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# Desk Review of FADs fisheries development in the WECAFC region and the impact on stock assessments

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# 1. Introduction

It has been known for centuries that marine organisms aggregate around floating objects and many of today's theories that try to explain the ecological context of such behavioral evolutionary conditions, are still inconclusive. One aspect that is certain is that this particular animal behavior led fishers to intentionally utilize artificial resource aggregating objects to increase fishing efficiency. An immediate added result has been the increase of exploitation rates as fishing effort units associated with such devices capture a larger fraction of the stocks per unit of fishing time. Fish Aggregating Devices (FADs) may take many different designs and ways of operating (e.g. drifting and moored or anchored FADs) mostly as a function of population dynamics and ecosystem characteristics of the resources sought by fishers. The discourse as to whether FADs increase population production or simply increase population densities that enhance fishery production are still in debate. Arguably, the most significant contribution to modern tuna fisheries development is due to the massive adoption of drifting FAD technologies in tuna purse seining worldwide (Fig. 1).

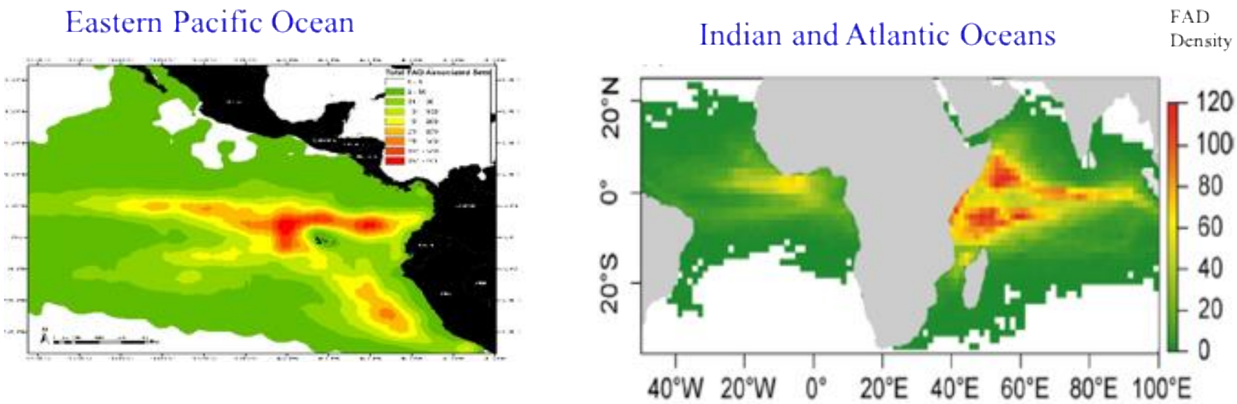


Figure 1. Geographical distribution of drifting FADs in tuna purse seining fisheries (Left created using IATTC public domain data, Right from Maufroy et al. 2015)

Concomitant with FAD fisheries developments, concerns surrounding FAD use in fisheries has generated attention about uncertainty on their ecological and ecosystem impacts. All major tuna Regional Fishery Management Organizations (tRFMOs) are actively pursuing research to quantitatively assess the impact of FADs in their diverse designs and to consider potential management options. One common recommendation from the tRFMOs working groups has been on the need to generate more data on how, where and why FADs are used. Such efforts, however, appear to be modest and out of pace relative to the very fast and vast evolution of numerous innovations that have made FADs in purse seine tuna fisheries the most advanced technological "instruments" to capture fish. Such innovations are identified with the application of sophisticated remotely operated satellite hydroacoustic tracking buoys to FADs that are likely the most significant technological development that has occurred in fisheries within the last 20-30 years. Globally, three tuna species are the main target of the FAD tuna purse seine fleets (skipjack, *Katsuonus pelamis*, yellowfin, *Thunnus albacares*, and bigeye tuna, *Thunnus obesus*). However, they also draw in non-targeted marine life, such as sharks, sea turtles, and other bony fish. Developing methods to mitigate the impact of FAD fishing on non-targeted by-catch is also an active area of research promoted by the tRFMOs and several regulations on FAD construction and design have been recommended in support of the desire to avoid bycatch and mitigate ecological impacts.

In the WECAFC area, moored FAD fishing was effectively introduced in the late 1990's and 2000's and a rapid *ad hoc* development of such fisheries is still taking place. Development aimed at, among other things, removing the excess of fishing effort exerted on depleted inshore fishery resources to offshore areas where large migratory pelagic species could be aggregated with man-made floating objects. The expectation was that such transfer of target species would improve the revenues of small scale fishers by more efficiently fishing the offshore pelagic resources. Since then, growing recognition of the need for a harmonized sub-regional approach to the moored FAD fishery has taken place and the Caribbean Regional Fisheries Mechanism (CFRM) issued relevant terms of reference for the development of a draft of a sub-regional FAD management plan.

Significant research on moored FADs sponsored by the European Union has taken place in French territories (i.e. IFREMER) in the WECAFC area. These efforts greatly improved the knowledge of data needs for better FAD fishery planning and management. Initially, the research focused on the individual behavior of fish and later at the sub-stock scale considering structure and dynamics of the fish aggregations around moored FADs. Sampling catch from fisheries operating on moored FADs in the WECAFC region reveals that, based on weight, the main species caught were blue marlin (*Makaira nigricans*), yellowfin tuna (*Thunnus albacares*), blackfin tuna (*Thunnus atlanticus),* dolphinfish (*Coryphaena hippurus*) and Little Tunny (*Euthynnus alletteratus*)(summarized in CRFM Technical & Advisory Document Number 2015/05). Catches under moored FADs are found dominated by juvenile fish for several of the key target species, with juveniles accounting for 87%, 56% and 76% of the number of yellowfin tuna, blackfin tuna and dolphinfish, respectively (Reynal et al. 2015). Other important findings are that species compositions and abundance vary greatly among islands and among fishing grounds within islands, both seasonally and inter annually. Important descriptions of the moored FAD fisheries are available from extensive literature on the subject matter and in summarized form in the CRFM Sub-Regional Management Plan for FAD Fisheries in the Eastern Caribbean (CRFM Technical & Advisory Document Number 2015/05). In the WECAFC area FAD technology development has been important from contributions from several international sources (Gervain et al. 2013) while ICCAT (Joint tRFMOs Working Group on FADs, Madrid, Spain, April 2017) recommended research and use of biodegradable materials to ameliorate the ecological and ecosystem impacts of FAD use.

The *Ad Hoc* character of moored FAD fisheries developments in the WECAFC area has created considerable issues regarding resources use, property rights, fishing access, definition of management units, and social disputes and sub-sector controversies (e.g. recreational catch-and-release versus commercial consumption). Additionally, moored FAD fisheries interact with navigational and other maritime use areas around the islands that are reflected in losses of FADs and potential damage to vessels. Disputes with and among FAD owners can prompt illegal fishing and pouching which has impacts on tourism. These issues are well enumerated and described in the CRFM Sub-Regional Management Plan for FAD Fisheries in the Eastern Caribbean. Such issues are troublesome as they indicate the urgent need for better organized development and control of FAD fisheries at the governmental institutional levels, and at the participative level via co-management as suggested in the proposed sub-regional management plan.

This report summarizes the most salient points found in a desk review on FAD fisheries requested by the FAO focusing on the needs to better understand the dynamics of FAD fishing in the WECAFC area. Special emphasis is on the question of data characterizations needed for stock assessment models used by ICCAT as the tRFMO responsible for principal tuna and billfish resources in the Atlantic and of incidence in the WECAFC area. Therefore, this summary work: emphasizes aspects relative to FADs as fish attractants, examines the evolution of technologies that enhance catchability of the targeted resources, conceptualizes the issue of catch per unit of effort as an index of relative abundance that is impacted by the aggregation nature of new harvesting gear, and finally summarizes the findings in a few points that are strategic to support recommendations of the that should emerge from the WECAFC.

## 2. Conceptual theories on FADs as fish attractants

Pelagic fish species are known to associate with each other as well as floating objects and other anomalies in the three-dimensional open ocean pelagic environment. Tunas are schooling fish of particular importance to the world’s fisheries, which are captured in significantly higher numbers in purse seine sets that employ floating objects (including FADs) rather than sets on schools that are FAD-unassociated. There is considerable evidence that the dynamics of the tuna school changes in the presence of a floating object. Historically, floating objects meant natural logs or debris, large whales, or whale sharks. Now, commercial, artisanal, and recreational fishermen all recognize the potential for high catch rates when using FADs, and they extensively employ the use of the man-made attractants. The use of FADs in commercial fisheries operating in the Atlantic and Indian Oceans has steadily increased since the early 2000s, and there are now approximately 7,000 actively deployed on a single day (Maufroy et al. 2016) while PEW reports that over 120,000 FADs are used annually in tuna fisheries. Globally, tropical tunas caught on FADs represent almost 2 million of the 4.5 million tons harvested annually (Scott and Lopez 2014). There is a large diversity of fish species, from many trophic levels that aggregate around FADs. It is likely that there is no one single explanation for the highly diverse pelagic aggregation behavior (Fig. 2), and motivations are still poorly understood. In fact, research on fish behavior relative to FADs is one of the top priorities of tRFMOs to define units of relative abundance from these attractants.

Fish behavior in the open ocean pelagic habitat has a single physical reference, the sea surface. Tunas and billfish rely heavily on vision and light to detect prey and to perform other population dynamic requirements. Solar light incidence angle and retinal color recognition in the tropical pelagic environment are particularly conspicuous (Fig. 3) suggesting fundamental biophysical driving characteristics should regulate habitat depth use and daily rhythms on pelagic fish (Fig. 4). Many other evolutionary processes, as explained below, may be responsible for extraordinarily successful evolution of foraging and reproductive dynamics of pelagic species in the open oceans.


Figure 2. Objects (natural or man-made) attract fish in the pelagic environment (pictures from several sources), yet the cause(s) are still poorly understood relative to FAD enhanced fishing.

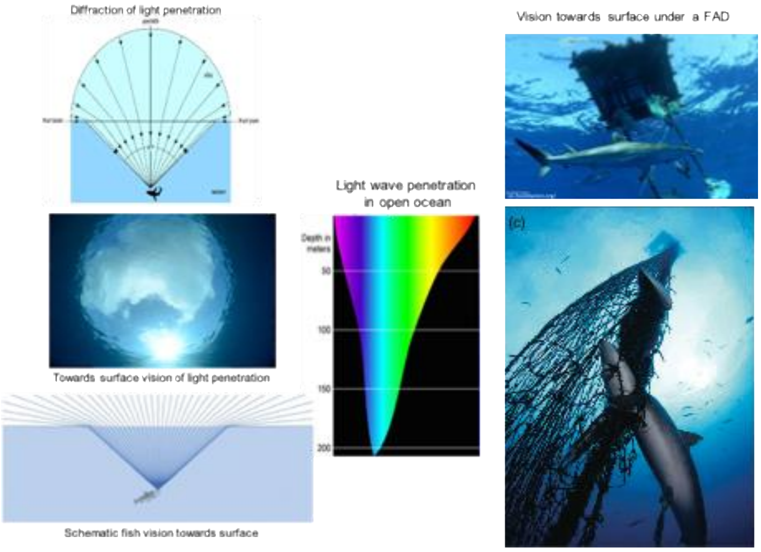


Figure 3. Light incident angles and projected fish vision (left), light wave depth penetration (center) and vision of light refraction from a point under FADs.

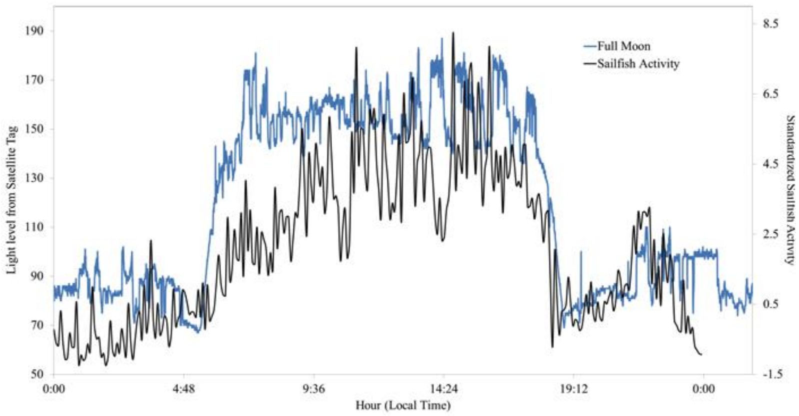


Figure 4. Photokinetic response of Pacific sailfish activity to day light and full moon light (From Pohlot and Ehrhardt 2016).

