G Model
FISH-4256; No. of Pages 8

ARTICLE IN PRESS

Fisheries Research xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Fish aggregating devices (FADs) as scientific platforms

G. Moreno[a,b,*], L. Dagorn[c], M. Capello[c], J. Lopez[b,e], J. Filmalter[a,d], F. Forget[a,c], I. Sancristobal[b], K. Holland[f]

[a] *International Seafood Sustainability Foundation (ISSF), 805 15th Street NW, Washington, DC 20005, USA*
[b] *Azti-Tecnalia, Herrera kaia, Portualdea z/g, 20110, Pasaia, Spain*
[c] *Institut de Recherche pour le Développement (IRD), MARBEC Marine Biodiversity, Exploitation & Conservation, UMR IRD, Ifremer, Univ. Montpellier, CNRS, Avenue J. Monnet, CS 30171, 34200 Sète Cedex, France*
[d] *South African Institute of Aquatic Biodiversity, Grahamstown, 6140, South Africa*
[e] *Instituto Español de Oceanografía (IEO), Calle del Corazón de María, 8, 28020 Madrid, Spain*
[f] *Hawaii Institute of Marine Biology Coconut Island, Kaneohe, HI 9674, USA*

ARTICLE INFO

Article history:
Received 15 March 2015
Received in revised form
16 September 2015
Accepted 29 September 2015
Available online xxx

Keywords:
FAD
Echo-sounder buoy
Tuna
Abundance
Acoustic tags
Pelagic ecosystem
Fishing technology

ABSTRACT

Fish aggregating devices (FADs) are floating objects used by fishers to aggregate pelagic fish such as tunas, and enhance the catch of these species. Because this is so important for tuna fisheries, nearly 100,000 FADs are deployed by fishers every year in the world's tropical oceans. Fishers use geo-locating buoys to track and maintain these FADs by visiting them regularly, reinforcing them if they are weak or replacing them. Many of these buoys are now equipped with echo-sounders in order to provide remote information on the aggregated biomass. FADs are currently only used for fishing purposes but they can also serve scientific objectives. In this paper, we investigate the potential of these data for improving our knowledge on the ecology of tunas and other pelagic animals as well as to obtain fishery-independent indices of distribution and abundance. These FADs also represent platforms for scientists to deploy scientific instruments, such as electronic tag receivers, cameras and hydrophones. Because FADs naturally aggregate several pelagic species other than tuna, these instrumented FADs can be a unique opportunity to observe pelagic ecosystem dynamics that are not possible from conventional research vessels. The amount of cost-effective data that they can provide would make a significant contribution to the scientific understanding of pelagic ecosystems. This information is vital for improved conservation and management of pelagic fisheries.

1. Introduction

Marine governance strategies must be supported by rigorous and relevant scientific data obtained from both fishery-dependent and independent sources. The vastness of the open ocean is an intrinsic hindrance to the collection of useful information at the scales needed to understand the ecology of this ecosystem. As a consequence, we do not currently know enough about how pelagic ecosystems are influenced by human exploitation of marine resources, such as industrial fishing activities. Management systems for the pelagic ecosystem still rely, to a large degree, on fisheries-dependent data. As such, the stock assessments of the main commercial pelagic fish species are currently based on standardized catch-per-unit-of-effort (CPUE), (Maunder and Punt, 2004). This method relies on having a consistent, standardized measure of effort, which is necessary for the relative CPUE to be considered as a proxy for abundance, and used in the stock assessment. The rapid technological changes in the fishing industry make it difficult to quantify effort consistently and highlight the urgent need for new scientific methodologies in marine resource management. This is particularly the case for the tropical tuna purse seine fishery, where the metric (search time) traditionally used to reflect nominal effort does not account for technological or fishing strategy changes, which may mask stock abundance changes (Fonteneau et al., 2013). Furthermore, there is no evaluation of the uncertainty associated surrounding the assumption that CPUE is truly a proxy for abundance. Additionally, stock assessments based on catch statistics generally focus on the

* Corresponding author at: International Seafood Sustainability Foundation (ISSF), 805 15th Street NW, Washington, DC 20005, USA.
E-mail addresses: gmoreno@iss-foundation.org (G. Moreno), laurent.dagorn@ird.fr (L. Dagorn), manuela.capello@ird.fr (M. Capello), jon.lopez@md.ieo.es (J. Lopez), jdfilmalter@gmail.com (J. Filmalter), fabienforget@gmail.com (F. Forget), isancristobal@azti.es (I. Sancristobal), kholland@hawaii.edu (K. Holland).

http://dx.doi.org/10.1016/j.fishres.2015.09.021
0165-7836/© 2015 Published by Elsevier B.V.

target species and neglect the impact of the fisheries on the rest of the pelagic ecosystem. Thus there is an urgent need for alternative, fishery-independent methods of determining the status of the many non-commercial/non-targeted species (the so-called by-catch species) that are accidentally caught during the fishing operations and whose catches are often underreported. In order to move towards an ecosystem based fishery management approach, it is necessary to go beyond the mono-specific stock assessment of target species based solely on catch data. Even for the target species, the lack of uniform reporting standards and variability in the quality of the official catch and effort data provided by different management agencies compromise the results of current stock assessments. Thus, for several reasons, there is a need for new alternative methods capable of assessing the status of the pelagic ecosystem on a multi-specific basis and for quantifying the impact of pelagic fisheries on both target and by-catch species.

