Marine Policy 45 (2014) 163–170

Contents lists available at ScienceDirect

Marine Policy

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

The past, present and future use of drifting fish aggregating devices (FADs) in the Indian Ocean

Tim K. Davies [a,*], Chris C. Mees [b], E.J. Milner-Gulland [a]

[a] Imperial College London, Silwood Park Campus, Ascot, Berkshire SL5 7P7, UK
[b] MRAG Ltd., 18 Queen Street, London W1J 5PN, UK

ARTICLE INFO

Article history:
Received 11 September 2013
Received in revised form
17 December 2013
Accepted 21 December 2013
Available online 14 January 2014

Keywords:
Tropical tuna
Purse seine
Fleet dynamics
Implementation error
Management evaluation
Bycatch

ABSTRACT

The use of drifting fish aggregating devices (FADs) has become the dominant practice in tropical tuna purse seine fishing. However, just as FADs can increase fishing efficiency, their use has been associated with several negative ecosystem impacts, and moves are being made to manage the use of FADs. In the evaluation of potential management options it is important to consider how fishers will respond to the introduction of control measures, which first requires an understanding of fishery and fleet dynamics. This paper addresses this need by characterising the past and present use of FADs in the Indian Ocean tropical tuna purse seine fishery. The paper describes historical trends in fishing practices, summarises spatiotemporal patterns in the use of FADs and establishes and attributes variation in FAD fishing strategies within the fleet. It also provides an overview of current FAD management policies in the Indian Ocean and examines the observed effects of existing measures on the behaviour of the purse seine fleet. Using this comprehensive understanding, the potential impact on the purse seine fleet of a number of plausible FAD management options are discussed and inferences are drawn for the future sustainability of tropical tuna purse seine fishing in the Indian Ocean.

1. Introduction

In the open ocean many species, including tunas, associate with objects drifting on the surface, such as logs or branches [1]. This is highly advantageous to purse seine fishing as floating objects aggregate sparsely distributed schools, are more easily spotted than tuna swimming freely beneath the surface, stabilise schools and reduce the speed at which they travel, making them comparatively easy to catch [2,3]. Consequently, fishing around floating objects is associated with a higher successful haul, or 'set', rate than targeting free swimming schools [2,4]. In the mid-1980s skippers started experimenting with ways to maximise the potential of floating objects as fishing tools. Initially, reflectors and radio beacons were attached to logs to improve their detection over greater distances and fishers eventually started constructing purpose built drifting fish aggregating devices (FADs; Fig. 1) fitted with electronic buoys to simultaneously boost the number of floating objects in the ocean and further aid their detection.

The development of FADs has dramatically improved the searching efficiency of purse seiners and today approximately half of the global tuna catch comes from this fishing practice [3]. FADs can be located quickly, minimising search time and operating costs, and because they can be located at any time of the day using a computer screen they can be can fished on at dawn (unlike free-swimming schools which must be located in daylight hours). The most recent generation of FADs are equipped with echosounders that transmit daily or hourly estimates of biomass beneath the buoy, allowing skippers to confirm the presence of a school beneath a FAD before visiting it, and in some oceans (e.g. Atlantic and Indian oceans), auxiliary supply vessels are allied with purse seine skippers and used to deploy and monitor FADs using sonar and other fish-finding technologies [5].

Whilst FADs are evidently useful fishing tools, their use has been associated with several potential negative ecosystem impacts, including catch of juvenile tunas and bycatch of vulnerable non-target species [6–8]. Furthermore, there is concern that the highly efficient practice of FAD fishing, if left unchecked, might exacerbate issues of overcapacity and ultimately lead to the unsustainable exploitation of tuna stocks [2,9]. There is currently little control on the use of FADs in purse seine fisheries and there has been increasing discussion within tuna Regional Fisheries Management Organisations (tRFMOs) on managing their use more

* Corresponding author. Tel.: +44 20 7594 2429.
E-mail addresses: timothy.davies08@imperial.ac.uk (T.K. Davies), c.mees@mrag.co.uk (C.C. Mees), e.j.milner-gulland@imperial.ac.uk (E.J. Milner-Gulland).