## 2.1. ASSOCIATION WITH OTHER INDIVIDUALS

Many fish species, including skipjack and juvenile yellowfin tuna are known to associate with conspecifics or in mixed schools of similar sized fish, and schooling behavior is seen in both the presence of and absence of other environmental anomalies such as FADs. The benefits of schooling associative behavior is well-documented for many species. Over 50% of fish species school at some point in their life histories (Shaw, 1978), and there are many theorized mechanisms to explain the evolutionary advantage that is gained by forming large schools. Fish schools display complex dynamic properties such as coordinated motion, and the specific shape (compression, hourglass, parabola, etc.) of the school is shown to aid in predator avoidance or hunting efficiency (Parrish et al. 2002). Many mathematical models of fish schooling propose a reduction in drag for the individuals, who subsequently become more metabolically efficient. These models work best for fish that are spaced approximately 1 body-length away from neighbors, which is commonly seen in nature. In terms of feeding success, larger schools of predators are most effective at breaking up schools of prey quickly, resulting in increased numbers of prey becoming isolated. Conversely, schools of prey have an advantage over isolated individuals in avoiding predation (Major 1978). The multi-ton schools of pelagic species could be the result of an evolutionary arms race, with prey and predators constantly seeking larger groups to gain the advantage. Finally, it is possible that the tendency to school offers no metabolic or reproductive advantage other than reducing the odds of being targeted by a predator, who would hopefully be satiated long before the school is reduced. This reasoning backfires, however, when modern fishing practices are taken into consideration. Purse Seine sets often take the entire school.

## 2.2. ASSOCIATION WITH FADS

The metabolic and reproductive benefits of fish association with non-living, floating objects is not well-understood, especially for pelagic species, nor the mechanisms by which these benefits are gained. There are several theories among scientists, and one or several may be applicable to the tunas, while others are applicable to the other species known to associate. There is a great diversity of species that are observed to associate with floating objects (Dagorn et al. 2013) (Noranarttragoon et al. 2013) (Gaertner et al. 2008) and they should be grouped in accordance with their trophic level and known behavior. Sharks, sea turtles, tunas, marlin, and small pelagic species are all known to associate with FADs. Skipjack, yellowfin, and bigeye tuna are grouped together, and small pelagic species that can be considered “baitfish” are grouped together for this review. Sharks, marlin, and other non-tuna predators constitute a third group. Although sea turtles also associate with FADs, they will not be the focus of this discussion.

Fish schools can be further divided into categories describing their preferred distance to the FAD. Parin and Fedoryako (1999) define “intranatants” as those who remain within ½ meter of the FAD, “extranatants” as those between ½ and 2 meters of the FAD, and “circumnatantants” as those between 2 meters and several nautical miles of the FAD. In most regions, yellowfin and skipjack tuna seem to have a preference to stay in larger schools around the FAD during the day (Fig. 5). Studies in the WECAFC area indicate differential day to night distributions of species biomass (Fig. 6) undergoing short excursions, presumably to feed, during the night. Silky sharks have shown similar diurnal patterns. Continuous residence time (CRT) is defined as the duration of association during which short term excursions may occur, but are not longer than one day. CRT varies considerably by species and region. Annex summarizes previous research devoted to describing the associative behavior of different species. Similar studies have not been carried out for small pelagic fish.

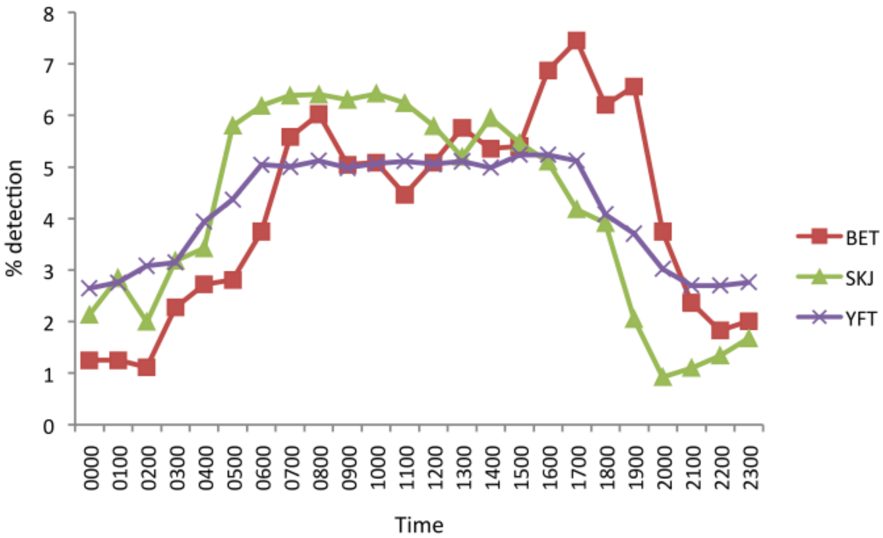


Figure 5. Daily pattern of aggregation, figure from Govinden et al. 2010.

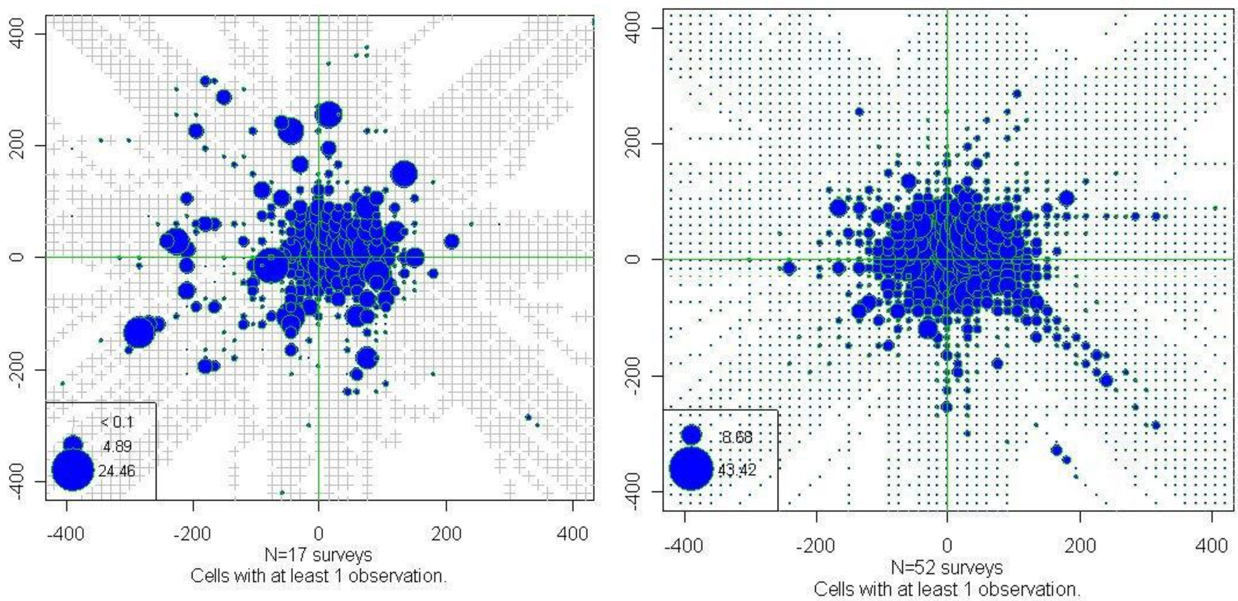


Figure 6. Day and night distribution of fish resources aggregated under moored FAD in the eastern Caribbean and as detected by hydroacoustics. Left night distribution, Right day distribution (from Doray et al. 2005).

**Skipjack, yellowfin, and bigeye**

The skipjack and juvenile yellowfin tuna of similar size range dominate the commercial catches for dFAD purse seine sets in all oceans, and they seem have extremely high fidelity to the FAD, returning to it from up to 6 nm away. Tunas show strong diel fluctuations in their associative behavior with the FAD (Figure 5.), which seems to be species, season, and region specific (Lopez et al. 2016). There is even some evidence that the size of the tuna plays a more important role in the associative behavior than the species, which may suggest adaptive behavior patterns. Bigeye are also caught in purse seine sets around FADs, but to a much lesser degree.

The *food chain* hypothesis proposes that large, predatory fish are actively predating upon the smaller fish, which are aggregating at the floating objects, and thus an entire food chain builds up with the FADs as it's foundation. The hypothesis was originally proposed for the mahi, which also associate with FADs, but was extended to tuna and marlin. The large diversity of fish that are found associated with FADs would seem to support this theory (Amandè et al. 2010), however there is little evidence that there are enough small bait fish present to support a 20-40 ton school of tuna, which need to eat approximately 5% of their body weight per day (Olson and Boggs 1986). Stomach contents of tuna associated with floating objects show that they are predominantly feeding on species that are not associated with the floating object (Malone et al. 2011). Tuna offshore of Costa Rica do not feed on species associated with natural floating objects (Hunter 1966). 435 skipjack and 149 yellowfin stomach contents were analyzed, and only 1 skipjack and 6 yellowfin stomachs contained species that were associated with the log. Furthermore, the presence of predatory fish has been observed at coastal FADs that have little or no prey fish associated (Klima and Wickham 1971). In this same study, although predatory fish (amberjacks) were regularly found at the object, they were never observed actively predating upon the smaller fish. On the other hand, tunas have been observed actively engaged in hunting activities when associated with a FAD.  Longline and pole-and-line fisheries that use FADs are successful (Miller, Nadheeh et al. 2017) and these gears require active predatory behavior.

The *indicator-log* hypothesis articulates that fish of all sizes/trophic levels are attracted to natural floating objects because they tend to accumulate in waters that are relatively rich. Either they originate from rivers with high export of land-based nutrients, or they drift to rich frontal zones. Frontal zones in the vast pelagic environment especially represent areas suitable for the “triad” (enrichment, concentration, retention) of physical ocean properties that are advantageous to fish (Bakun 1996). One indicator that this hypothesis applies to tunas is the observation that tunas associated with man-made FADs, which are often artificially seeded in areas that are considered low-productivity, are in poorer condition (empty stomachs, lower fat content) than their free-school counterparts (Hallier and Gaertner 2008, Robert, Dagorn et al. 2014). This suggests that the fish are being “tricked” into thinking that they are being drawn or led into rich waters, when they actually are not, also known as the *ecological trap* theory. The higher proportion of empty stomachs in FAD-associated tunas (Ménard, Stéquert et al. 2000  can be interpreted as evidence of the ecological trap (Table 1) . Ménard and co-authors have published several papers documenting the inability of associated tunas to feed as efficiently as free-school tunas. Unfortunately, these studies only sampled fish at one time point, so we do not know if the fish arrive to the FAD already in poor condition, or if they become less nourished because of the time they spend at the FAD. This same study also compared fish that were associated with natural logs in an area known to be naturally enriched with floating objects coming from the mouth of a river. These fish were also in poorer condition than free-swimming schools. So, it is possible that floating objects have never been a natural indicator leading fish to relatively rich waters with abundant food sources in the vicinity.

Table 1. Feeding Efficiency of associated and unassociated tunas, from Menard, Stequert et al 2000.

| | | FADs | Unassociated schools |
|---|---|---|---|
| Yellowfin | N | 69 | 36 |
| | % empty | 65.2 | 16.7 |
| Skipjack | N | 333 | 115 |
| | % empty | 91 | 27 |
| Bigeye | N | 191 | 32 |
| | % empty | 82.7 | 25 |
| Total | N | 593 | 183 |
| | % empty | 85.3 | 24.6 |

The last main hypothesis pertaining to tunas is the *meet up point* hypothesis, proposed by Dagorn (1999). This hypothesis states that fish seek out anomalies in the pelagic environment in hopes that others will do the same, and subsequently form larger schools. This has been described as an enhanced encounter rate. The benefits of large school formation have been described above. Commercial data and Fontenenau (2013) confirm that FAD associated schools of tuna are larger than free-schools. Additionally, associated schools have a larger range of sizes compared to the relatively homogenous sizes of fish in free-swimming schools (Wang et al. 2012) suggesting that the mechanism for schooling around a FAD is either different, or the impulse is stronger than fish that are free-swimming, either as individuals or as “sub optimal” size schools. Additionally, FAD caught tuna are smaller than free schooling tuna, and this phenomenon is particularly conspicuous for skipjack and yellowfin. Acoustic telemetry experiments performed on bigeye scad endorse the hypothesis that fish are more likely to arrive as individuals or small groups, and leave the FAD in larger groups (Soria et al. 2009). In a binary choice experiment, tunas were shown to form aggregations at two identical FADs asymmetrically, suggesting that they preferred the FAD with a slightly larger school, creating a feedback loop (Robert et al. 2013). This sample size, however, is only 1 comparison, so it is difficult to say with confidence that the two FADs were indeed equal in all ways. There is evidence that some tuna associate with FADs temporarily, and there may be a limit to the size a school can reach before the disadvantages outweigh the benefits. The school size eventually plateaus over time, and fish begin to leave the school.

The main hypothesis reviewed in the modern literature pertaining to tunas are not mutually-exclusive, and it is possible or even likely that predatory fish like tunas are attracted to FADs for several reasons. It is interesting to note that some of the species that associate with FADs are also thought to associate with seamounts, possibly signifying that these species are seeking out anomalies in their environment, and not specifically floating objects.

### Sharks and marlin

Blue marlin and sharks are considered bycatch, yet they are taken in significantly higher proportions in FAD sets than free-school sets, demonstrating their similar tendency to associate with floating objects. Blue marlin is particularly aggregated in the moored FAD in the eastern Caribbean and recreational fishing reports confirm that blue marlin has the strongest tendency to associate of the recreationally-targeted billfishes, even when other species are present in the vicinity. Of the elasmobranchs, silky sharks suffer the highest incidental mortality from FAD bycatch (Filmalter et al. 2013). The following hypotheses are proposed to explain the benefits and mechanism for the associative behavior in these species.

