technological investigations (Gilman 2011).

It is likely that drastically reducing the DFAD-associated catch will be a difficult challenge for the fishing industry and canneries, as it will result in significantly lower tuna catch, especially skipjack. It has become difficult to restrict the widespread use of DFADs because of their importance in fishing and the lack of alternate fishing methods that enable similar quantities of skipjack catch. The management of DFADs, developed by tuna-RFMOs during recent years, has been mainly based on time-area closures that restrict DFAD fishing (Davies et al. 2012). It is unlikely that these measures in isolation will prove sufficient to achieve a sustainable and efficient level of management. Additional measures, for example, trigger catch limits, trans-shipment bans, and discard bans may also complement the management of DFAD fishing (Bromhead et al. 2003). Alternative fishing schemes for purse seiners, as well as global limitations on fleet capacity and their use of DFADs will also likely be necessary to ensure a reduction in DFAD fishing resultant beneficial effects on tuna stocks without ruining the tropical tuna purse seine industry. It will also be essential to achieve full compliance with tuna-RFMO resolutions, such as limits on the number of DFADs used, as management benefits can disappear if some fleets do not comply. This was observed in the Atlantic Ocean, where major unregulated fleets failed to comply with the moratorium implemented by ICCAT in 2000.

6 Conclusion

The active development of DFAD fishing by purse seiners over the last 20 years has strongly modified world tuna fisheries with some positive consequences, for instance, the large and sustainable increase in skipjack catches. However, this efficient fishing method has also become an increasing source of worry for tuna-RFMOs and for fishermen using artisanal and longline gears because of their negative influence on skipjack, bigeye, and yellowfin biomass. Increasing levels of accidental mortality for several sensitive species impacted by DFAD fisheries are also concerning tuna-RFMOs and environmental non-governmental organizations. Despite bycatch rates and accidental mortality most often being at quite moderate levels, relative to many other fisheries, there is now a consensus among scientists, managers, and fishermen that the extent of their use and numbers deployed should be reduced. However, the full impacts of DFAD fisheries, including bycatch rates, remain difficult to estimate. Adopting a precautionary approach to the monitoring and control of DFAD fisheries appears then essential to account for all their direct and indirect effects on open-sea ecosystems and efforts should be devoted to make such precautionary measures consistent among all tuna-RFMOs, and across all oceans (de Bruyn et al. 2013).

A more active and well-coordinated investigation by tuna-RFMOs should aim to better evaluate the impact of DFADs, including (i) their effects on the yield-per-recruit of yellowfin and bigeye stocks; (ii) their biological and ecological impacts and their potential role as "ecological trap", and (iii) opportunities to reduce their negative impacts on sensitive bycatch species associated with DFADs to almost zero.

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Supplementary information

Figure S1. Annual percentage of tuna catch from purse seiners on drifting fish aggregating devices (DFADs) for each oceanic basin.

Figure S2. Mean annual species composition of purse seine catch on drifting fish aggregating devices (DFADs) during 2000-2009 in the 4 oceanic basins.

Figure S3. Annual percentage of skipjack in the total purse seine catch (i.e. the cumulated catch of yellowfin, bigeye, and skipjack) on drifting fish aggregating devices (DFADs) for each oceanic basin during 1990-2010.

Figure S4. Percentage of skipjack catch on drifting fish aggregating devices (DFADs) over the total catch of skipjack (i.e. the cumulated catch of all fishing modes) by purse seiners for each oceanic basin during 1990-2010.

Figure S5. Relative size-frequency histograms (in numbers) of (a) skipjack (b) yellowfin and (c) bigeye caught by purse seine fisheries on drifting fish aggregating devices (DFADs) during 2000-2009 for each oceanic basin.

Supplementary information is only available in electronic form at http://www.alr-journal.org

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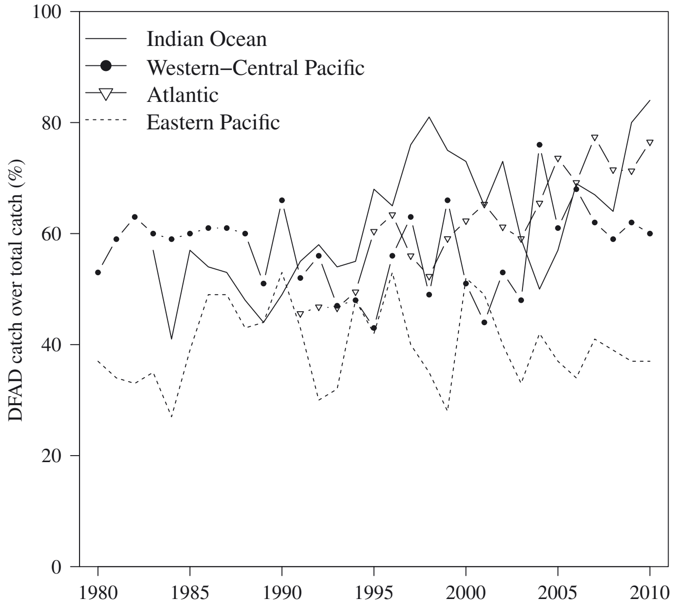

Fig. S1. Annual percentage of tuna catch from purse seiners on drifting fish aggregating devices (DFADs) for each oceanic basin.