A specific case that clearly illustrates how a rapidly evolving fishery can outpace scientific understanding is the massive global expansion in the use of drifting fish aggregating devices (DFADs) by purse seiners targeting tropical tunas. The DFAD fishing strategy has greatly increased this fishery's efficiency. DFADs are drifting objects floating at or near the ocean surface. Originally, these DFADs were natural objects such as logs but the rapid expansion of the fishery has depended on large scale deployments of man-made structures. Fishers monitor the location of each of these objects by attaching a satellite linked geolocating buoy to each DFAD (Moreno et al., 2007a; Lopez et al., 2014). Much of the concern surrounding DFAD fishing (which yields nearly half of the world catch of tropical tunas—i.e., skipjack *Katsuwonus pelamis*, yellowfin *Thunnus albacares* and bigeye *Thunnus obesus*), comes from the uncertainty around their impact on tuna stocks and on the pelagic ecosystem of which they are a part. Specific concerns relate to the potential effects on the catch of small tuna (i.e., yellowfin and bigeye), on tuna populations, the alteration of the natural movements and behavior of tunas (i.e., the 'ecological trap'; Marsac et al., 2000) and the possible impact on the biodiversity of the supporting ecosystem (Dagorn et al., 2012; Leroy et al., 2013). Oceanic megafauna (e.g., sharks, billfishes, turtles, cetaceans) are also taken as by-catch in purse seine fisheries (as well as other pelagic fisheries such as long lining) (Hall et al., 2000). Biological and fisheries data are severely limited for most of these non-target stocks (Anonymous, 2014) and the impact of DFAD fishing on these species is unknown. An historic lack of dedicated attention to these species has now resulted in the need for immediate compensation through quantitative and effective scientific approaches. Strong conservation strategies for target and non-target pelagic fauna require the collection of large-scale data on their spatial dynamics and distribution and on their interaction with the fishing gear (defined here as both the purse seine nets and the FADs).

The economic and human costs of research cruises and autonomous scientific platforms (e.g., buoys and gliders) limit their use. Recently, an increasing proportion of DFADs are equipped with echo-sounder buoys that provide fishers not only with accurate geolocation information for the DFAD but also rough estimates of aggregated biomass (Lopez et al., 2014). That is, they detect the assemblage of various pelagic species that has become associated with the FAD. These FADS and buoys represent a powerful tool that could autonomously collect continuous streams of data on pelagic life at an oceanic scale, which cannot be achieved by other scientific means. Just as DFADs provide fishers with easier access to fish, these objects can provide access to data for scientists.

This paper aims to highlight the potential of DFADs, if correctly managed, to meet the needs of scientists and fisheries managers by making the specific object of interest (FADs) also serve as the key observational component of the investigation. We present and discuss the concept of using FADs as scientific platforms and describe the conceptual underpinnings of FADs as automated observatories of the pelagic ecosystem. Furthermore, we highlight the capabilities that such devices should have and discuss whether the available technology and their current fishery context consigns this concept to no more than a dream or realistic opportunity for future development.

2. Pertinence of DFADs as scientific platforms

2.1. Biological relevance

At least 333 fish species (80% of these in early life history or juvenile stages) have been observed around floating structures (Castro et al., 2002). However, only 25–40 of these species are regularly encountered in FAD aggregations (Romanov, 2002; Taquet et al., 2007). Non fish species such as sea turtles, sea birds and marine mammals also aggregate around FADs (Amandè et al., 2010; Brehmer et al., 2012; Capietto et al., 2014). Through their aggregating effect on pelagic species, FADs increase their availability to observe and thus facilitate access to large numbers of the diverse species that inhabit the vast open ocean. Since fish consider artificial DFADs as natural floating objects, they display a natural behaviour around them, in such a way that, as with prominent habitat features such as seamounts or shelf breaks, FADs represent mini hotspots within the pelagic ecosystem and should thus be optimally exploited for scientific purposes.

Tropical tunas have been observed to remain associated with anchored FADs for several days at a time (Ohta and Kakuma, 2005; Dagorn et al., 2007a; Mitsunaga et al., 2012; Robert et al., 2012) with records of 64 days at a single FAD also being reported (Dagorn et al., 2007a). The limited number of experiments conducted at DFADs have also revealed that tropical tunas, as well as other species such as silky sharks and dolphinfish, could remain associated for periods spanning several days to weeks (Dagorn et al., 2007a; Taquet et al., 2007; Filmalter et al., 2011). Besides attracting numerous species, these floating objects retain fish in great numbers (Kingsford, 1993), which provides insight into the potential that they hold for studying pelagic biodiversity which, in their absence, would be virtually impossible.

FADs therefore represent a "sampling tool" of open ocean biodiversity, comparable to fishing, and could be used as such. To be considered as sampling tools, they should provide data that are similar to that currently collected through fishing: species composition and estimates of abundance. The main difference would be the fact that fishing represents a snapshot in the trajectory of the DFAD, a single point of data on fish biomass and the information is fishery dependent. Conversely, the data provided by the echo-sounder buoys at DFADs would provide biomass evolution throughout the DFAD's deployment, which could range from several weeks up to a year. In addition to being sampling tools, FADs can also be considered as preferred passage points, and can be used to monitor distribution and movements of animals. Finally, because some species can remain associated with FADs for extended periods, they can be used for collecting behavioral information.

2.2. A large scale array of drifting platforms deployed and maintained by fishers

Large marine fauna make extensive use of the pelagic realm, as do the resource users who exploit them. The international purse seine fleet maintains approximately 50,000–100,000 DFADs worldwide at any point in time (Baske et al., 2012). The annual production estimated for the five major tracking buoy companies that supply this fishery has been estimated between 47,500–70,000, further corroborating these estimates. Additional estimates have put the

Fig. 1. Deployment of DFAD structure with an echo-sounder buoy from a purse seiner.

number of FADs active at any one time in the Indian Ocean to be between 3750 and 7500 (Filmalter et al., 2013) while others have estimated this number to be 5700 in 2013 (Maufroy et al., 2014). The behavioral ecology of large pelagic fish species involves multiple temporal and spatial scales that can span several orders of magnitude, from the meter to thousands of kilometers. In order to improve our knowledge on the key processes occurring over this wide range of scales, it is necessary to expand the current spatio-temporal coverage and rates of data acquisition. Using fishersí networks of autonomous buoys that are already deployed on DFADs can provide scientists with the operational tools to reach such a goal. The deployment of DFADs by industrial purse seiner fleets covers large portions of the equatorial and tropical waters of the world's oceans (Fig. 2). There are areas such as the equatorial Pacific where the predominant westward flux of the surface water masses, propelled by the North Equatorial Current and South Equatorial Current, is efficiently used by fishers to maintain a network of DFADs covering this vast expanse. Pacific Equatorial fishers try to deploy their DFADs near the eastern boundary of their fishing grounds, let them drift naturally by the NEC and SEC and revisit them once they are further west. This way the entire equatorial Pacific is permanently covered by arrays of DFADs. Equatorial and tropical oceanic areas of the Indian and Atlantic oceans are similarly swept by the FADs of purse seine vessels following the predominant oceanic currents.