*Food chain:* Similar to tunas, marlin have been observed actively hunting in the immediate vicinity of FADs. Successful recreational fishing, which uses lures or bait instead of nets, necessitates that the fish is engaged in hunting activities. Currently, record-breaking catches of blue marlin are being reported by anglers fishing on drifting and anchored FADs. Silky sharks, on the other hand, are not typically targeted by recreational anglers. Unlike tuna, there is some evidence that these predators are deriving significant nutritional benefit from their association with the floating object. Stomach contents from sharks associated with FADs contained mostly other species that were also associated with the FAD (Duffy et al. 2015).

The *indicator log* hypothesis could apply equally to marlin and sharks as it does to tunas. Highly migratory species could benefit by following floating objects to relatively rich waters, where juveniles and larvae have a higher chance of survival (Castro et al. 2002). As such, drifting objects may lead to potential spawning grounds. The *meet up point* hypothesis does not seem to apply to marlin and sharks, because they do not naturally form large schools.

### Small pelagics and baitfish

Small pelagic species have different nutritional requirements, movement patterns, and general life cycle characteristics than predators at higher trophic levels, so their main motivations for associating with a floating object could be different. Some of the main hypotheses applying to tunas also apply to their prey, such as the *indicator log* and *meet up point* hypothesis. The *indicator log* hypothesis is especially strong for those species that use natural floating objects as substrate for egg dispersal, flying fish being the most notable example. In this section, we review additional hypothesis that relate specifically to small pelagic fish that are commonly prey items for larger fish like tunas and marlin.

The *shelter from predators* hypothesis applies to intranatant species that prefer to stay very close to the FAD. In the three dimensional environment, it is impossible to be looking in all directions at once. So, by staying very close to an object, there is one less direction to monitor for predator attack. This theory applies to all structures, not just floating ones.

The *seeking shade* hypothesis also applies to intranatant species that remain very close to the FAD. Helfman (1981) proved that observers in shade can see an illuminated object 2.5 further than an illuminated observer could see an object in shade. Clearly, the vision is improved in the shade, and any human with a baseball cap can confirm this. Further evidence that some fish may take advantage of the change in visibility is the fact that dark colored fish have higher preference for being directly under the FAD than light, silvery fish (Hunter 1966). The darker fish may gain a greater camouflage advantage in the shade. Many authors note that very few fish of any color are actually located directly in the shade of the FAD, which would suggest that it is not their main motivation for association. However, Gooding and Colleagues (1967) describe observations of a solitary mahi that sheltered directly under the FAD to avoid predation from a bottlenose dolphin. The mahi visibly changed to a darker color, taking advantage of shading to camouflage itself. When other mahi were present, this behavior was not observed. It is unclear whether this hypothesis applies to certain species, age groups, or whether it broadly applies to fish that lack other defenses, such as schooling, at a given point in time.

The *food chain* hypothesis, that fish are attracted to the smaller prey forming around a FAD, is not as strong when applied to small, planktivorous fish. Fish that consume plankton will not find higher abundances of their meals under a FAD, because most plankton species cannot swim against a current. Zooplankton and small crustaceans are found in equal abundance under FADs as in the open ocean (Deudero and Morales-Nin 2001). Zooplankton may be able to detect a FAD; however, they are incapable of the horizontal movements necessary to localize themselves under it. On the other hand, there is some evidence that the feeding ecology is tied to FAD association for small epipelagic fish. The degree of association is highly dependent on the size or life stage for many associated fish species (Sinopoli et al. 2011), suggesting that changes in feeding strategy coincide with changes in associative behavior. Other behaviors relating to size may also explain the stratified spatial distribution. Very small juvenile fish may use the FAD as shelter from predators until they obtain greater swimming ability and are capable of forming schools as an anti-predator strategy, indicating the *shelter from predators* hypothesis.

Clearly, the affinity for certain fish to associate with floating objects, and subsequent changes in daily or seasonal behavior affects the overall ecology of the pelagic environment. Vis-à-vis, the surrounding ecology and presence of others appears to change the behavior and probable motivations for individual fish associated with the floating object. For target species like tuna, behavioral changes are likely to be significant, and there is a need to factor this into estimates of catchability for fisheries assessment.

# 3. Satellite Hydroacoustic Technologies for FAD Control and Management

## 3.1. HISTORIC EVOLUTION OF FAD TECHNOLOGIES

Since the commercial acceptance of electronic buoy equipped FAD usage around 1984 (Lopez et al. 2014) (Fig. 7), technological improvements have continuously advanced the efficiency of fishing around these devices. The early FAD designs incorporated radio signal beacons used to locate buoys and required a relative close distance for signal detection. As technology advanced in global positioning by the mid to late 1990s, FADs were suddenly able to be located from over 1000nm away, dramatically reducing the time and cost of searching.

Possibly one of the most impactful technological advancements occurred from the late 1990s into the early 2000s when echo-sounders were first incorporated into GPS equipped FAD buoys. These early first generation echo-sounders were able to transmit basic information on sea surface temperatures (SST) and biomass level via satellite making this data available anywhere on Earth. The second generation of echo-sounders, implemented in the mid-2000s, were able to generate their own power via solar panels making them capable of much longer deployment durations and able to transmit environmental variables such as ocean current vectors. The echo-sounder information was incorporated with oceanographic conditions which was newly available onboard vessels beginning in 2005, greatly increasing knowledge of the environment immediately surrounding deployed FADs. Finally, the third generation of echo-sounders was implemented in 2012 and includes substantially more precision and accuracy in biomass estimation, size composition, and in some cases, species discrimination through the use of transducers capable of multiple frequency soundings.

Research performed on fleet behavior following implementation of echo-sounder technology suggests it was quickly adopted by the purse seine fishery throughout the 2000s (Baske et al. 2012, Lopez et al. 2014). This rapid adoption was due to significantly higher catch rates witnessed on FADs equipped with echo-sounder buoys compared to those without echo-sounders and decreased searching time between FAD sets (Artetxe and Mosqueira 2003, Delgado de Molina et al. 2012a, 2012b). The rapid speed at which this technology was adopted indicates the usefulness to fishers especially considering the increased cost of echo-sounder buoys compared to the standard GPS or radio beacons. Figures estimated from market research indicated 47,500-70,000 buoys per year were being purchased from five major buoy suppliers suggesting a large majority of all FAD buoys being deployed contained echo-sounders (Baske et al. 2012)

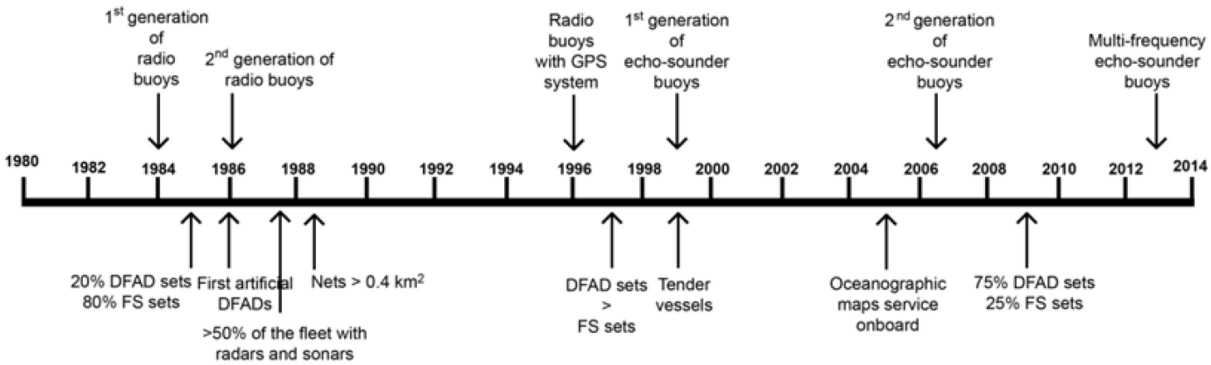


Figure 7: Historic evolution of electronic buoy developments associated with FAD technologies in tuna purse seine fisheries (Figure from Lopez et al. 2014)

## 3.2. TECHNOLOGY CHARACTERISTICS OF THE LATEST GENERATION OF BUOYS

Common echo-sounder buoys used currently on FADS are in constant communication with satellites and fleets operating worldwide. Manufacturers of echo-sounder buoys advertise permanently open communications between ship captains, fleet owners, and every buoy active through satellite communication and land earth stations (Fig. 8). This is a bi-directional communication where echo-sounder data is sent from the buoy but fleet operators and captains can also communicate with the buoys by actively changing settings such as the gain, without need to be nearby or making any physical contact with the buoy.

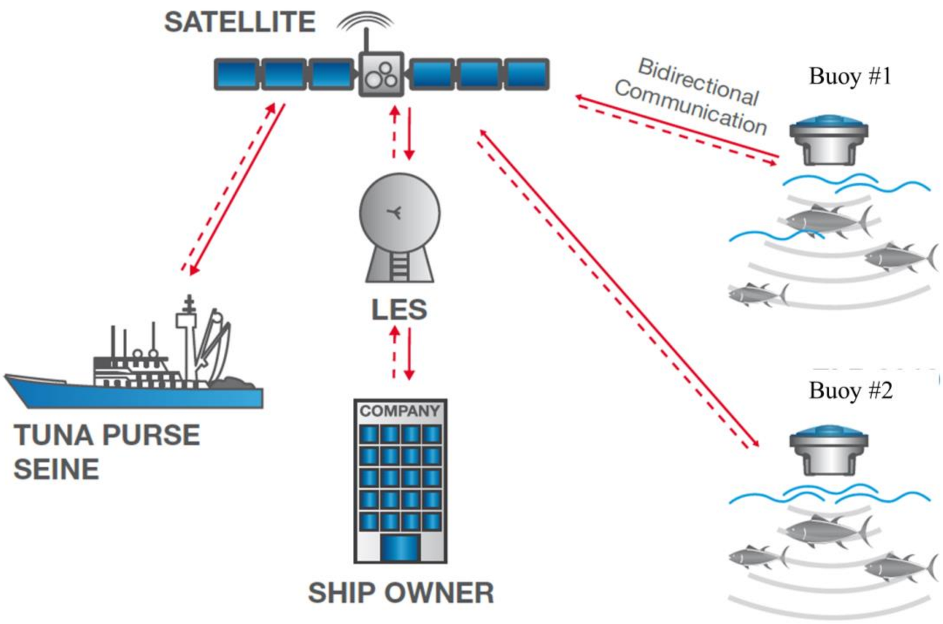


Figure 8. Example of communication web. Adapted from Satlink documentation. (www.satlink.es)

The most recent generation of commercial echo-sounder buoys incorporate multi-frequency transducers, typically 38kHz, 50kHz, 120kHz, or 200kHz depending on manufacturer. Multiple frequencies allow better discrimination of size and species, assuming Target Strength (TS) is known for the species. The newest advancements in echo-sounder designs can incorporate three frequencies for even further improved distinction of the environment below the buoy. Lower kHz frequencies tend to be more sensitive to species with a swim bladder such as target species of bigeye and yellowfin tuna where higher kHz frequencies are more sensitive to species without swim bladders such as skipjack which represents a majority of worldwide FAD catch (Marine Instruments Documentation, Moreno et al. 2017). The number of soundings and pings per sounding are user controlled, with soundings available at one minute intervals in most cases and up to 256 pings per sounding. These multi-frequency signals are integrated simultaneously down to over 100m below the buoy with depth resolution as high as 1.6m per layer and generally visualized using the manufacturer's software (Fig. 9) that is capable of incorporating meteorological and oceanographic conditions such as chlorophyll, SST, current information, and wind speed. Software integrating multiple sources of data provides a clear visualization using various color palettes and user options providing an easily interpreted output of biomass and composition of target species directly below the FAD at any given time with little lag in information delivery (Fig. 10).