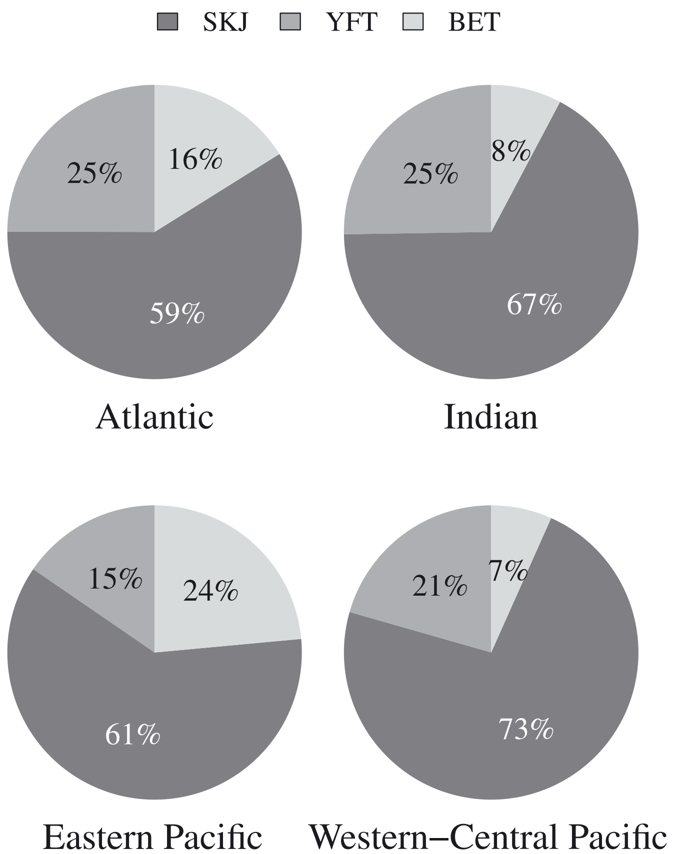

Fig. S2. Mean annual species composition of purse seine catch on drifting fish aggregating devices (DFADs) during 2000–2009 in the 4 oceanic basins.

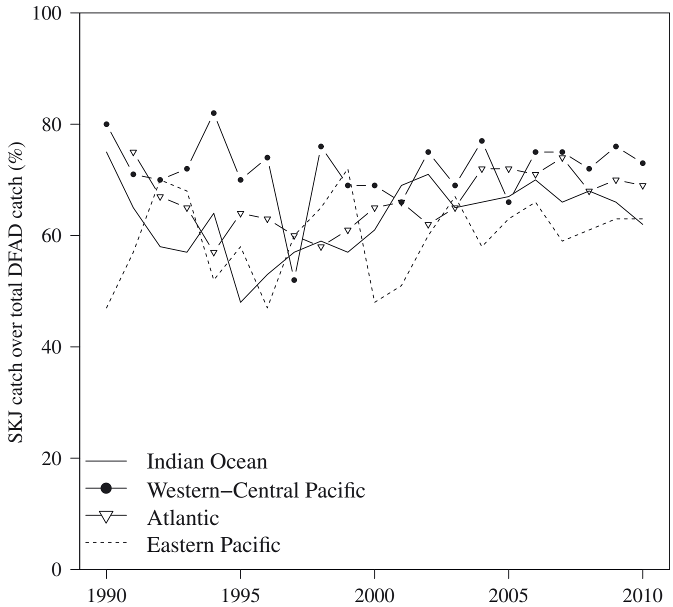

Fig. S3. Annual percentage of skipjack in the total purse seine catch (i.e. the cumulated catch of yellowfin, bigeye, and skipjack) on drifting fish aggregating devices (DFADs) for each oceanic basin during 1990–2010.