0308-597X
http://dx.doi.org/10.1016/j.marpol.2013.12.014

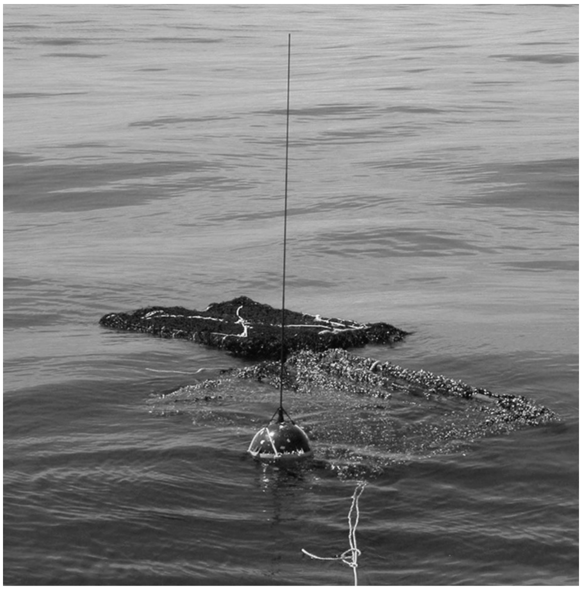

Fig. 1. A typical FAD constructed from a bamboo raft with netting hung beneath and a buoy fitted with location-tracking technology. Photo copyright: FADIO/IRD-Ifremer/B. Wendling.

strictly [9]. So far, this discussion has served mainly to highlight uncertainties in our understanding of the sustainability of catches on FADs and the consequences of modification of the pelagic habitat on tuna biology but has also begun to tentatively explore the impact of potential management solutions on purse seine catches [9–12].

Consideration of potential management must also consider how fishers will respond to the introduction of management measures [13,14]. It is widely recognised that designing fisheries management with the behaviour of fishers explicitly accounted for can reduce the risk of implementation error, i.e. where management outcomes deviate from those intended [15]. In considering how purse seine fleets will respond to controls on the use of FADs it is necessary to have an understanding of the role FADs play in fleet dynamics, from long term trends in fleet characteristics to how effort is allocated in space. Yet, despite the importance of understanding the role of FADs in driving these dynamics, to date this topic has received much less attention than the ecological issues associated with the use of FADs.

This paper characterises the past and present use of FADs in the Indian Ocean tropical tuna purse seine fishery. First, the potential ecological impacts of FADs are summarised (see [5] for a full review). Next, the role of FADs in the development of the Indian Ocean purse seine fishery is discussed, spatio-temporal patterns in their use are characterised, and their influence on effort allocation dynamics is examined. Finally, the potential impact of a number of plausible FAD management options on the purse seine fleet is discussed and inferences are drawn for the future sustainability of tropical tuna purse seine fishing in the Indian Ocean.

2. Ecological impacts associated with fishing on FADs

2.1. Impacts on tuna stocks

Floating objects have facilitated extremely high catches of tuna in every ocean, including the Indian Ocean, and potentially have two types of impact on tuna stocks [2]: overfishing (a reduction in spawning stock biomass) and a loss in potential yield (catching smaller fish and reducing the number of large breeding individuals in the stock). The extent of these impacts is complicated by differences in the resilience of the three main species of tropical tunas caught in purse seine fisheries. Fishing on floating objects is mainly associated with skipjack tuna *Katsuwonus pelamis*, which makes up 57–82% of the catch using this fishing practice across all four oceans [5]. Skipjack tuna is a fast growing, highly fecund species and is generally thought to be resilient to fishing [16] and although the use of FADs has increased dramatically since the 1990s, skipjack tuna are not currently considered to be overfished in any ocean. Whilst this suggests that the use of FADs does not in itself result in overfishing of skipjack stocks, there is concern that this situation might change with continued increase in exploitation rates using FADs in the future [17].

The proportions of yellowfin *Thunnus albacares* and bigeye tuna *T. obesus* in catches on floating objects are smaller (typically 14–25% and 4–28% respectively; [5]), although these are mostly small or juvenile fish [6] and as such these species are thought to have less resilience to FAD fishing. Whilst stocks of yellowfin and bigeye have been overfished in some oceans it is difficult to assess the role of FADs in this overfishing as there is no obvious pattern between the relative magnitude of the catch on floating objects and whether a stock is overfished [5,18]. Catches of small individuals might also result in a loss of potential yield through a reduction in the number of large spawning fish in the stock (i.e. lower yield per recruit). However, again the evaluation of these negative effects is difficult due to uncertainty in growth rates and natural mortality of juvenile tunas and currently no definite conclusion can be drawn [9].

2.2. Impacts on non-target species

A more tangible ecological impact associated with FAD fishing is bycatch of non-target species. Over time floating objects attract whole communities of non-target species that can also be taken as part of the purse seine catch [6,19,20]. Fishing on free-swimming schools is comparatively more selective, with bycatch 2.8–6.7 times lower than sets on floating objects [5]. Majority of the non-target species caught incidentally around floating objects are small tunas and other bony fishes [7–8,20]. Many of these species are known to be fast growing and have high fecundity (see [5] for references) and thus their vulnerability to incidental capture around FADs is likely to be low. However, sharks, rays and billfishes are also commonly taken as bycatch and are considered to have much higher vulnerability to fishing [7,8]. Shark bycatch on FADs is almost exclusively composed of two species; silky sharks *Carcharhinus falciformis* and oceanic white tip sharks *Carcharhinus longimanus*, together comprising over 90% of the shark bycatch by number [21]. As with many sharks, these species have slow growth rates, mature late and have long reproductive cycles with few offspring, and as such are highly susceptible to population decline from excessive fishing pressure [22]. FADs in particular are also associated with the mortality of sharks and turtles through entanglement with the net hanging beneath a raft (i.e. ghost fishing), although the extent of this mortality is not usually estimated [23].