While these extensive arrays of DFADS, which are generally viewed simply as fishing tools for enhancing exploitation with detrimental impacts on the ecosystem, they simultaneously harbour immense observational power. A single DFAD can remain at sea for months and even years (Moreno et al., 2007a; Lopez et al., 2014) and can drift for thousands of kilometers, including into areas far beyond the fishing grounds, thus constituting ideal monitoring stations for pelagic species that associate with DFADs as well as the environment. Fishers regularly deploy new DFADs in specific areas depending on the season so that they drift, at least for some period, through productive waters to aggregate tunas (Fig. 1). After a given time adrift, they revisit these DFADs to assess the size of the aggregation and to capture the associated tunas (Moreno et al., 2007a). During these visits, DFADs' structures are carefully examined and reinforced if necessary, ensuring that they withstand extended periods at sea. Likewise, tracking buoys are either replaced or the batteries changed so that they can continue transmitting information throughout the lifespan of the DFAD. This activity is constantly performed to maintain the network of DFADs, as this is essential for the fishing success of the majority of tropical tuna purse seine vessels. Some purse seine companies have auxiliary vessels that are dedicated to work on their DFADs. Such vessels help to maintain the integrity and spatial coverage of the networks of FADs by deploying new DFADs, reinforcing old DFADs, and replacing buoys where necessary. Scientists could benefit for this enormous effort that is constantly carried out by fishers.

3. Using FADs to derive fishery-independent indices of abundance

The use of DFADs by fishers to find and catch tropical tunas has significantly modified the measure of effort, and as standardized effort is essential for assuming a proportional relationship between CPUE and abundance, the relationship between local biomass and CPUE has become obscured. (Fonteneau et al., 1999). Currently, the discussion on how to properly define an "effort" for the purse-seine FAD fisheries is playing a disproportionately large role in stock assessments of tropical tuna. This is largely due to CPUE data being relatively inexpensive and easy to collect compared to other stock assessment inputs (Branch and Hilborn, 2006; Anonymous, 2012). The challenge for scientists is to improve the standardization of purse seine fishing effort given the dynamics of the use of FADs as well as to develop fishery-independent indices of abundance of tropical tunas.

While some coastal fisheries benefit from fishery-independent stock abundance data derived from acoustic or aerial surveys, these techniques are generally only applicable for species that occur in shallow coastal waters or have fairly predictable distributions. These techniques have been applied to species such as capelin, herring and sardinella (Fréon and Misund, 1999) and bluefin tuna when they occur in coastal regions (e.g. Royer et al., 2004) but these methods are not practical for tropical tunas. The immensity of tropical tuna habitat, their highly vagile behaviour and the fact they are not frequently near the surface has precluded the use of fisheries-independent assessment approaches for these species. We consider that FADs could be used to provide fishery-independent estimates

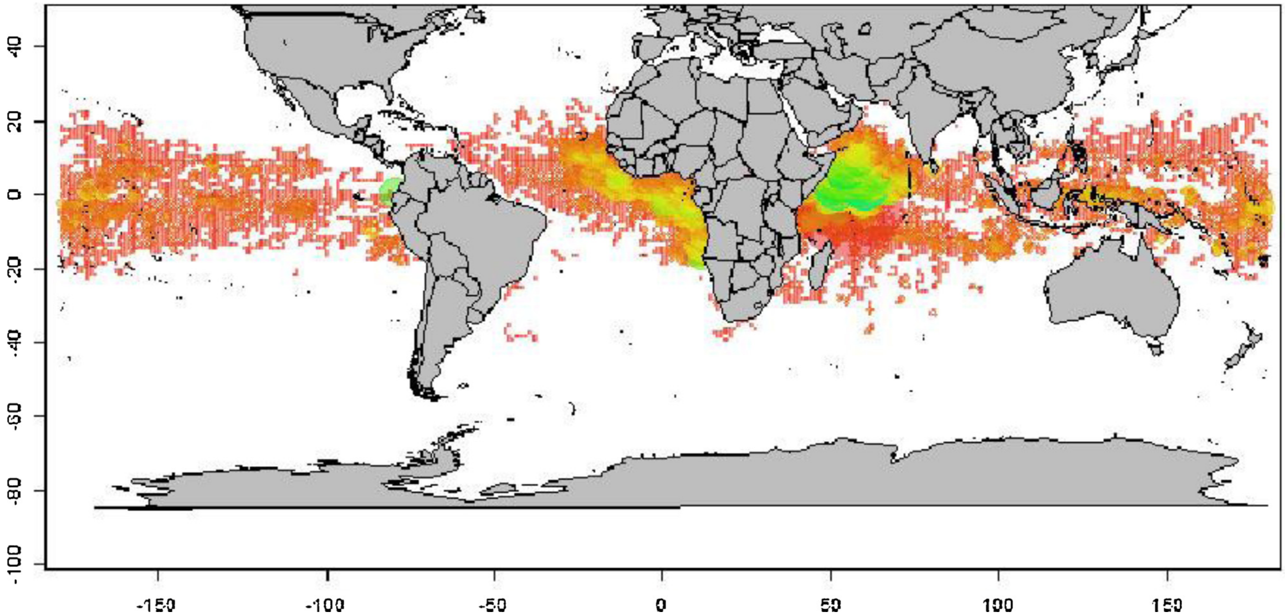

Fig. 2. Spatial coverage of fisher's echo-sounder buoys from data received during one month from 49 purse seiners operating in Indian, Atlantic and Pacific Oceans.

of abundance of tropical tunas as well as of other FAD associated species.

Fishers are currently using echo-sounder buoys that provide information on aggregated biomass at DFADs. One of the major contributions of DFADs as scientific platforms would be obtaining direct, near real time abundance estimates for the population assessment of pelagic fish species that associate with floating objects. Following the results of recent research projects and through the joint effort of scientist and buoy manufacturers these buoys will provide estimates of tuna species composition at FADs in the near future. The echo-sounder buoys data already collected by fishers from DFADs could allow for the estimation of the spatio-temporal evolution of the biomass associated with the DFADs over their full lifespan. Furthermore, this information can provide insight into the evolution of the species composition of the DFADs aggregations through time and space (Table 1).