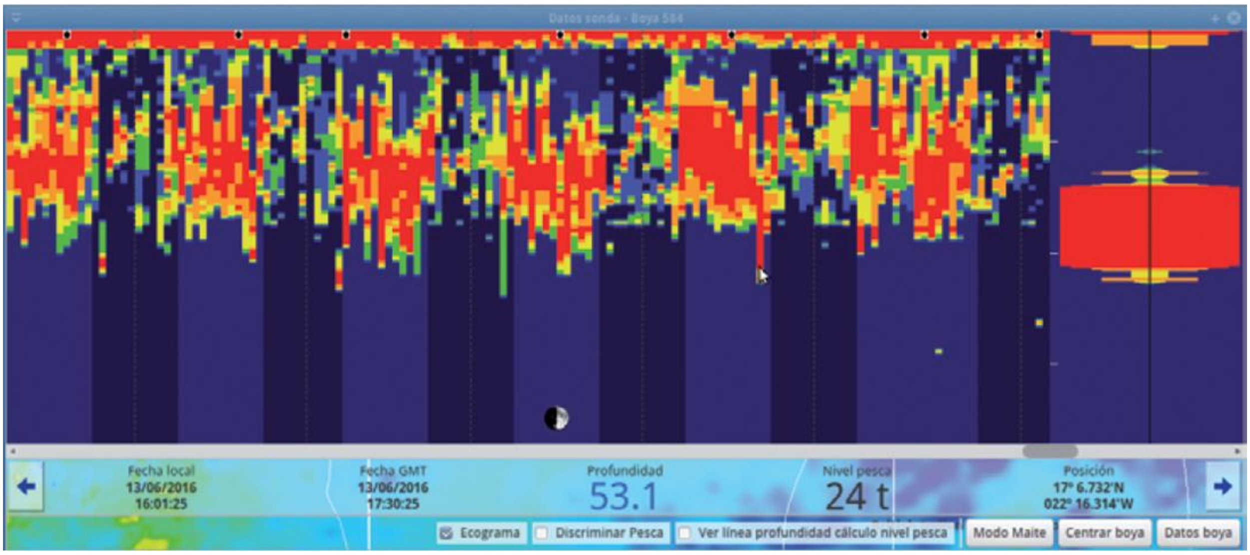


Figure 9: Echogram output from Zunibal's Tuna8 Explorer buoy and software. Courtesy of Zunibal.com

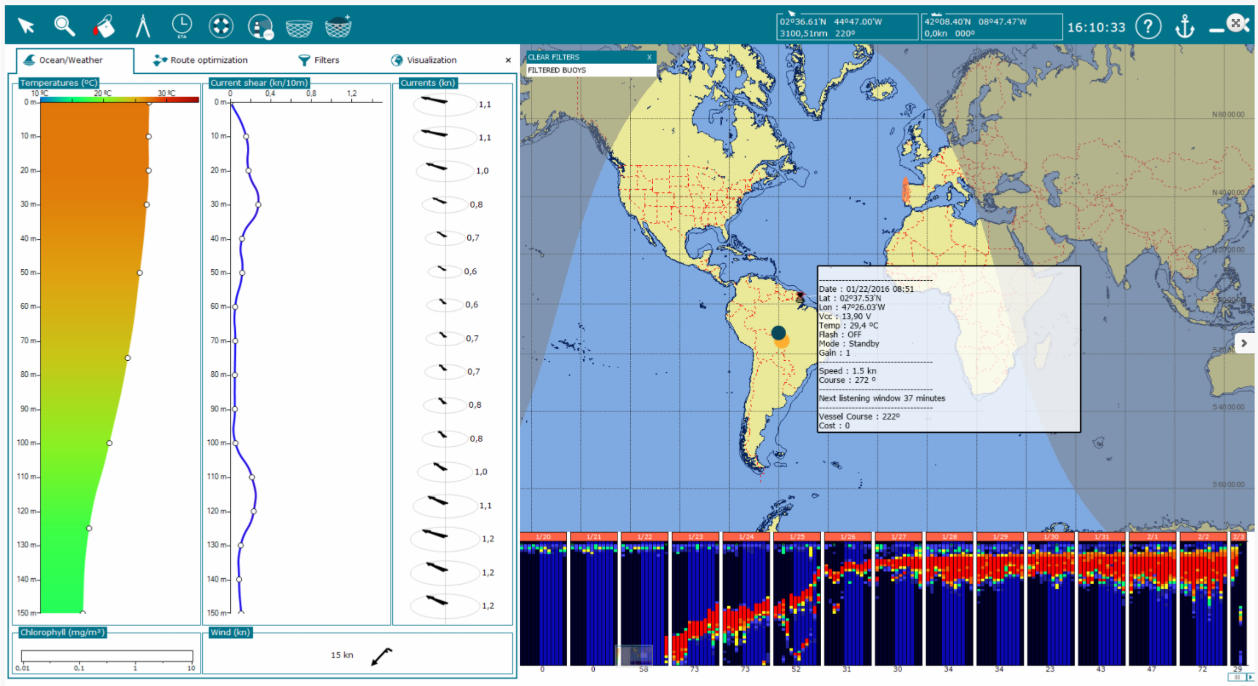


Figure 10: Example of visualization software from Marine Instruments providing environmental and oceanographic information along with maps and echogram outputs. Courtesy of MarineInstruments.es

The most recent advance still yet to be implemented in the majority of the world's tuna fisheries is the advent of self-propelled FADs that can be remotely controlled from anywhere on Earth. These FADs can be set to remain in productive regions as opposed to free floating FAD designs that can drift away from the most productive regions where much of the target species are harvested.

### 3.3. ANALYSES OF DETECTED BIOMASS VERSUS ACTUAL CATCHES

The increased knowledge of biomass level and, to an extent, species composition with the use of multi-frequency echo-sounder buoys is widely accepted amongst fishers; however, the relationship of biomass estimated by echo-sounder buoys should directly relate to the biomass of harvest for efficient use of the equipped FAD. Preliminary research has been conducted using echo-sounder equipped FADs (Lopez et al. 2016, Moreno et al. 2007) resulting in a model for estimated detected biomass under a FAD that matches the actual catch quite well (Fig. 11). In examining this estimated detected biomass and actual catch, a direct relationship is found with a slope of 1.0196. This slope indicates that with each increase in detected biomass by the echo-sounder equipped FAD, the associated level of harvest will also increase proportionally. This straightforward relationship is a result of improved technology within these echo-sounders buoys as well as improved knowledge of echo-sounder data analysis. The ability to predetermine the level of biomass under the FAD eliminates the need for searching time by the fishery thus improved efficiency of “harvesting” effort management; however, with advances in this technology occurring so rapidly, it becomes increasingly difficult to make interpretations and quantifications of effort in fisheries using FADs. With a reliable method of estimating biomass, the effective effort further decreases to a point where one could suggest the fishery no longer “fishes” but rather “harvests” implying there is little effective effort necessary to find fish.

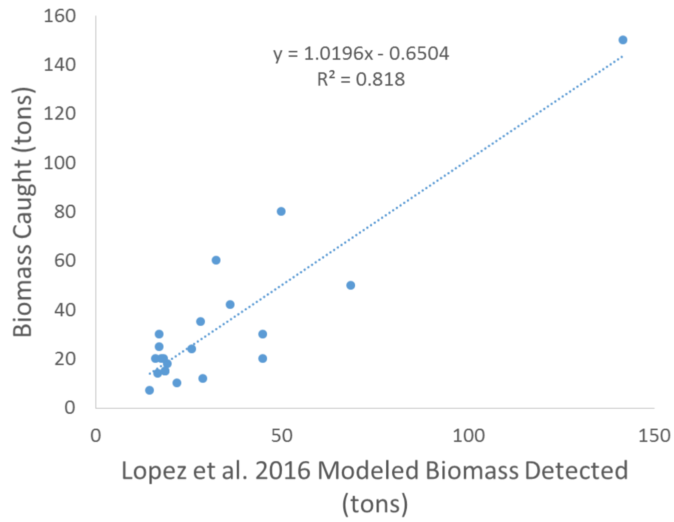


Figure 11. Model expressing relationship between actual catch (y-axis) at a FAD versus the amount of biomass using modelled data (x-axis) published by Lopez et al. 2016) from an echo-sounder equipped FAD.

### 3.4. FAD ECHO-SOUNDER DATA GENERATION CAPABILITIES IMPORTANT TO FISHERY STATISTICAL SYSTEMS

Worldwide distribution of FADs provides an extremely unique opportunity for scientific exploration with at least 333 species having been observed near the floating structures (Moreno et al. 2016). Each of these FADS equipped with echo-sounder buoys presents an opportunity to continuously monitor aggregated pelagic biomass and species composition (target and bycatch) wherever the FAD drifts or is anchored. This level of biomass information on a massive scale is simply not possible through standard fishery dependent statistical assessments making the collaboration of fishing organizations, scientists and buoy manufacturers ever more vital to proper management and use of FAD related natural resources. Recent advances in the quality and quantity of data collection by echo-sounder buoys is well documented and provides tremendous opportunity for scientific exploration and collaboration with management organizations. Moreno et al. (2016) refers to FADs as “sampling tools” of open ocean biodiversity and that they should provide information on species composition and estimates of abundance. These “sampling tools” are improving at a rapid pace and are now reaching the stage where the species composition and estimates of abundance are estimated in real time and have been shown to be accurate and precise.

The types of fishery independent data collection using FADs is only limited to devices that can fit and operate on the FAD, providing seemingly endless possibilities for research. The ability to visualize what is being shown on the echo-sounder’s output can be provided with camera equipment time-synced with the echo-sounder buoy. This combination allows for the specific analysis of individual fish to further examine target strengths of individuals. Camera equipment allows for the capture of species composition thus biodiversity, as well as the time at which varying species begin to colonize the FAD. Visual censuses were found to produce reliable indices of biodiversity when measured with FADs equipped with multiple technologies (Gaertner et al. 2008). This is not limited to fish species alone; as sea turtles, sharks, and mammals are commonly observed around FADs and, in the case of sharks, not typically recorded using the echo-sounder buoy. Individual fish behaviors such as feeding or sheltering within range of the FAD can also be captured using high quality video equipment operating under the surface of the FAD during the day.

Further research capability to distinguish individual behavior, especially at night when cameras do not record, comes in the form of acoustic tagging by attaching an acoustic receiver to the FAD and deploying transmitters on individuals of the species of interest. As these fish colonize and remain aggregated in the FAD area, the receiver records the passing of the transmitter each time it is nearby with the potential to download other information collected by the acoustic transmitter attached to the fish. With a wide variety of acoustic tag capabilities, it is possible to examine a multitude of traits relative to fish behavior such as: predator prey dynamics, diel behavioral patterns, migration around and between FADs, depth profiles, etc. Another more costly option is the implementation of pop-up satellite tags to monitor behavior and habitat use of species associated with FADs that may be more difficult to monitor using acoustic tagging, cameras, and the echo-sounder.

Beyond ecological research of fish behavior and habitat use, FAD platforms equipped with echo-sounder buoys can help provide fishery-independent indices of aggregated abundance as well as a more informed estimation of fishing effort when coupled with fishery dependent data. Tuna species are typically difficult and costly to assess in a fishery independent manner; however, data provided by modern multi-frequency echo-sounder buoys can be adopted as an indicator of abundance in that location at that time the FAD was operating. The critical missing piece specific to tropical tuna research is the ability to distinguish between yellowfin and bigeye as well as size variability within each species in terms of TS. Research has been done and is ongoing in this field and as newer technology continues to advance, multi-frequency echo-sounder equipped buoys will provide the ability to delineate between tuna species and size classes within each species (Moreno et al. 2017, Sancristobal et al. 2014; 2016). With researchers and manufacturers working to experimentally develop TS to length relationships for these target species, the potential for tuna species research can be even further enhanced by incorporating FAD based research programs. The relative low transmission cost and price per unit makes echo-sounder equipped FAD buoys accessible for scientific monitoring and research in the WECAFC region. However, in spite of all these technological advances, the question still remains as to what extent is aggregated biomass an unbiased estimator of population abundance, which ultimately is the leading piece of information needed for management.

# 4. Fish Aggregating Devices (FAD) and CPUE hyper stability concepts

Fishing gear technologies represent ingenious engineering developments made to take advantage of certain fish behavioral characteristics that otherwise allow fish to escape capture or avoid predation or remain dispersed over larger areas of the ocean. As fish population abundance declines due to exploitation, fishing gear and fishing operation designs need to be continuously improved to increase fishing power. Higher catching efficiency per unit of fishing time is always an evolving concept in fishing technologies such that the economics of fishing operations are sustained as resources dwindle. Many effective ways of gathering (i.e. attracting and retaining) resources exist, and these transform the traditional fishing practices of searching and catching into collecting, or harvesting, gathered fish. Some examples of these practices in the WECAFC area are: a) the condominium or "Cuban casitas" used to gather spiny lobsters in such artificial habitats for divers to retrieve them, b) spiny lobster trap fisheries that use conspecific attraction behavior by using sublegal lobsters as bait in commercial traps to attract legal-sized adults, and c) the use fish attracting devices (FADs) in costal migratory pelagic fisheries.

Development of FAD fisheries in the WECAFC area (CRFM 2015) was triggered by depletion of the islands nearshore fishery resources and the resulting economic stress created among small scale fishers. The objective of such development consisted of transferring fishing effort to utilize offshore highly migratory pelagic resources, such as tunas, billfish, dolphinfish (mahi), etc., if those resources could be attracted and aggregated to areas where local fishers could harvest them. Hence, the introduction of moored FADs was seen as a socio-economic solution under the paradigm of expected increased economic yield based on suspected higher catch rates. Under premises that pelagic migratory species will aggregate around moored FADs, fishery statistics such as catch per unit of effort (CPUE) in FAD fisheries may not be an index of relative population abundance as traditionally used in stock assessments. In fact, it is an index of local fish density resulting from the aggregating properties of the FADs and ecological conditions of the fish at the time they were migrating through the area.

Hyper-stability of catch per unit of effort is when CPUE remains stable while the population declines. Such condition is cryptic given that population abundance is unknown; therefore, difficult to detect until signals of severe stock depletion or fishery collapse become evident. Even under such a depleted condition, CPUE may still portray a stock presumably in healthy condition. Fishery independent estimates of abundance are needed in these cases to test the hyper-stability condition. In other words, the existence of hyper-stability may be detectable after the fact and most assessments become retrospective analyses of preventable conditions of fishing.