2.3. Impacts on tuna habitat

The reason for the natural aggregation of tunas beneath floating objects is not entirely clear although the two most credible explanations for this behaviour are the meeting point hypothesis [24] and the indicator-log hypothesis [19]. The meeting point hypothesis suggests that fish associate with floating objects to facilitate schooling behaviour and subsequently benefit from this social interaction whilst the indicator-log hypothesis suggests that natural floating objects are indicators of productive habitat given

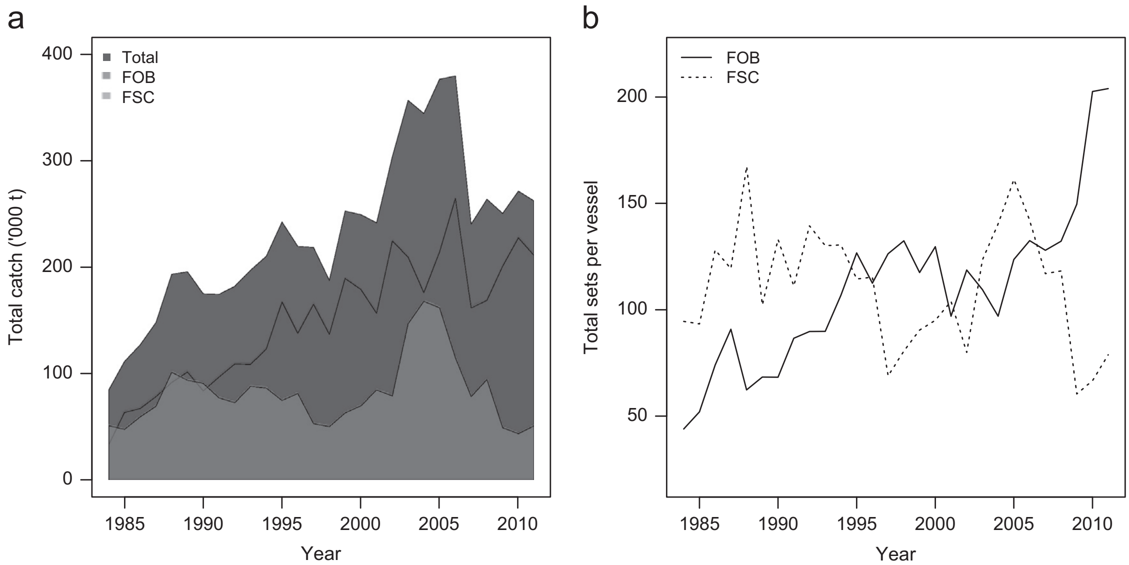

Fig. 2. Trends in (a) total catch on floating object sets (FOB) and free school sets (FSC) of three main tropical tuna species (yellowfin, skipjack and bigeye tuna) in the Indian Ocean and (b) total number of sets per vessel by fishing practice over the history of the tuna purse seine fishery in the Indian Ocean. Data from [4].

that they originate from nutrient-rich areas (e.g. river mouths, mangrove swamps) and subsequently drift with these patches of productivity into the ocean.

Given these possible explanations for the association of tunas with floating objects there is concern that the deployment of large numbers of FADs in the pelagic ocean could change the natural environment of tunas, a theory known as the 'ecological trap hypothesis' [25,26]. Large numbers of floating objects could potentially modify the movement patterns of tunas and carry associated schools in ecologically unsuitable areas and thus affect their growth rate or increase natural mortality and/or predation [26,27]. Although this subject has received considerable research attention, it is difficult to evaluate the impacts of FADs on the ecology of tunas, largely due to uncertainty in how tunas interact with floating objects (e.g. length of association, reasons for joining/leaving an object). Consequently the ecological trap hypothesis remains open to discussion [5,9].