Owing to a combination of cost efficiency and utility, instrumented buoys currently used by fishers on DFADs are commercially mature and well-established products. They contain low-cost, autonomous echo-sounders, powered by solar panels, which scan the water column to detect the presence of fish. The raw data are integrated within the buoy, simplified into depth layers in order to be transmitted via satellite in the form of a brief data series summarizing the detected signal. Currently, there are 5 different buoys types with integrated echo-sounders on the market for FAD-fishing purposes. They provide heterogeneous outputs due to their unique operating frequencies, ranges, coverages and spatio-temporal resolution (Lopez et al., 2014). Only one manufacturer claims to provide relative biomass estimates in tons, while others provide numbers representing the percentage of the beam that is occupied by fish. The large variability of outputs provided by the different buoy manufacturers complicates the harmonious integration of data across the various brands. Inter-calibrating the different buoys could help in obtaining a comparable magnitude and hence fishery-independent abundances using all buoy types at sea.

One of the challenges that scientist are faced with when trying to use fishersí echo-sounder buoys to estimate relative abundance is the quality control of the data provided by the large array of buoys (estimated from 50,000–100,000) that drift at sea. Most buoy manufacturers calibrate 100% of their buoys at origin using a standard target. Currently there are joint efforts between buoy manufacturers and research institutes to determine the relationship between acoustic backscatter from buoys and biologically relevant quantities. These research projects are working on simultaneous comparisons between purse seine catches at FADs, EK60 scientific echo-sounder data and the acoustic backscatter provided by the different buoy brands from the same aggregation. The cooperation between manufacturers and scientist is already established and should allow the development of routines or protocols for buoys calibration in the near future. However, considering the large number of buoys, and the spatial coverage that scientist and manufacturers need to cope with, calibration strategy, data mining and quality control of data should be guaranteed through a pilot study, in order to facilitate a global comparison of acoustic data. For the model proposed in this paper (see below) relative abundance estimates are required, due to the great number of buoys, calibrating a subset of each batch appears more feasible, although such a pilot project should explore various calibration strategies and assess biases to achieve the data quality needed.

Echo-sounder buoy technology is evolving rapidly and manufacturers, through collaboration with scientists, have already begun to solve the challenges associated with acoustic measurements on autonomous platforms, such as energy requirements and remote target classification. As Handegard et al. (2013) stated, one of the major constraints when dealing with remote devices is the lack of biological sampling for verifying taxonomic composition and validating the conversion of acoustic backscatter into biologically relevant measures such as biomass. In this regard, some buoy manufacturers have begun to integrate multiple frequencies into their echo-sounder buoys. This should allow for increased success in species discrimination capability, especially between swim-bladder (Yellowfin and Bigeye tunas) and non-swim bladder (skipjack) tunas (Table 1).

As FADs tend to aggregate most of the fish in a radius of 400–500 m (Cillaurren, 1994; Moreno et al., 2007b), the restricted vertical 'view' of the echo-sounder is also being improved by manufacturers by adding horizontal transducers. This modification will significantly improve biomass estimations of DFAD-associated fish.

In order to exploit the data from echo-sounder buoys for deriving quantitative indices of abundance for FAD associated species,

Table 1
Summary of data needs, type of autonomous instrumets that can be used to observe pelagic fauna and end users of the data.

Data	Type of instruments	Operational	Developed but need testing for this specific application	Fishers	Scientist
Species	Underwater cameras		x	x	x
Identification	Multi-frequency echo-sounders for tunas	x		x	x
Species	Underwater cameras for sharks		x	x	x
Abundance	Echo-sounders	x		x	x
Species association time and movements	Acoustic receivers (with or without satellite link)	x			x
Biology & behaviour	Coded tags	x			x
	CHAT tags		x		
Biological environment (DSL)	Echo-sounders	x			x

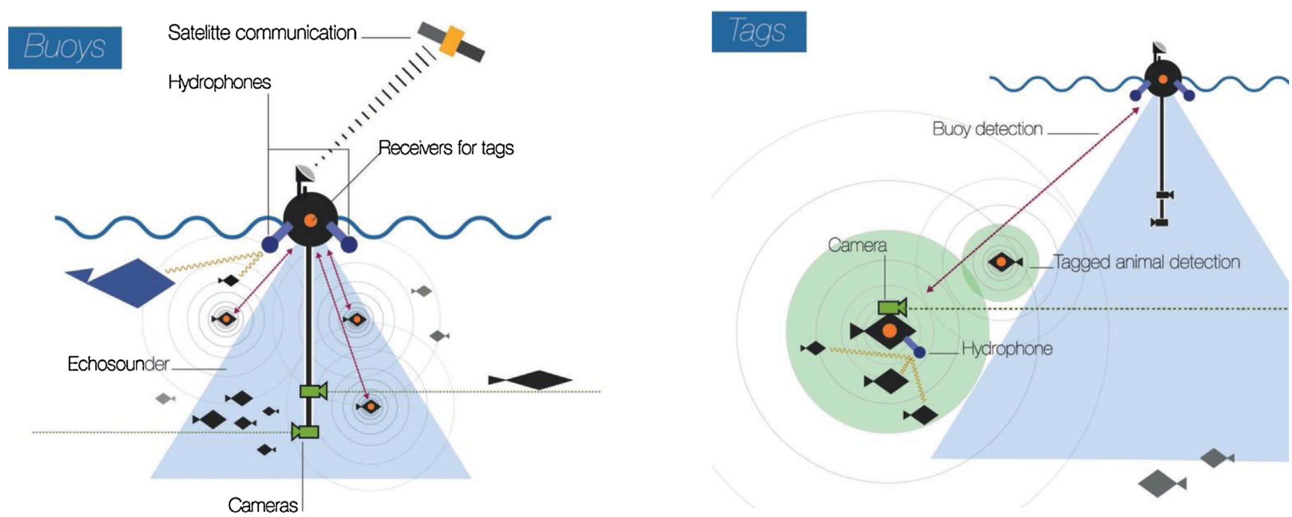

Fig. 3. Schematic diagram of the nodes that would form the observational network: buoys and tagged fauna.

clarifying the relationship between the associated biomass and the overall local population is key. Recently, Capello et al. (2013) proposed an integrated modelling approach that uses data collected around DFADs to derive relative and absolute abundance indices. This approach relies on measuring association times of fish at DFADS as well as the duration between consecutive associations, and couples this information with knowledge of the associated biomass at the DFADs (Fig. 3).