Most commonly, stock assessment relies on proxies based on fisheries data to estimate population size and then set management targets. Catch (C) is the product of average abundance ($\bar{N}$) of a fish stock and fishing mortality (F) applied to the stock. F is the product of the fraction of the stock that is caught per unit of fishing effort (q) times the amount of fishing effort (f) exerted on the stock. That is, for any time period (t), $F_t = qf_t$ and $C_t = F_t\bar{N}_t$ or equal to q$f_f\bar{N}_t$. From these relationships catch per unit of fishing effort ($\frac{C_t}{f_t}$) in a period of time (t) can be expressed as $\frac{C_t}{f_t} = q\bar{N}_t$. Thus CPUE is a proxy for relative abundance under the assumption of direct proportionality and that such proportionality, the catchability coefficient, does not change.

Statistics of catch and standardized fishing effort from a fishery may be used to estimate average population abundance if q may be estimated, "somehow", from fisheries data. It is noted that the catchability coefficient, q, is a direct proportionality coefficient that will depend on other factors that may not be related to stock abundance such as: relative seasonal behavioral conditions of the fish, differences in the fishing efficiency of the different gears used to catch the fish, environmental conditions that can possibly affect availability and/or retention of the fish, etc. It is assumed that fishing effort is always standardized taking some of the driving variables into consideration. Under the circumstances of availability of data, most stock assessment models try to estimate q and use catch per unit of effort statistics from the fisheries to assess the abundance of the stock during a given period. Once abundance is estimated, fishing mortality can be elucidated from its formulation. An extraordinarily ample literature exists regarding catchability estimation and some important summaries of findings about q estimations are also available (e.g. Arreguín-Sánchez 1996). In many cases fishery independent estimators of abundance are used to tune or calibrate the stock assessment models.

The ICCAT stock assessment protocols include several sophisticated statistical algorithms to assess abundance and status of exploitation of tuna and billfish stocks in the ICCAT region (e.g. dynamic production ASPIC, size/age structured Stock Synthesis, etc.). At the Joint tRFMOs FAD Working Group meeting held in Madrid, Spain (April 2017) recommendations regarding the collection of FAD fishery statistics for stock assessment were provided including the recommendation that studies pertaining to the behavior of fish aggregated by FADs be included in the interpretation of such statistics. Yet, the CPUE hyper-stability issue was not resolved and most likely fishery independent estimates of abundance indices will have to be developed for the species and fisheries as one, or only one, plausible way to link the nature of the relationship between FAD CPUE and wild stock abundance. This is further complicated by the fact that research on moored FADs in the WECAFC area indicate the presence of species and sizes (therefore ages) stratified by depths as well as significant differences in species compositions among islands and among FAD fields within islands. The implication for proper and objectively collected FAD data for stock assessments is then exacerbated because exploitation patterns may change depending on the depth of fishing operations at each FAD.

This review did not find data that could be used to elucidate hyper-stability values for the target species in the WECAFC moored FAD fisheries. However, CPUE data from free schooling and FAD associated sets of the tuna purse seine fishing operation by the French fleet in the Indian Ocean was explored for indications of hyper-stability. Such data (Floch et al. 2012) originated on the same stock and for over 20 years. It is hypothesized that CPUE from each of the fishing modes should be a proxy for the same relative abundance. This may be possible for skipjack that is the species most attracted and captured both in FAD associated sets as well as in free school sets. The skipjack species does not show juvenile stratifications such as in the case of bigeye and yellowfin tunas found associated with dFADs. The FAD associated CPUE was plotted relative to the free schooling CPUE in similar years and areas, assuming that a linear relationship exists for the latter CPUE and relative abundance. Such plots are segregated by series of years when productivity of the FAD associated fishery was at different stratifications (i.e. most likely due to changes in fishing power by the introduction of larger vessels; Fonteneau et al. 2013). The results are shown in figure 12. In the figure it can be observed that over the regressional range in the free schooling CPUE, there is low discernable association with FAD associated CPUE. Such condition can only exist if in fact FAD associated CPUE does not reflect exploitation conditions of the stock but stable aggregating conditions of the population biomass that will not reflect an impending depletion until it may be too late for conservation actions to take place.

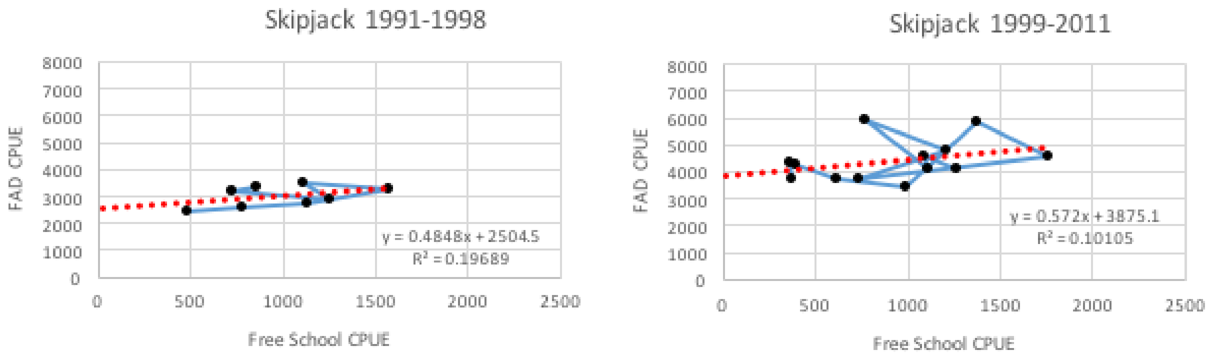


Figure 12. CPUEs for two periods (1991-1998 and 1999-2011) for FAD associated and school free fisheries in the Indian Ocean (Adapted from data in Floch et al. (2012).

The ratio of CPUEs in the free schooling and FAD associated fisheries should help understanding the concept of hyper-stability explained above. For this we make,

$$\frac{CPUE_{FS}}{CPUE_{FD}} = \frac{q_{FS}}{q_{FD}} \overline{N}^{(1-b)}$$

where FS and FD are the indices expressing free schooling and FAD associated CPUEs, respectively, and b is the exponent of a power function between $CPUE_{FD}$ and relative abundance. Thus, if hyper-stability in the FAD associated fishery does not exist, then a directly proportional linear relationship must should exist between CPUE and relative abundance, this is b=1. Under such condition the ratio between the two CPUEs in the above formulation is reduced to a relative fishing efficiency (or relative fishing power) condition expressed by the ratio of the respective catchabilities only. Conversely, if hyper-stability exists, then b<1 and the exponent in the above relationship is nonlinearly related to relative abundance.

Another approach would be to compare the ratios of null to successful purse seine sets in the FAD associated fishery and the free schooling set success rates. One should expect that FAD associated sets should always be more successful due to the electronic FAD support used in decisions to set the purse seines. Such operational procedure differs largely from the search, find and set nets experienced by the free schooling fleets. The free schools reflecting more the wild status of the resource. Figure 13 shows such ratios and clearly the successful to null set ratios in the FAD associated fishery indicate that when abundance decreases as expressed by the set success ratio in the free schooling fishery, this decreases faster and not proportionally than in the FAD fishery. This statistical behavior can only exist if hyper-stability plays a role in such fisheries.

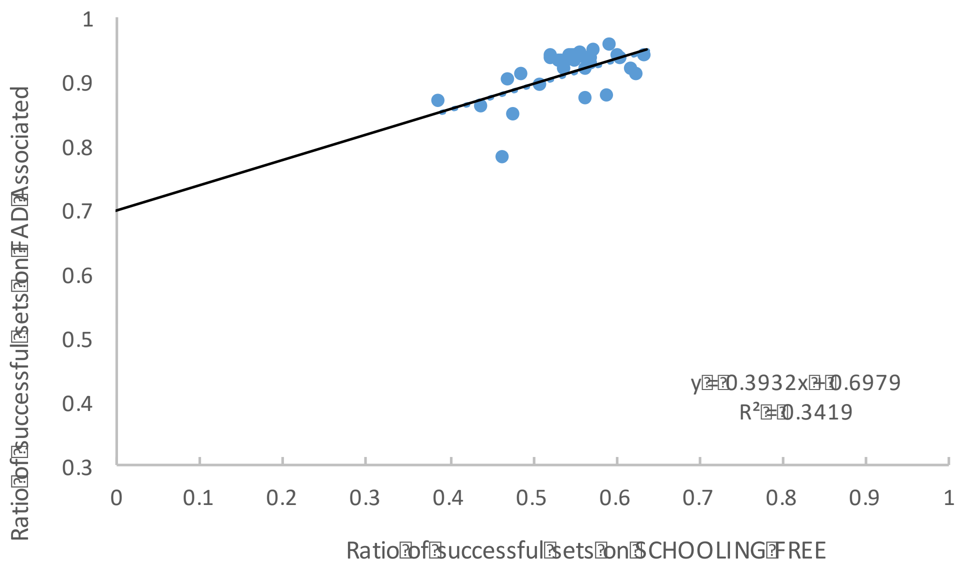


Figure13. Fraction of successful purse seine sets on FAD associated on fraction of purse seine sets on free schooling tuna in the Indian Ocean (Adapted from data in Floch et al. 2012).

## 5. FAD fisheries development in the WECAF region

The Lesser Antilles region of the WECAFC initiated a moored FAD (mFAD) fishery program in the late 1980's under the PNUD/FAO with the aim to reduce fishing pressure on inshore or reef fish populations (Heloise et al. 2013). The project was introduced under the acronym MAGDELESA (**M**oored fish **AG**gregating **DE**vice in the **LES**ser **A**ntilles). Participating nations Martinique, Guadeloupe, and Dominica each developed their own small scale mFAD fishery for pelagic species starting in the 1980's, followed by others. Pelagic landings have increased for many of the participating countries (FAO 2015). However, regulations pertaining to mFAD installation and location have not been uniformly enforced, resulting in a chaotic system of publicly-registered, group, and privately owned mFADs, which are infrequently monitored, and all types of fishing are permitted. Patterns of landings have emerged resulting from the seasonality of the ocean currents (Doray et al. 2009), local seafood preferences, and fishers' behavior and conflicts over user rights. The artisanal nature of the moored FAD fishery in the Caribbean illustrates stark contrasts with the technologically advanced, large scale purse seine fisheries operating sophisticated FAD technologies in the high seas. The following is a synthesis of considerations found in the desk review that may help conservation and development of mFAD fisheries in the Caribbean.

### Variability in Landings in FAD Fisheries

Existing industrial purse seiner fleets targeting tuna are presently capable of capturing most of the total allowable catch from estimated population biomass. In fact, ICCAT has declared the status of exploitation of tuna and billfish stocks in the Atlantic that are of interest to the fishers in the WECAFC area as either fully exploited, over exploited or over exploited undergoing overfishing. For comparison purposes, a summary of historic landings in the 1960's and 2000's for blue marlin, white marlin, yellowfin tuna, skipjack and bigeye tuna and their status of exploitation are presented in figures 14 to 18. From the figures it is possible to visualize that catch of marlins has been significantly reduced spatially and the status of exploitation is particularly concerning for blue marlin that is presently found in the red area of overfished undergoing overfishing (Fig 14).

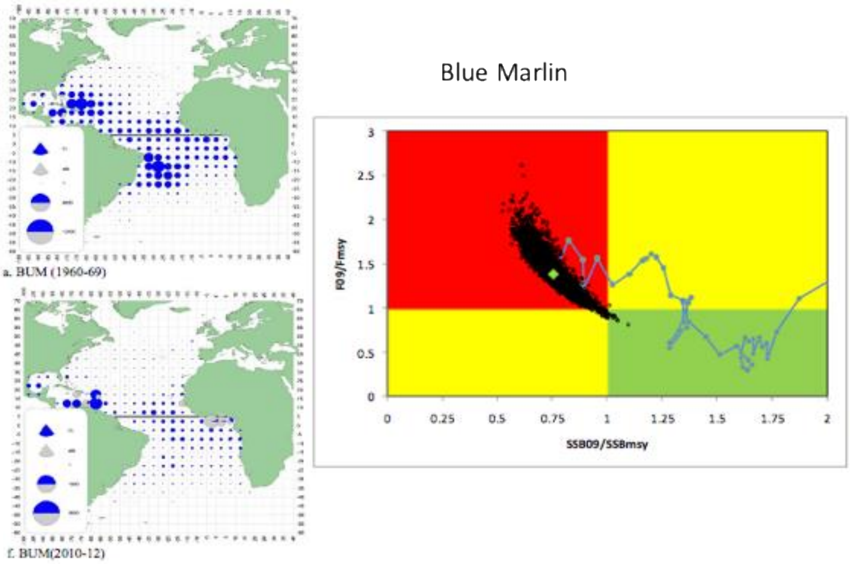


Figure 14. Accumulated landings in the 1960's and 2000's for blue marlin (left panel) and a KOBE plot showing the present status of exploitation in the red area (right panel) (Data from ICCAT stock assessments).

White marlin shows a very significant collapse of landings (Fig. 15 left panel) between the 1960's and 2000's, while exploitation expressed in the Kobe plot (Fig. 15 right panel) is highly uncertain but mostly falling in the yellow area of overfished condition as well as the red area expressing overfished and undergoing overfishing.