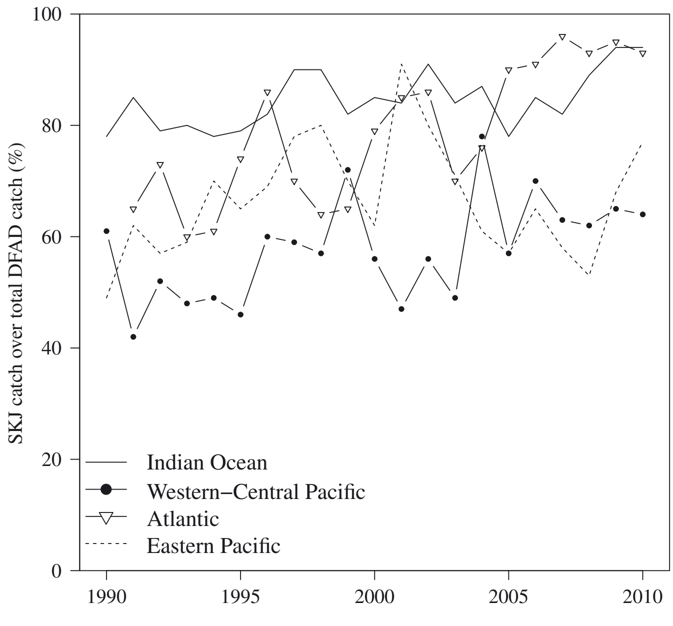

Fig. S4. Percentage of skipjack catch on drifting fish aggregating devices (DFADs) over the total catch of skipjack (i.e. the cumulated catch of all fishing modes) by purse seiners for each oceanic basin during 1990–2010.

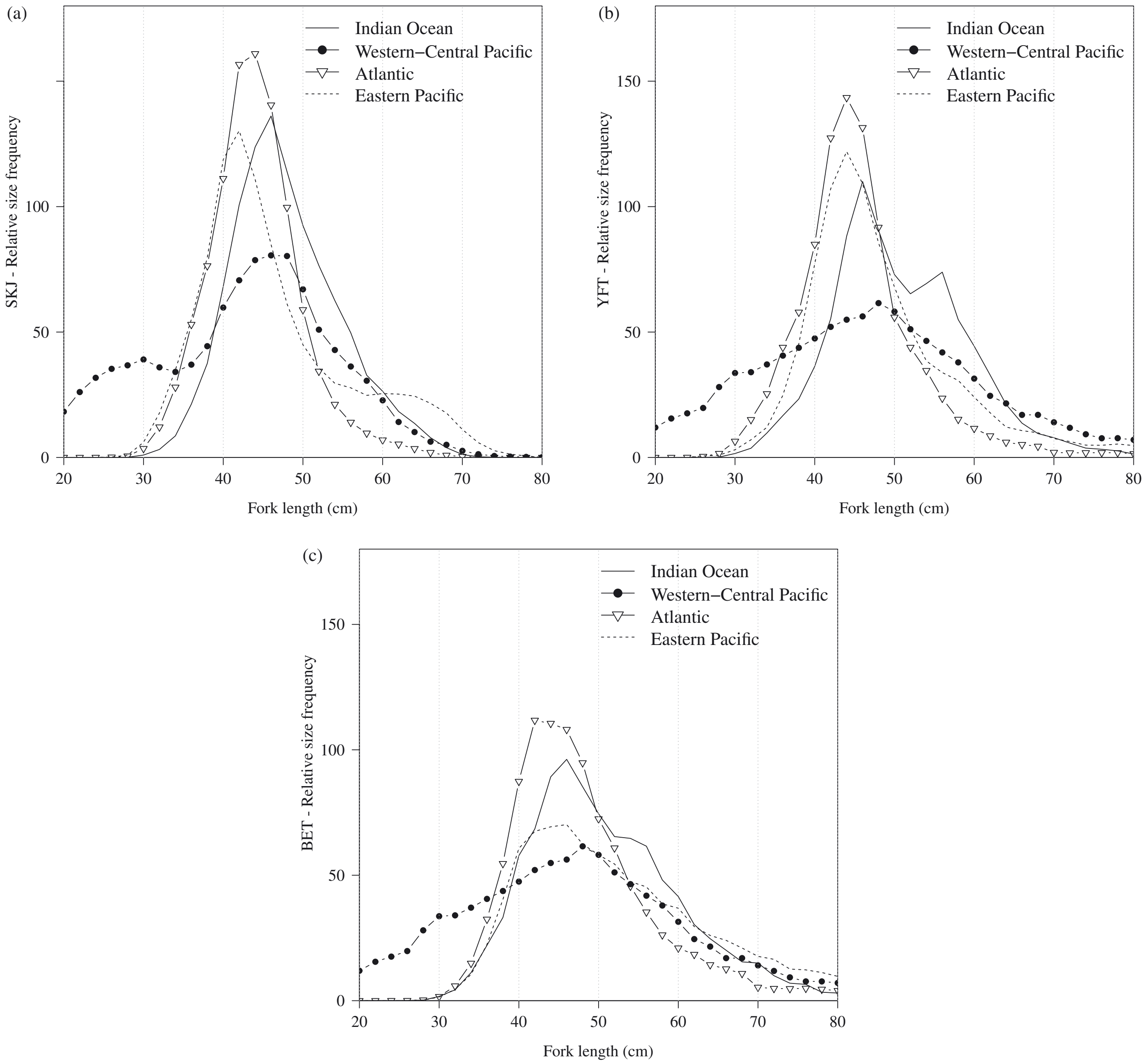

Fig. S5. Relative size-frequency histograms (in numbers) of (a) skipjack (b) yellowfin and (c) bigeye caught by purse seine fisheries on drifting fish aggregating devices (DFADs) during 2000–2009 for each oceanic basin.