The area of the ocean populated with FADs is extensive in the tropical waters of all oceans. A scientific program alone could not achieve such spatio-temporal coverage, which underpins the concept presented in this paper. In our vision, this coverage is key, and a prerequisit for any scientific project that aims to monitoring the pelagic realm, and particularly the populations of large pelagic fish species. The key point in our approach is not controlling the numbers (therefore densities) of FADs (or keeping them constant) but rather knowing these numbers exactly, and the dynamics of the FADs at a fine spatio-temporal scale, in order to precisely characterize the densities of FADs. For this reason the cooperation with fishers, together with the quantification of the associative behavior of fish, is crucial.

In terms of areas not covered by FADs, the abundance estimates would follow the assumption of a single stock per ocean, as is the current practice in stock assessment approaches. Therefore, the abundance estimated in the region occupied by FADs would be directly related to the overall tuna abundance in each ocean. The sub-regions where the assessment of tuna populations through FADs will be operated would be determined by their FAD densities, since the number of FADs is a key factor in the abundance indicator. These sub-regions will potentially be different from the geographic sub-regions currently used in classical fisheries-based stock assessment.

The spatio-temporal variability in the DFAD array may also affect the associative behavior of tuna and consequently the ratio between the associated and total biomass. For this reason, the parallel monitoring of individual associative behavior of tuna through electronic tagging is necessary to guarantee scientifically-sound abundance indicators. When the fish behavior and the DFAD densities, as well as their variability, are jointly known and quantified, there is no bias in the derivation of the abundance index.

The technology to measure residency times of fish at FADs, as well as time between two associations, exists (Table 1). These variables can be collected by instrumenting individual fish with coded acoustic tags and equipping FADs with acoustic receivers, as demonstrated by Dagorn et al. (2007a) and Robert et al. (2013). While the measures of residency time at FADs does not necessitate the exhaustive instrumentation of all FADs in an area with acoustic receivers (see Ohta and Kakuma, 2005; Mitsunaga et al., 2012), measuring the time between two associations requires constraining protocol (Dagorn et al., 2007a; Robert et al., 2013). Because purse seiners often service their FADs, it is possible to use regular acoustic receivers that archive the acoustic detection data and can be downloaded when retrieved. In other cases, it is possible to use satellite-linked acoustic receivers (Dagorn et al., 2007b).

Alternatives exist when a species displays a vertical behaviour that significantly differs between periods of association and non-association. Such distinctions in behavioural patterns appear to be evident in the case of the bigeye tuna (Schaefer and Fuller, 2010). For these species, the use of archival tags (or pop-up archival tags) allows scientists to avoid having to attach acoustic receivers to every DFAD. However, for species that do not display such FAD-dependent vertical behaviour, or are too small to carry archival tags, it is essential that all FADs within an area are equipped with acoustic receivers.

However, due to the lack of full coverage of DFADs equipped with acoustic receivers, such coverage should be ensured during pilot studies, at least at the level of small areas, in order to assess the order of magnitude and the variability of duration of the non-associated phase of tuna. Such pilot studies, coupled with models, will allow for the estimation of the uncertainties due to the lack of full coverage. For example, models may produce different scenarios of tuna abundance, by considering variable amounts of time spent away from FADs.

Further technical developments based on the so-called 'business card tags' (Holland et al., 2009) (see next section), where tags would record the unique ID code emitted by other tags (that could be attached to buoys), may allow overcoming the full instrumentation of buoys through acoustic receivers.

4. Using FADs to monitor the movements of pelagic animals

An important advantage of DFADs as scientific platforms is that field data on the local associated population, fish movements and the environment can be simultaneously collected. Brill and Lutcavage (2001), clearly showed the importance of understanding the effect of the environment on fish behavior which is critical for robust population assessment, especially for the highly mobile top predators. Similarly, Soria et al. (2009) and Capello et al. (2011) demonstrated the importance of schooling behavior and social interactions in the spatio-temporal dynamics of fish around FADs. One of the major questions therefore concerns determining the effects of the environment, the conspecifics and allospecifics on the presence of fish at FADs, their residence times and their propensity to aggregate. In other words, under which conditions are tuna and other species found at DFADs? Do we find tunas associated with DFADs under very specific conditions, and if so, what are they?

Classically, scientists have used conventional dart tags to investigate the movements of pelagic species. However, although this method provides information on thousands of individuals, it only provides two points in the trajectory of the fish, and requires that each tagged individual is recaptured to collect the data. The emergence of archival tags, including archival pop-up tags, has revolutionized the investigation of large-scale movements of pelagic animals. However, the size of these tags currently prevents scientists from investigating the large-scale movements of small pelagic individuals (<100 cm FL for pop-up tags, and <60-cm FL for archival tags). Acoustic tags can be smaller and can be implanted in small individuals, such as small tunas, juvenile sharks, or species such as *Oceanic triggerfish* and *Rainbow runners*, which are major bycatch species of the purse seine fishery. Large-scale arrays of demersal acoustic receivers (usually on the bottom of the sea) exist in coastal areas (see the Ocean Tracking Network), but not in remote oceanic zones. Extending the large array of DFADs, by electronically tagged large pelagic fauna could address questions that remain unanswered regarding the movements of both tuna and non-tuna species. The concept would be the collection of complementary data on the spatio-temporal distribution of marine biodiversity through the development of new tags that can interact with and relay information to fisher's instrumented buoys (Fig. 3). These technologies generally function independently of fisheries but we believe that integrated systems, where tags and buoys interact, are key for assessing the spatial distribution of pelagic predators (Fig. 3). Thus, this approach represents a significant added observational capacity to the currently adopted separate view, where fishing platforms and tagged fish provide different, unrelated and limited information sets.

Simple coded ID tags could be used to provide the individual's identity. This could be scaled-up with the use of 'business card' concept, whereby the tag combines a small acoustic receiver to detect and record other tags during the migrations of the animals. The information stored in the tags could be relayed back to the buoy using acoustic communications (CHAT tag), a technology that has existed since the 1990's but not fully explored in this application.