In the case of yellowfin tuna, landings between the 1960's and 2000's show a significant increase in the WECAFC area and a change in the landings by gear type in the eastern Atlantic, mostly due to the introduction of drifting FADs in that region in the 2000's (Fig. 16 left panel). The status of exploitation according to the Kobe plot is showing an overfished condition (Fig. 16 right panel).

Skipjack tuna shows a healthy stock condition (Fig. 17 right panel) and showing catches by bait boats as important in the WECAFC area but not by purse seiners that concentrate effort for this species in the eastern Atlantic Ocean.

Bigeye tuna is the least important of the tuna landings from the Caribbean Sea showing an increase in the spatial landings in the 4 decades of data presented while there is a recuperation of the status of overfished undergoing overfishing to a transitional status into the safe quadrat (Fig. 18 right panel).

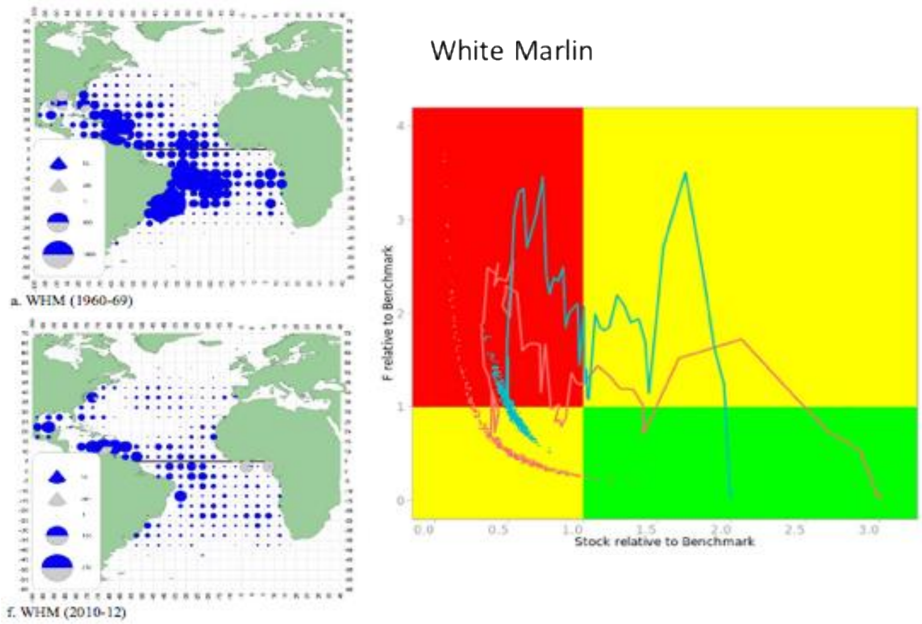


Figure 15. Accumulated landings in the 1960's and 2000's for white marlin (left panel) and a KOBE plot showing the present status of exploitation in the red and yellow areas (right panel)(Data from ICCAT stock assessments).

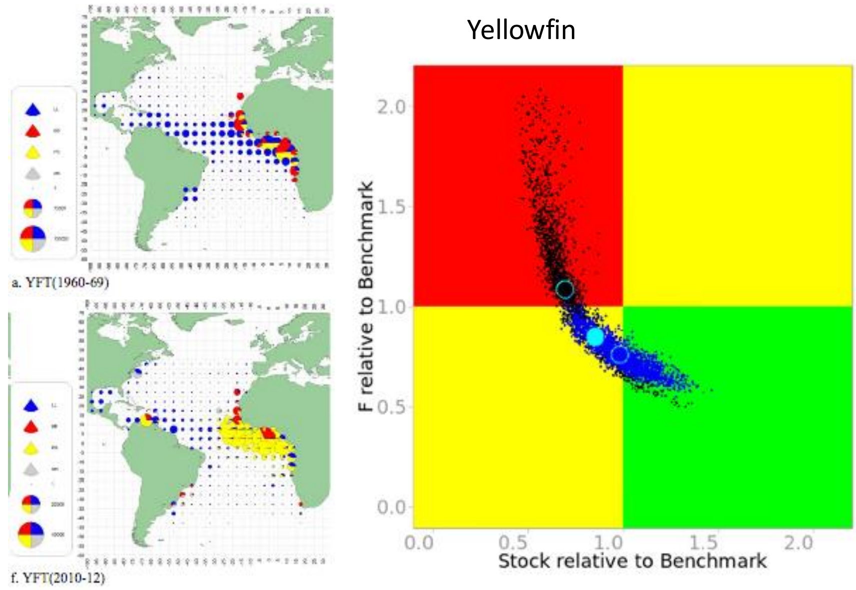


Figure 16. Accumulated landings in the 1960's and 2000's for Yellowfin tuna (left panel) and a KOBE plot showing the present status of exploitation in the yellow area (right panel) (Data from ICCAT stock assessments).

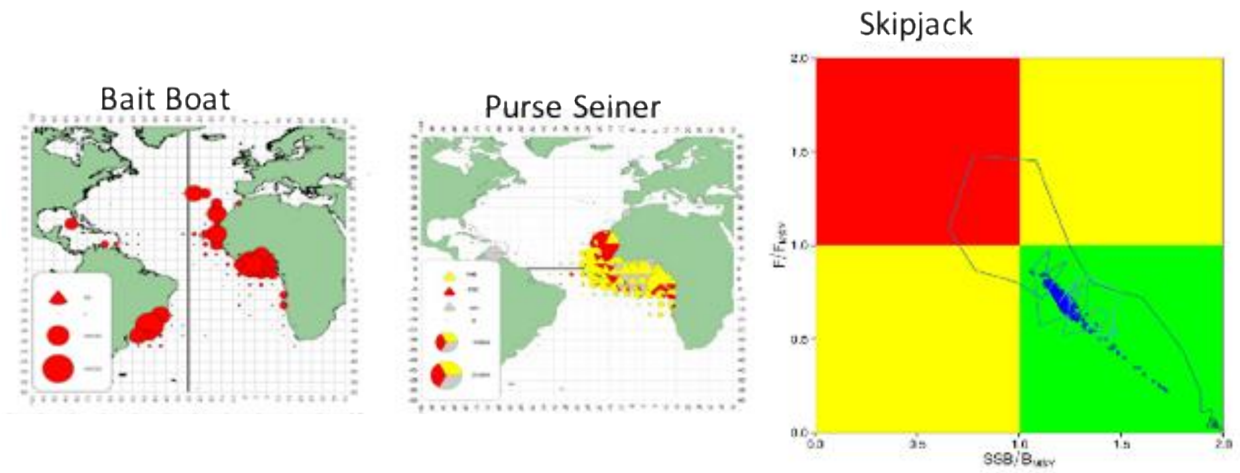


Figure 17. Accumulated landings in the of skipjack tuna (two left panels) and a KOBE plot showing the present status of exploitation in the green area (right panel)(Data from ICCAT stock assessments).

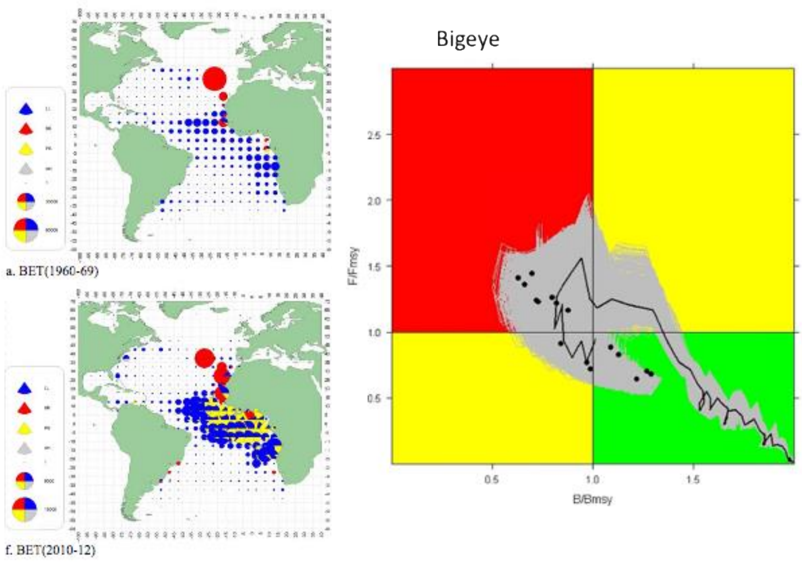


Figure 18. Accumulated landings in the 1960’s and 2010’s for albacore (left panel) and a KOBE plot showing the present status of exploitation in transition between red area and potentially the green area (right panel) (Data from ICCAT stock assessments).

Artisanal fishermen utilize a combination of moored and drifting FADs in the Caribbean. The majority of effort on dFADs is targeted toward flying fish, however mFAD fishing is quite heterogeneous. In Haiti and other nations with a high vessel to FAD ratio, it is typical for 3-4 small boats to be fishing on any given mFAD at a time (Valles 2015), while other island fleets fish in relative solitude. The species targeted vary by island and even by locality within a single country; yellowfin tuna, blackfin tuna, skipjack and little tunny, billfishes, dolphinfish, and rainbow runners constitute the majority of the landings (Fig. 19).

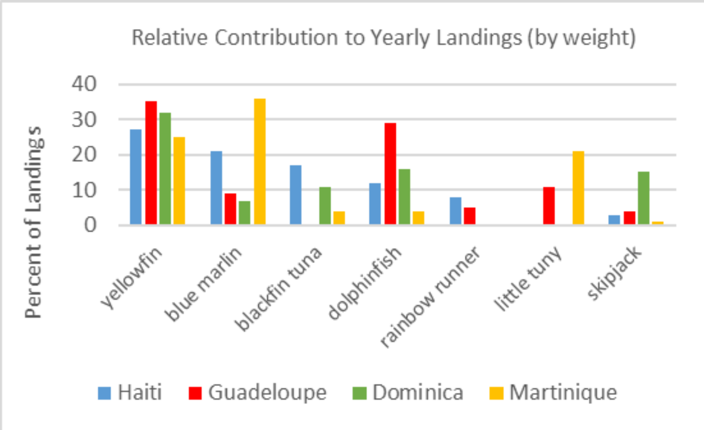


Figure 19. Relative landings of top 7 species for 4 countries participating in the moored FAD development program in the Caribbean. Estimates from Valles (2015) and Heloise et al. (2013).

Landings of large predatory fish (blue marlin) from scientific estimates are high relative to their total biomass and numbers under the FAD (Table 2), demonstrating the selective abilities of the multi-gear artisanal fleet. A primary contributing factor to the selectivity of landings in the WECAFC region is the variable, diel behavior of different fish and micronecton species relative to the mFADs. Fish of various species and size tend to aggregate closer to the surface buoy during the day (Fig. 20). Micronecton show just the reverse; their density was 2.5 times higher at night (Nelson et al. 2007).

Table 2. Fish aggregations at moored FAD in Martinique, sampled using echo-sounder buoys, underwater video, trawl fishing, and longline fishing. Adapted from Doray (2007).

| | Species | Location | Abundance |
|---|---|---|---|
| 1 | Small tunas (blackfin, yellowfin, skipjack, frigate) average 20 cm | Surface layer (0-10 m ) | Little biomass (2%) |
| 2 | Wreckfishes (jacks, triggerfish, dolphinfishes) | 20 m close to mooring line | Little biomass (2%) |
| 3 | Larger tunas. Mostly blackfin 50 cm, skipjack and yellowfin also. | 30-100 m | 95% of estimated biomass from echosounder |
| 4 | Scattered large predators, blue marlin mostly. | subsurface | Low biomass (1%) |
| 5 | Large plankton | Above thermocline, widely spread | Density varies with season |

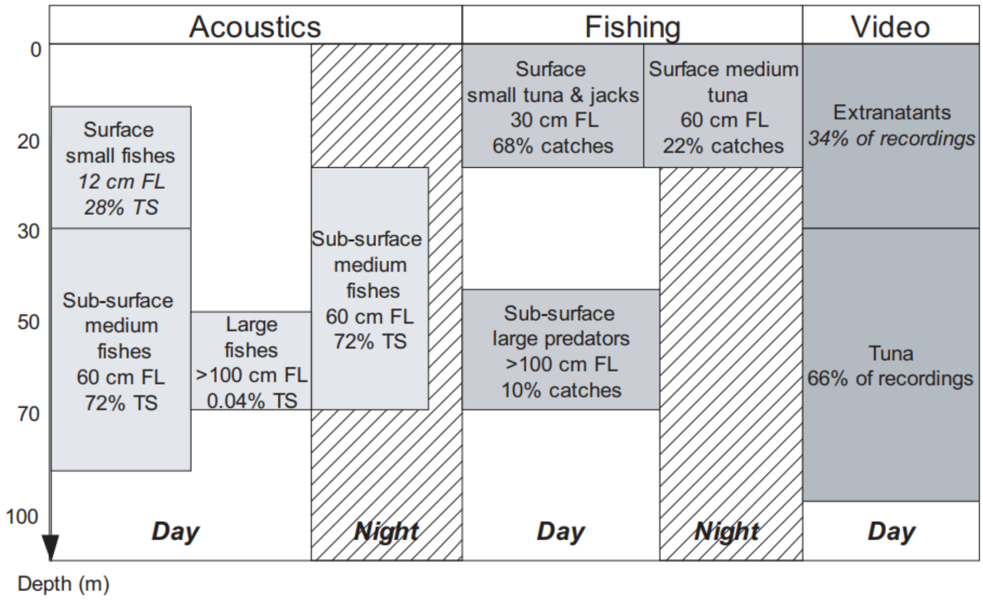


Figure 20. Diel behavior of major fish assemblages under mFADs. Figure from Doray et al. (2007).