The use of passive acoustic telemetry, i.e., receivers, to detect and collect data from electronically tagged animals would be a key aspect in the instrumented DFADs. Existing experience in pelagic acoustic telemetry could be customized, in order to scale up to an extensive large-scale acoustic detection network. To do this, the pivotal element would be the inclusion of acoustic receivers with the capacity to not only (i) detect the identity of the transmitter, that is the individual, but also (ii) to communicate with the tag (with a transducer) and receive stored information from it (including the identity of other tags collected by that tag). This would represent a very significant advancement in the current capacity of electronic tagging in providing a quantitative, large-scale detection network at the population level.

5. Using FADs to monitor the fish diversity of the pelagic realm

Fishers need to know the biomass and species composition at their DFADs, as accurately as possible. This is because their strategy consists of carefully planning which DFADs, from their ocean-wide network of DFADs to visit. The loss of time and cost of fuel (sometimes navigating for 2 days or more to a given DFAD) is high when reaching an unproductive DFADs. Thus, several years ago fishers began to show interest in having "eyes" at DFADs. Ideally these systems would provide them with information on the species composition of tunas, as well as the presence of other species that are not detected by an echo-sounder, such as sharks and other by-catch species that occupy the blind zone of the transducers. Just as they promoted the use of echo-sounder buoys in the past, they are also now focusing on the possibility of integrating cameras to identify species composition at DFADs.

Scientist would also benefit from visual observations at DFADs. Underwater visual census at FADs (anchored and drifting) by scientific divers have been successfully used to describe diversity of assemblages (Deudero et al., 1999; Dempster, 2005; Addis et al., 2006; Gaertner et al., 2008). Gaertner et al. (2008) advocated that sampling diversity at FADs was a suitable fisheries independent method for monitoring and study the diversity of pelagic fish communities. DFADs thus represent a unique opportunity to study pelagic fish diversity at a large scale. However traditional sampling techniques (UVC, Underwater visual census) or (fishing) are too labor intensive and are thus inappropriate to answer long term and large-scale questions concerning diversity patterns at an ocean scale. Recently, pelagic stereo-BRUVS (Baited Remote Underwater Video Stations) were used as a monitoring technique to study the effect of spatial area closures on pelagic fish assemblages (Santana-Garcon et al., 2014). While this sampling technique proved to be effective the experiment required considerable logistical effort as the units had to be deployed and recovered by scientist on a regular basis to collect the data. It is clear that technological advances are required to make such remote underwater video systems autonomous so that they can be used at a larger scale. The inclusion of automated remote underwater video systems to DFADs will allow the identification of associated species, their size and abundance. While echo-sounder buoys appear to be appropriate for collecting biomass of tunas aggregated at FADs, they would not provide abundance estimates for other associated species such as sharks, which are of major concerns for the sustainability of this fishery. There is currently no buoy that facilitates the assessment of the number of sharks associated with a FAD, some sharks should be detectable by an echo-sounder, especially when using multi-frequency systems, but such research has not yet been conducted on sharks found at FADs. These measures could be achieved by developing robotic cameras that can work from the buoys to observe the fauna beyond their immediate vicinity (Table 1).

This observation technique is complementary to echo-sounder buoy data in its ability to (i) distinguish species present at the FAD and (ii) provide the means to observe species that are otherwise difficult to observe using acoustics (e.g., sharks). Further technological improvements could include automated cameras equipped vehicles that can detach from the buoys to observe the fauna beyond the DFADs immediate vicinity in order to have a larger sampling area. The automated cameras equipped vehicles could also be triggered by specific sounds (e.g., cetaceans) or biomass threshold recorded by other sensors.

Studies investigating the fish diversity in pelagic ecosystems mainly used fisheries dependent datasets (Worm et al., 2003; Trebilco et al., 2011). While fisheries dependent data remain essential, fisheries independent methods are needed to better characterize the patterns of fish diversity in these ecosystems (Murphy and Jenkins, 2010).

6. Conclusion

The main challenge currently faced in marine science is the collection of large amounts of data and the development of new methods and models to assess the effects of climate change and anthropic pressure on the oceans. This challenge concerns fisheries scientists who are looking for new data on exploited species to complement traditional fisheries derived data in order to improve stock assessment (in particular for large predators such as tunas, sharks and billfishes) and find methods to mitigate adverse impacts of fisheries. It also concerns marine biologists and ecologists who study the pelagic biodiversity which remains poorly investigated, mainly due to the difficulties in accessing these ecosystems. Using scientific-observer records from pelagic longline fisheries in the Atlantic and Pacific oceans, Worm et al. (2003) could identify that individual hotspots for large marine predators correspond to prominent habitat features such as reefs, shelf breaks, or seamounts. Due to their capacity to attract and concentrate many marine species, DFADs should be added to this list of open ocean hotspots. The use of these DFADs as scientific platforms for studying pelagic ecosystems would represent a radical departure from the classic data collection methods that have proven to be increasingly incapable of providing pelagic realm data at the temporal and spatial scales necessary to address key questions. FADs are currently only used for fishing purposes but we consider that they can also serve for meeting the needs of scientists and fisheries managers.

There are already existing instruments, some of them with remote capabilities that could transform FADs into scientific platforms (see Table 1) and there is an opportunity to associate fishers to the challenges faced by scientists. Fishers already deploy, monitor and maintain large arrays of drifting FADs in all tropical oceans. They already equip their DFADs with echo-sounder buoys. Just as DFADs provide fishers with easier access to fish, these objects can provide access to data for scientists. The rapid technological advances that have occurred during recent years now make it possible to design and implement systems that can bridge the existing data gap and provide the critical fishery-independent data necessary for the sustainable management and conservation of the oceanic biodiversity.