The draft of sub-regional FAD fisheries management plan suggests that several species of significance to the moored FAD fisheries undergo different considerations for exploitation. For example: Serra spanish mackerel is recommended to maintain the status quo. This strategy will be satisfactory in the short-medium term but will be problematic in the long-term. With king mackerel the precautionary approach should be applied and current levels of fishing effort should not be increased. In the case of wahoo, again the precautionary approach is suggested with no large increases in fishing pressure recommended until stock dynamics are better understood. The dolphinfish management plan, due to uncertainties in assessment, cannot make predictions on long-term stock sustainability, and scientists therefore suggest a precautionary approach to management. Accordingly, no further development is recommended until the stock structure and dynamics are better understood. Finally, for the blackfin tuna, the plan mentions that catch levels should not be allowed to increase beyond current levels due to concerns regards impacts of recent catch increases likely caused by FAD fishing and improvements in data collection.

In sum, moored FAD fisheries development has in the WECAFC area followed an *Ad Hoc* path with an objective that needs to be clarified. All species considered to support these fisheries initiatives are currently affected by high levels of exploitation that may require regulations to promote future sustainability.

**Fishing Strategies**

The mFAD fishermen may use knowledge of fish behavior to target desired species depending on the time (or season) when they are most vulnerable. Fishers' preferences for certain species and subsequent fishing strategies vary within the WECAFC and CFRMP areas (Table 3). Fishermen may vary the gear, bait, or time of day for fishing activities to preferentially capture favored species (Reynal et al. 2015). Artisanal fishermen can be successful using surface or deep trolls, drifting buoys, and "jigging" because the targeted species, particularly blue marlin and large yellowfin, may be actively engaged in predation activities. Medium sized tuna have relatively low vulnerability to bait or lure fishing techniques (Doray et al. 2007), especially during the day. Furthermore, their attraction to FAD displayed diel fluctuations in accordance with the diel migrations of mesopelagic organisms, a major component of yellowfin tuna stomach contents around mFADs in the Pacific (Buckley, Miller 1994). Doray and colleagues suggest that this behavior is compatible with the *meeting point* hypothesis, which is most applicable to the majority of medium-sized tunas that congregate near the FAD during the daytime and only leave at dawn and dusk to opportunistically prey on the available mesopelagic organisms undertaking the nightly migration.

Table 3. Fishermen's preference for catching FAD associated fish, by island, (Gomes et al. 1998).

| SPECIES | SLU | BGI | SVG | GRN | TOB |
|---|---|---|---|---|---|
| Flying fish | 6.0 | 4.1 | 3.8 | 0.0 | 6.0 |
| Dolphin fish | 28.0 | 85.4 | 52.8 | 56.0 | 22.0 |
| King fish | 64.0 | 4.2 | 32.1 | 16.0 | 62.0 |
| Tuna | 0.0 | 6.3 | 11.3 | 22.0 | 2.0 |
| Shark | 0.0 | 0.0 | 0.0 | 0.0 | 4.0 |
| Billfish | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Swordfish | 0.0 | 0.0 | 0.0 | 4.0 | 0.0 |
| No preference | 2.0 | 0.0 | 0.0 | 2.0 | 4.0 |

Additionally, mFADs can be installed at specific distances offshore to preferentially target different species. Skipjack are especially preferential to offshore mFADs (Reynal et al. 2015). Hourly yield inshore (0-12 miles) is approximately 8.2 kg compared to 19.4 kg further than 24 miles. Of course, the increased travel time and required boat power has economic costs, so these mFADs may not be economically viable to the entire pelagic fishing sector. In comparison to their inshore counterparts, the mFAD fishing fleet has higher capital value and wages per crew member, but they also had considerably higher subsidized investment and fuel cost (Table 4).

Fishing strategies and fleet dynamics should be incorporated into management plans, especially for mFAD fleets. They are multidimensional, and effort allocation directly influences effort in other fisheries. State subsidies are intended to incentivize offshore fishing on mFADs, but they may be creating winners and losers within the fleet. User rights conflicts and territoriality among fishermen have been documented (Alvard et al. 2015) and should also factor into management plans.

**Barriers to Economic Sustainability of Artisanal mFAD Fisheries**

In addition to the much-needed institutional oversight and formal data collection, there remains further economic barriers to the sustainable development of mFAD fisheries in the Lesser Antilles. The fleets are highly multidimensional, and thus the decisions of fishermen to allocate time and effort to various fishing activities are highly variable. Although in-depth economic reviews for the region are scarce, several broad patterns are evident. Firstly, mFAD fishing has higher fuel costs and there is considerable cost to construction and installation of the mFAD. Secondly, landings are highly variable and highly seasonal. Thirdly, fishermen have opportunities to engage in multiple fishing strategies simultaneously, and the intended redirection of effort away from inshore resources has had questionable success (Mathieu et al. 2013).

Performance indicators from Guadeloupe have been collected under a Fishery Information System (FIS), and the resulting publication is probably the most exhaustive review of economic performance for any of the islands' mFAD fisheries to date (Guyader et al. 2013). Guadeloupe has 282 mFAD fishing vessels out of 767 as of 2008 (Table 4). 61 of the vessels allocated effort exclusively to mFAD fishing, and the rest combined mFAD fishing with other gears, including coastal fishing pots (traps). Trip duration is a particularly important factor influencing the decisions of effort allocation for these fishermen. Coastal fishing trips require, on average, less than half as long as fishing on an offshore, moored FAD. Coastal fishermen have the opportunity to allocate their time to other additional activities which may have economic benefits that outweigh the benefits offered by mFAD fishing for an entire day. This opportunity cost is notoriously difficult to estimate; however, it is reflected in the higher gross value added per hour of coastal fishing gears compared to mFAD fishing (Fig. 21). In other words, unless mFAD fishing becomes either much more lucrative or much shorter in duration, inshore fishing will continue to be attractive for artisanal fishermen. Additionally, mFAD fishing seems to be more variable, with good and bad days, while inshore fishing is more consistent. Guyader and colleagues offer a final hurdle to economic efficiency of mFAD fishing in Guadeloupe: current FAD density is too high. Setting too many FADs has costs, and the density of mFADs influences their ability to aggregate surrounding fish populations, diminishing their economic viability (Guyader et al. 2017).

Table 4 Economic performance of fishing fleets operating in Guadeloupe, from Guyader et al. (2013).

| | **Coastal Vessels** | | **FAD Vessels** | |
|---|---|---|---|---|
| | **< 7 meters** | **> 7 meters** | **< 7 meters** | **> 7 meters** |
| **Sample Size** | 24 | 20 | 22 | 48 |
| **Length (m)** | 6 | 8 | 6.4 | 7.9 |
| **Engine Power (kW)** | 61 | 162 | 91 | 169 |
| **Year of Construction** | 1992 | 1998 | 1997 | 2001 |
| **Crew Size** | 1.8 | 2.1 | 1.9 | 2.1 |
| **Days at Sea** | 130 | 153 | 117 | 143 |
| **Dependence on FADs (%)** | 0 | 0 | 27 | 53 |
| **Capital Value per Crew Member** | 2410 | 11699 | 6235 | 19304 |
| **Vessel Subsidies (% investment cost)** | 3 | 9 | 11 | 19 |
| **Engine Subsidies (% investment cost)** | 7 | 4 | 8 | 14 |
| **Gross Revenue** | 289 | 330 | 447 | 526 |
| **Fuel Cost** | 35 | 49 | 54 | 82 |
| **Bait, Ice, ETC.** | 10 | 10 | 23 | 23 |
| **Gear Cost (Including FAD)** | 45 | 54 | 70 | 85 |
| **Repairs, Maintenance, ETC.** | 8 | 12 | 14 | 20 |
| **Total Intermediary Consumption** | 98 | 125 | 161 | 210 |
| **Gross Added Value** | 190 | 205 | 286 | 316 |
| **Crew Cost** | 153 | 160 | 228 | 279 |
| **Wage per Crew Member** | 85 | 74 | 118 | 136 |
| **Vessel Gross Surplus** | 37 | 45 | 58 | 37 |
| **Full Equity Profit** | 34 | 38 | 53 | 27 |
| **Owner Operator's Income** | 117 | 107 | 166 | 155 |

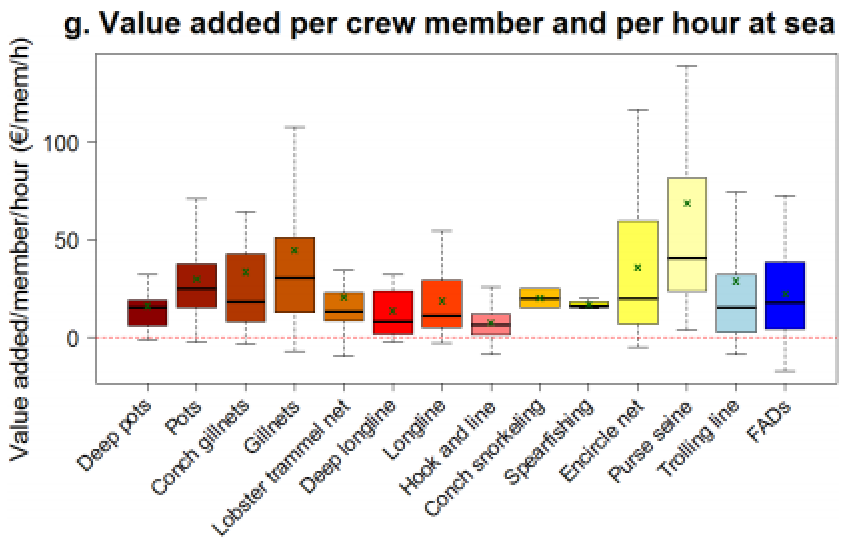


Figure 21. Per trip, FAD fishing yields higher landings and daily wages, however value added / crew member / hour is higher for inshore fishing activities because the trips are considerably shorter. (Guyader et al. 2013)

Valles (2015) carried out an additional survey through a series of meetings to provide much needed baseline data for Haiti's mFAD fishery, which developed in the 1990's. At the time, 136 vessels were involved in mFAD fishing within the survey area (Fig. 22), which did not encompass the entire island nation, however it provides an adequate snapshot of the fishery. FAD construction cost ranged between $1,500-5,000 US Dollars per FAD. This is prohibitively expensive for Haitian artisanal fishermen; in fact, many may contribute to the construction of a single FAD. Otherwise, it is funded by outside organizations such as the Spanish Cooperation or the United Nations Environmental Program. Unlike the Guadeloupe survey, this survey does not address other economic costs or benefits derived from various fishing effort, but it is clear that variability of landings (Table 5) is an issue for mFAD fishing in Haiti as well. For some locations, the majority of boats returned with no fish.


Figure 22. Locations of known (yellow dots) and approximate (green dots) mFADs in South Haiti in 2015, and landings ports (red). Valles (2015).

Table 5. Landings are highly variable, by location and season. For some ports, there are considerable trips returning with zero fish. Valles (2015).

| Commune | No of fishing trips | Fish catch (kg) per fishing trip | | | | Per cent of trips with zero catch |
|---|---|---|---|---|---|---|
| | | average | min | max | sd | |
| Anse D'Hainault | 4 | 0.5 | 0.0 | 1.8 | 0.9 | 75.0 |
| Bainet | 18 | 15.0 | 0.0 | 45.6 | 16.9 | 22.2 |
| Belle Anse | 20 | 26.9 | 0.0 | 73.6 | 25.9 | 5.0 |
| Port-Salut | 6 | 21.9 | 0.0 | 74.7 | 29.9 | 50.0 |
| Tiburon | 3 | 3.8 | 0.0 | 10.7 | 6.0 | 33.3 |
| **Overall** | **51** | **18.7** | **0.0** | **74.7** | **22.7** | **23.5** |

Regional analysis indicates similar issues for mFAD fishery development among other nations. A major factor affecting the fleet size seems to be the price of imported seafood (Mathieu et al. 2013). Figure 23 illustrates that FAD fleet for Martinique and Guadeloupe started to reach their maximum capacity around 2001. Mathieu and colleagues speculate that fishermen had to find an alternative income around that time because they could not compete with the rising influx of imported seafood (Figure 24.) They note that the sale of wire used for fish traps increased between 2002 and 2004 among the fishermen cooperatives in Martinique, further indication that fish pots are still being built and set inshore.