The economic and human costs of research cruises and autonomous scientific platforms (e.g., buoys and gliders) limit their use. As an example, GOOS (Global Ocean Observing System) which is the oceanographic component of GEOSS (the Global Earth Observing System of Systems), maintains roughly 1250 drifting buoys and 200 moorings to collect oceanographic data worldwide. The estimates of the number of DFADs 50–100.000 (Baske et al., 2012) deployed and maintained by the purse seine fleet shows the great potential that FADs offer in terms of floating platforms dedicated to the observation of the ocean. Existing technology and ongoing research projects aimed at reducing the current knowledge gaps in species identification, make the use of DFADs as scientific platforms realistic possibility in the near future. Through an appropriate collaborative scheme between fishers, scientists and buoy manufacturers, and through pilot projects aimed at establishing calibration standards, sound design of data flows as well as the development of models to couple with acoustic data, scientists can now envisage large arrays of scientifically equipped DFADs that can provide unique data on pelagic animals and fish biodiversity of the open ocean. Fishers can become observers of the open ocean.

Acknowledgments

The views in this paper stem from different research projects on Fish Aggregating Devices, founded by European Union: FADIO (contract QLRI-CT-2002-02773), MADE (Mitigating Adverse Ecological Impacts of open ocean fisheries) funded by DG Research, collaborative project n°210496), GAP2 (Bridging the gap between science, stakeholders and policy makers). FP7-SCIENCE-IN-SOCIETY-2010-1, proposal no. (26654 4) and QUAESITUM (Marie Curie IEF, PEOPLE FP7).

References

Addis, P., Cau, A., Massutí, E., 2006. Spatial and temporal changes in the assemblage structure of fishes associated to fish aggregation devices in the Western Mediterranean. Aquat. Living Resour. 160, 149–160.

Amandè, M.J., Ariz, J., Chassot, E., et al., 2010. Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003–2007 period. Aquat. Living Resour. 23 (4), 353–362.

Anonymous, 2012. Report of the 2012 ISSF Stock Assessment Workshop: Understanding Purse Seine CPUE. ISSF Technical Report 2012–10. International Seafood Sustainability Foundation, Washington, D.C., USA.

Anonymous, 2014. IATTC Scientific and advisory committee fifth meeting. 12–16 May, La Jolla, California.

Baske, A., Gibbon, J., Benn, J., Nickson, A., 2012. Estimating the Use of Drifting Fish Aggregation Devices (fads) Around the Globe. PEW Environmental Group, pp. 8, discussion paper.

Branch, T.A., Hilborn, R., et al., 2006. Fleet dynamics and fishermen behavior: lessons for fisheries managers. Can. J. Fish. Aquat. Sci. 63 (7), 1647–1668.

Brehmer, P., Josse, E., Nøttestad, L., 2012. Evidence that whales (*Balaenoptera borealis*) visit drifting fish aggregating devices: do their presence affect the processes underlying fish aggregation? Mar. Ecol. 33, 176–182.

Brill, R., Lutcavage, M., 2001. Understanding environmental influences on movements and depth distributions of tunas and billfishes can significantly improve population assessments. American Fisheries Society Symposium, American Fisheries Society.

Capello, M., Soria, M., Cotel, P., Deneubourg, J.L., Dagorn, L., 2011. Quantifying the interplay between environmental and social effects on aggregated-fish dynamics. PLoS One 6 (12).

Capello, M., Deneubourg, J.L., Robert, M., Holland, K., Schaefer, K., Dagorn, L., 2013. A new fisheries independent method to estimate abundances of tropical tunas. IOTC. Tech. Rep., WPTT15-12.

Capietto, A., Escalle, L., Chavence, P., Dubroca, L., Delgado de Molina, A., et al., 2014. Mortality of marine megafauna induced by fisheries: insights from the whale shark. Biol. Conserv. 174, 147–151.

Castro, J., Santiago, J., Santana-Ortega, A., 2002. A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. Rev. Fish Biol. Fish. 11, 255–277.

Cillaurren, E., 1994. Daily fluctuations in the presence of *Thunnus albacares* and *Katsuwonus pelamis* around fish aggregating devices anchored in Vanuatu, Oceania. Bull. Mar. Sci. 55 (2–3), 581–591.

Dagorn, L., Holland, K.N., Itano, D.G., 2007a. Behavior of yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) tuna in a network of fish aggregating devices (FADs). Mar. Biol. 151, 595–606.

Dagorn, L., Holland, K., Dalen, J., Brault, P., Vrignaud, C., Josse, J., Moreno, G., Brehmer, P., Nottestad, L., Georgakarakos, S., Trigonis, V., Taquet, M., Aumeeruddy, R., Girard, C., Itano, D., Sancho, G., 2007b. New instruments to observe pelagic fish around FADs: satellite-linked acoustic receiver and buoys with sonar and cameras. In: Lyle, J.M., Furlani, D.M., Buxton, C.D. (Eds.), Cutting-edge Technologies in Fish and Fisheries Science. Australian Society for Fish Biology Workshop Proceedings. Hobart, Tasmania, August 2006, Australian Society for Fish Biology.

Dagorn, L., Holland, K.N., Restrepo, V., Moreno, G., 2012. Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems? Fish Fish. 14, 391–415.

Dempster, T., 2005. Temporal variability of pelagic fish assemblages around fish aggregation devices: biological and physical influences. J. Fish Biol. 66, 1237–1260.

Deudero, S., Merella, P., Morales-Nin, B., Massutí, E., Alemany, F., Massutí, E., Alemany, F., 1999. Fish communities associated with FADs. Sci. Mar. 63, 199–207.

Filmalter, J.D., Dagorn, L., Cowley, P.D., Taquet, M., 2011. First descriptions of the behavior of silky sharks, *Carcharhinus falciformis*, around drifting fish aggregating devices in the Indian Ocean. Bull. Mar. Sci. 87 (3), 325–337.

Filmalter, J.D., Capello, M., Deneubourg, J.-L., Cowley, P.D., Dagorn, L., 2013. Looking behind the curtain: quantifying massive shark mortality in fish aggregating devices. Front. Ecol. Environ. 11, 291–296.

Fonteneau, A., Gaertner, D., Nordstrom, V., 1999. An overview of problems in the catch per unit of effort and abundance relationship for the tropical purse seine fisheries. Col. Vol. Sci. Pap. ICCAT 49 (3), 258–278.

Fonteneau, A., Chassot, E., Bodin, N., 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): taking a historical perspective to inform current challenges. Aquat. Living Resour. 26, 37–48.