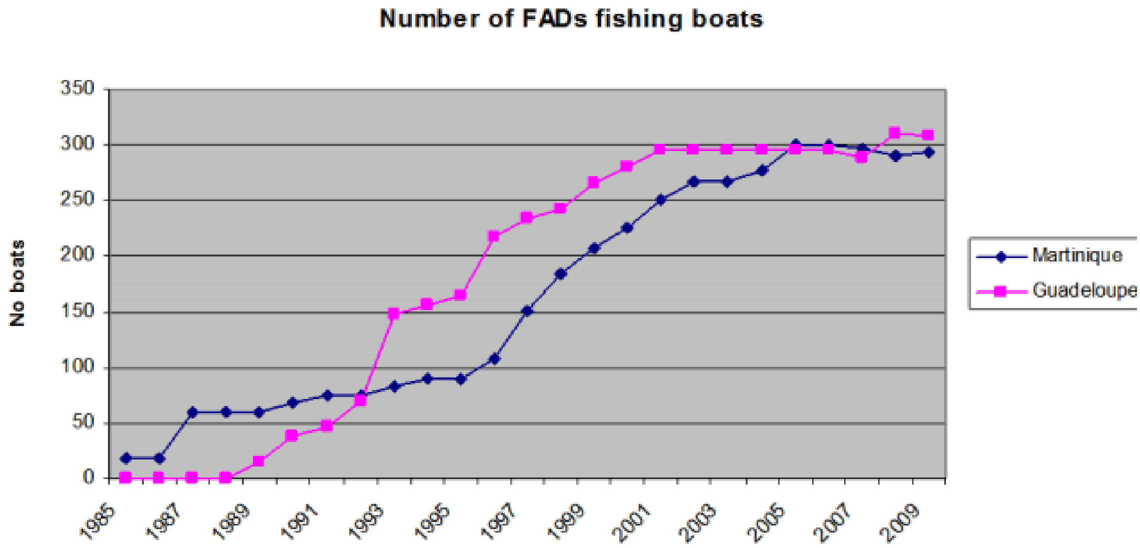


Figure 23 The FAD fleet began to reach capacity around 2001 for Martinique and Guadeloupe, Mathieu et al. 2013.

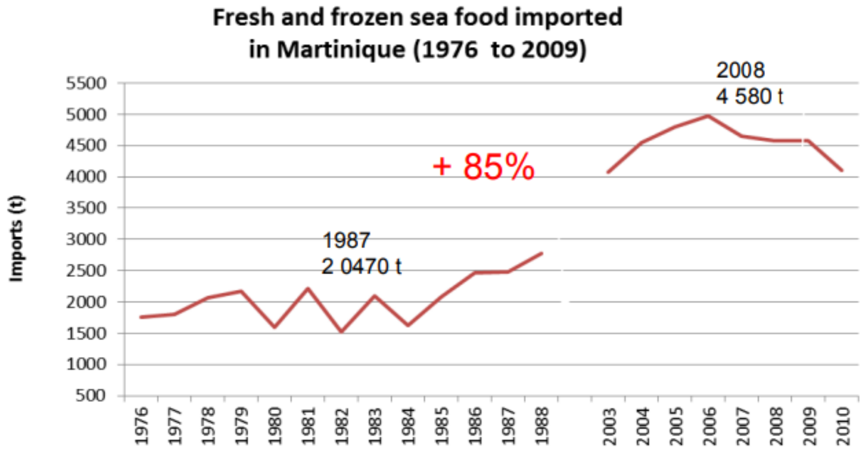


Figure 24. Imports of cheap, foreign seafood directly competes with local fishery products in the market. Mathieu et al. 2014.

Currently, there is a need for institutional framework and oversight for development of mFAD fisheries in the Caribbean. FAD fishery development has been unique for each participating nation; however, one commonality is that all nations lack either financial resources or human resources for proper enforcement of regulations. Fishermen show a variety of fishing strategies and subsequent landings, which should be taken into account by managers and scientists. Poor data gathering is another barrier to sustainable development and management of artisanal mFAD fisheries. Data collection has been, in general, *ad hoc* and vary considerably according to when projects begin and/or end. Finally, there are economic considerations affecting effort allocation within a multidimensional fleet. These analysis raise questions about the balance of costs and benefits of installing additional mFADs. This is especially troublesome if consideration is given to the fact that catch may decrease per unit of mFAD when number of mFADs increase. Studies in this regard presented at the Joint tFRMO FAD Working Group of April 2017 presented a paper with such results (Fig. 25). Although with a noticeable lack of data, similar trends appear to exist when data reported in the CRFM Sub-regional FAD management plan is used (Fig. 26). In addition the added interaction of mFAD fishing and recreational fishing in the WECAFC area (Fig. 27) is creating an environment of confrontation that needs to be controlled as expansion of mFADs in the recreational fisheries is being exercised as a response to similar trends in the artisanal fisheries.

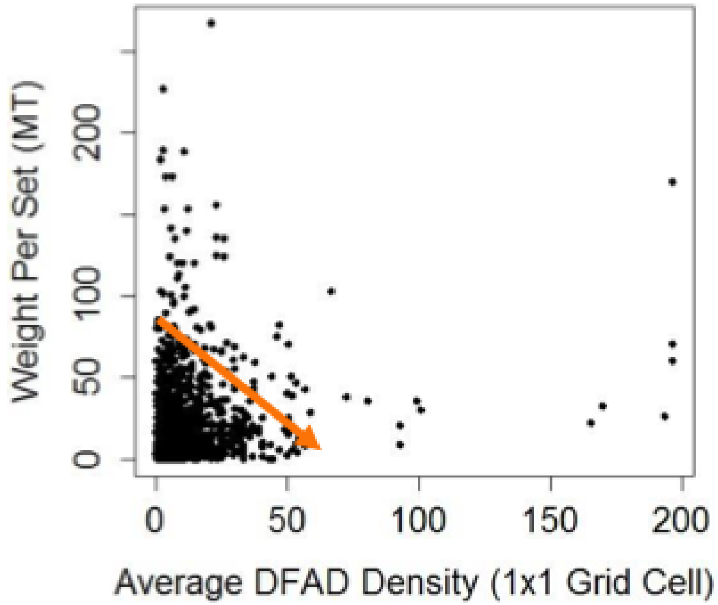


Figure 25. Relationship between catch of tunas in FAD associated Atlantic and Indian Ocean purse seine sets (From Kaplan et. al. 2017. Joint ICCAT, IATTC and IOTTC FAD Working Group, Madrid, Spain, April 2017)

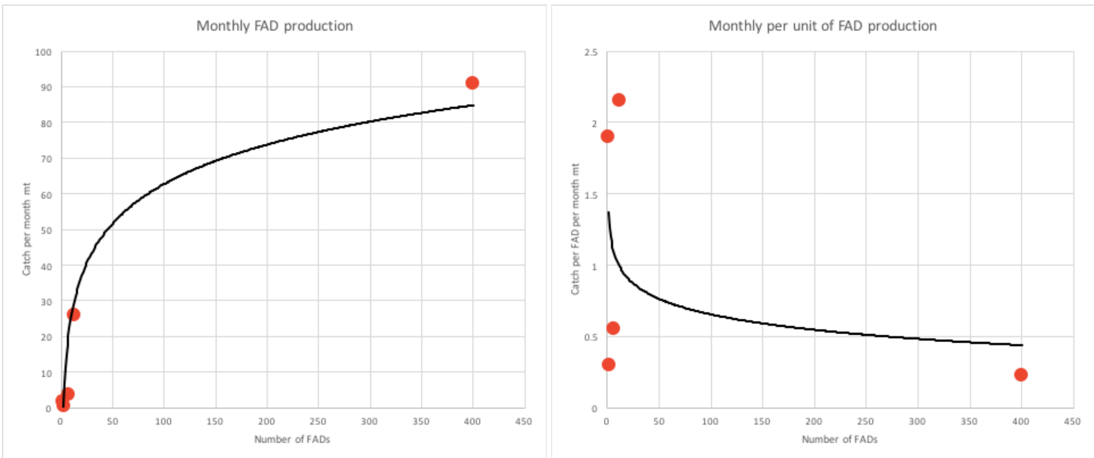


Figure 26. Catch per month in Eastern Caribbean moored FAD associated fisheries on number of FADs (left panel) and catch per FAD per month on number of FADs (right panel) (Data extracted from CRFM 2015).

Figure 27. Disputes registered between recreational billfish fishers in a catch-and-release mode and the forced taking over of the hooked marlin by mFAD fishers in the Dominican Republic (Source: available from news in the web).

As FADs continue to be utilized to aggregate and concentrate pelagic species all over the world, and with echo-sounder buoy technological improvements occurring constantly, the opportunity to employ FAD devices as research and management tools is evident. As a form of cost effective sampling, moored FAD research using the newest echo-sounder buoys represents a new, fishery independent, method for collecting abundance, biodiversity, and species interaction information that is critical for the conservation, assessment, and management of marine resources affected by FAD fishing. The collaboration of fishing organizations, fishers, buoy manufacturers, and scientists is pivotal to this endeavor to maintain and monitor FAD devices and associated fishing mortality effects.

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# ANNEX

| | Location | FAD type | Association Behavior and/or residence time | Citation |
|---|---|---|---|---|
| Skipjack | Western Indian Ocean | Drifting | Daytime | (Forget et al. 2015) |
| Yellowfin | Western Indian Ocean | Drifting | Daytime | (Forget et al. 2015) |
| Bigeye | Western Indian Ocean | Drifting | Daytime | (Forget et al. 2015) |
| Silky Shark | Western Indian Ocean | Drifting | Daytime | (Forget et al. 2015) |
| Dolphinfish | Western Indian Ocean | Drifting | Average residence 6.25 days. Form multiple small schools. Feeding excursions both day and night | (Taquet et al. 2007) |
| Yellowfin | Hawaii | Anchored | Daytime | (Holland et al. 1990) |
| Bigeye | Hawaii | Anchored | Daytime | (Holland et al. 1990) |
| Yellowfin | Indian Ocean (Comoros Islands) | Anchored | Daytime, night feeding excursions | (Cayre 1991) |
| Skipjack | Indian Ocean (Comoros Islands) | Anchored | Highly variable, no clear diurnal pattern | (Cayre 1991) |
| Yellowfin | Hawaii | Anchored | Daytime arrival mostly | (Klimley and Holloway 1999) |
| Yellowfin | Pacific Ocean (Okinawa Islands) | Anchored | 17 median, 66 maximum days residence, daytime feeding excursions | (Ohta and Kakuma 2005) |
| Bigeye | Pacific Ocean (Okinawa Islands) | Anchored | 16 median, 85 maximum days residence, daytime feeding excursions mostly around noon. | (Ohta and Kakuma 2005) |
| Juvenile Yellowfin | South China Sea (Philippines) | Anchored | No diel preference | (Babaran et al. 2009) |
| Juvenile Yellowfin | South China Sea (Philippines) | Anchored | Daytime, dispersed at night (Horizontal) Spend days at deeper depths than night (shallow) | (Mitsunaga, et al. 2013) (Mitsunaga et al. 2012) |
| Yellowfin | Indian Ocean (Mozambique Channel) | Drifting | 10 Continuous residence time, night excursions, deeper during day | (Govinden et al. 2010) |
| Skipjack | Indian Ocean (Mozambique Channel) | Drifting | 4.5 continuous residence time, night excursions, Deeper during day | (Govinden et al. 2010) |
| Bigeye | Indian Ocean (Mozambique Channel) | Drifting | 3.9 continuous residence time, night excursions, deeper during day | (Govinden et al. 2010) |
| Skipjack | Indian Ocean (Maldives | Anchored | Diurnal pattern only in November. Little synchronicity in departures. | (Govinden et al. 2013) |

Annex Continued

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|---|---|---|---|---|
| Yellowfin | Indian Ocean (Maldives | Anchored | No diurnal pattern. Little synchronicity in departures | (Govinden et al. 2013) |
| Skipjack | Pacific Ocean (Equatorial, Eastern) | Drifting | Daytime | (Schaefer and Fuller 2013) |
| Yellowfin | Pacific Ocean (Equatorial, Eastern) | Drifting | No diurnal pattern | (Schaefer and Fuller 2013) |
| Bigeye | Central Pacific | Drifting | No diurnal pattern for depth | (Matsumoto et al. 2006) |
| Yellowfin | Central Pacific | Drifting | Shallower at night | (Matsumoto et al. 2006) |
| Skipjack | Central Pacific | Drifting | Most shallow species | (Matsumoto et al. 2006) |
| Skipjack | Central Pacific | Drifting | Shallow, nighttime feeding excursions | (Matsumoto et al. 2014) |
| Tunas | Western Indian Ocean | Drifting | Multiple, separate schools within 500 meters of FAD, larger during daytime | (Trygonis et al. 2016) |
| Yellowfin | Indian Ocean (Seychelles) | Anchored | 9.6 days continuous residence and 30.1 total residence (averages) | (Rodriguez-Tress et al. 2017) |
| Bigeye | Indian Ocean (Seychelles) | Anchored | 5.2 days continuous residence and 35.3 total residence (averages) | (Rodriguez-Tress et al. 2017) |
| Skipjack | Indian Ocean (Seychelles) | Anchored | 2.5 days continuous residence and 17.6 total residence (averages) | (Rodriguez-Tress et al. 2017) |
| Silky Shark | Western Indian Ocean | Drifting | Short feeding excursions at night | (Filmalter et al. 2015) |