Fréon, P., Misund, O.A., 1999. Dynamics of Pelagic Fish Distribution and Behaviour: Effects on Fisheries and Stock Assessment. Blackwell Science, Oxford (UK).

Gaertner, J., Taquet, M., Dagorn, L., Mérigot, B., Aumeeruddy, R., Sancho, G., Itano, D., 2008. Visual censuses around drifting fish aggregating devices (FADs): a new approach for assessing the diversity of fish in open-ocean waters. Mar. Ecol. Prog. Ser. 366, 175–186.

Hall, M.A., Alverson, D., Metuzals, I., 2000. By-catch: problems and solutions. Mar. Pollut. Bull. 41, 204–219.

Handegard, N.O., Buisson, L., d, Brehmer, P., Chalmers, S.J., De Robertis, A., Huse, G., Kloser, R., Macaulay, G., Maury, O., Ressler, P.H., Stenseth, N.C., Godø, O.R., 2013. Towards an acoustic-based coupled observation and modelling system for monitoring and predicting ecosystem dynamics of the open ocean. Fish Fish. 14 (4), 605–615, http://dx.doi.org/10.1111/j.1467-2979.2012.00480.x.

Holland, K., Klieber, P., Kajiura, S.M., 2009. Different residence times of yellowfin tuna, *Thunnus albacares*, and bigeye tuna, *T. obesus* found in mixed aggregations over a seamount. Fish. Bull. 97, 392–395.

Kingsford, M.J., 1993. Biotic and abiotic structure in the pelagic environment: importance to small fishes. Bull. Mar. Sci. 53 (2), 393–415.

Leroy, B., Phillips, J.S., Nicol, S., Pilling, G.M., Harley, S., Bromhead, D., Holey, S., Caillot, S., Allain, V., Hampton, J., 2013. A critique of theecosystem impacts of drifting and anchored FADs use by purse-seine tuna fisheries in the Western and Central Pacific Ocean. Aquat. Living Resour. 26, 49–61.

Lopez, J., Moreno, G., Sancristobal, I., Murua, J., 2014. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fish. Res. 155, 127–137.

Marsac, F., Fonteneau, A., Ménard, F., 2000. Drifting FADs used in tuna fisheries: an ecological trap. In: Le Gall, J.Y., Cayré, P., Taquet, M. (Eds.), Pêche Thonière et Dispositifs de Concentration de Poissons, 28. Actes Colloques-IFREMER, pp. 537–552.

Maufroy, A., Bez, N., Kaplan, D.M., Delgado de Molina, A., Murua, H., Chassot, E., 2014. How many fish aggregating devices are currently driftingin the Indian Ocean? Combining sources of information to provide a reliable estimate. IOTC. Tech. Rep., WPTT16-21.

Maunder, M.N., Punt, A.E., 2004. Standardizing catch and effort data: a review of recent approaches. Fish. Res. 70 (2–3), 141–159.

Mitsunaga, Y., Endo, C., Anraku, K., Selorio, C.M., Babaran, R.P., 2012. Association of early juvenile tuna *Thunnus albacares* with a network of payaos in the Philippines. Fish. Sci. 78, 15–22.

Moreno, G., Dagorn, L., Sancho, G., Itano, D., 2007a. Fish behaviour from fishers knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). Can. J. Fish. Aquat. Sci. 64, 1517–1528.

Moreno, G., Josse, E., Brehmer, P., Nottestad, L., 2007b. Echotrace classification and spatial distribution of pelagic fish aggregations around drifting fish aggregating devices (DFAD). Aquat. Living Resour. 20 (04), 343–356.

Murphy, H.M., Jenkins, G.P., 2010. Observational methods used in marine spatial monitoring of fishes and associated habitats: a review. Mar. Freshw. Res. 61, 236.

Ohta, I., Kakuma, S., 2005. Periodic behavior and residence time of yellowfin and bigeye tuna associated with fish aggregating devices around Okinawa Islands, as identified with automated listening stations. Mar. Biol. 146, 581–594.

Robert, M., Dagorn, L., Denebourg, J.L., Itano, D., Holland, K., 2012. Size-dependent behavior of tuna in an array of fish aggregating devices (FADs). Mar. Biol. 159 (4), 907–914.

Robert, M., Dagorn, L., Filmater, J.D., Denebourg, J.L., Itano, D., Holland, K., 2013. Intra-individual behavioral variability displayed by tuna at fish aggregating devices (FADs). Mar. Ecol. Prog. Ser. 484, 239–247, http://dx.doi.org/10.3354/meps10303.

Romanov, E.V., 2002. Bycatch in the tuna purse-seine fisheries of the western Indian Ocean. Fish. Bull. 100 (1), 90–105.

Royer, F., Fromentin, J.M., Gaspar, P., 2004. Association between bluefin tuna schools and oceanic features in the western Mediterranean. Mar. Ecol. Prog. Ser. 269, 249–263, http://dx.doi.org/10.3354/meps269249.

Santana-Garcon, J., Newman, S.J., Harvey, E.S., 2014. Development and validation of a mid-water baited stereo-video technique for investigating pelagic fish assemblages. J. Exp. Mar. Bio. Ecol 452, 82–90.

Schaefer, K., Fuller, D., 2010. Vertical movements, behavior, and habitat of bigeye tuna (*Thunnus obesus*) in the equatorial eastern Pacific Ocean, ascertained from archival tag data. Mar. Biol. 157, 2625–2642.

Soria, M., Dagorn, L., Potin, G., Freon, P., 2009. First field-based experiment supporting the meeting point hypothesis for schooling in pelagic fish. Anim. Behav. 78, 1441–1446.

Taquet, M., Sancho, G., Dagorn, L., et al., 2007. Characterizing fish communities associated with drifting fish aggregating devices (FADs) in the Western Indian ocean using underwater visual surveys. Aquat. Living Resour. 30, 331–341.

Trebilco, R., Halpern, B.S., Flemming, J.M., Field, C., Blanchard, W., Worm, B., 2011. Mapping species richness and human impact drivers to inform global pelagic conservation prioritisation. Biol. Conserv. 144, 1758–1766.

Worm, B., Lotze, H.K., Myers, R., 2003. Predator diversity hotspots in the blue ocean. Proc. Natl. Acad. Sci. U. S. A. 100, 9884–9888.