3. FAD fishing in the Indian Ocean

3.1. Spatiotemporal patterns of FAD fishing

FADs have had a strong influence in shaping the spatial dynamics of the purse seine fishery. Floating objects are not distributed evenly throughout the western Indian Ocean and their location at any given time is determined largely by surface currents and winds. Floating logs and branches generally originate from large rivers and mangrove systems and drift with the currents throughout the coastal waters and potentially further offshore. This natural flotsam, which has always been a part of the ocean habitat of tuna, accumulates at particularly high densities in the Mozambique Channel where numerous river systems wash debris into the ocean [28]. Logs also occur in certain offshore regions of the western Indian Ocean, particularly within the large ocean gyres to the east of Somalia, but typically at lower densities [28]. It is in these areas where natural floating objects are less abundant that fishers have subsequently deployed the greatest number of artificial objects. FADs have a short life time (generally <6 months; [29]) and can sink or be appropriated by other vessels. Thus skippers constantly deploy new FADs or relocate older FADs (e.g. objects that have drifted into areas with poor fishing opportunities) and in doing so have effectively created a perpetual artificial floating object habitat across much of the northwest Indian Ocean.

Seasonal patterns of fishing activity by the purse seine fleet follow a roughly cyclical movement around the western Indian Ocean that is largely influenced by the distribution of floating objects and by seasonal changes in fishing opportunities (T. Davies; unpublished data). The main FAD-fishing season extends from August to November and the fleet fishes predominantly in the northwest Indian Ocean to the east of Somalia. Although this northwest region is reasonably small, catches are high and almost exclusively made on floating objects. The use of FADs in particular has consistently been high in this sector with a northwards extension of the fleet in the Arabian Sea region during the mid-1990s. It is interesting to note that these new northerly fishing grounds were discovered by FADs fitted with satellite buoys drifting into previously unfished (but productive) areas [29].

As primary productivity levels fall from November, catch rate on FADs decreases and the fleet moves into the equatorial Indian Ocean (southeast Seychelles and Chagos regions) in search of free-swimming schools. At this time schools of yellowfin and bigeye tunas are generally feeding or spawning near the surface and thus are easier to find and catch [30]. However, the spatial distribution of schools can vary considerably and as a result there is marked variation in the proportion of catches on free schools in the Chagos region during this period; vessels enter the region to search for free schools but will also fish on FADs where available, resulting in a higher proportion of FAD catches when free schools are scarce.

From March to July the fleet fishes mainly in the Mozambique Channel and northwest Seychelles region using a mixed strategy of floating objects (both natural and artificial) and free school sets. As there has always been an abundance of natural floating objects in this region [31] the proportion of catch on floating objects has always been reasonably high and the deployment of FADs has been more limited than further north in the Somali region.

3.2. Historical trends in FAD fishing

Although no distinction is made in the data, up until the late 1980s 'floating objects' are generally considered to be have been natural flotsam [3]. In this early period of the fishery the proportion of total catch from sets on free schooling tuna and floating objects was roughly equal (Fig. 2a). However, skippers were making a considerably higher number of sets on free schools (Fig. 2b) but with a much lower success rate than sets on floating objects (46% versus 89% success rate respectively during the period 1984–1990; data from [4]). The advantages of fishing on floating objects were obvious to skippers and fishing companies, yet opportunities to fish using this setting method were limited by the number of floating objects in the ocean. In order to continue the growth of the fishery it was necessary to generate more fishing opportunities and skippers realised that, whilst they could not influence the number of free-swimming schools, they could feasibly provide a greater number of floating objects for schools to associate with. Thus, the intensive use of purpose-built FADs began in the early 1990s and catches on floating objects increased steadily through the 1990s and 2000s.

The increasing use of FADs improved catch rates and greatly enhanced the productivity of the fishery, allowing boat owners to build the capacity of their fleets in an attempt to exploit more of the resource. Throughout the 1990s and early 2000s French and Spanish fishing companies invested in larger purse seine vessels, which offered numerous commercial advantages including the ability to make extended fishing trips with larger fish-wells [32]. The development of the fleet included the construction of several 'super-seiners' (> 2000 gross tonnage; GT) and even 'super super-seiners' (> 3500 GT) and the increasing trend in capacity matched the proliferating use of FADs (Fig. 3). However, because larger vessels are more sensitive to increasing operating costs (e.g. fuel price; [2]) it was necessary for fishing companies to adopt increasingly competitive fishing strategies to achieve high annual catch thresholds (e.g. circa 15–20,000 t; A. Fonteneau, personal communication). Consequently, the purse seine fishery has become increasing reliant on the use of FADs to achieve the very large catches needed to remain profitable [32,33].

Against the background trend in fishing capacity two episodes in particular show that other factors have an important effect on the relative use of FADs in the Indian Ocean. In the early 2000s the long-term increasing trend in the number of floating object sets flattened out and there was a clear spike in the number of sets made on free schools (Fig. 2b). This switch in the predominant fishing practice is thought to be explained by the comparatively high abundance of free-swimming tuna schools during 2003–2005, linked to increased availability of prey species as a result of higher-than-average primary productivity in the western Indian Ocean and greater vulnerability of schools to purse seine gear due to a shoaling of the thermocline [30].

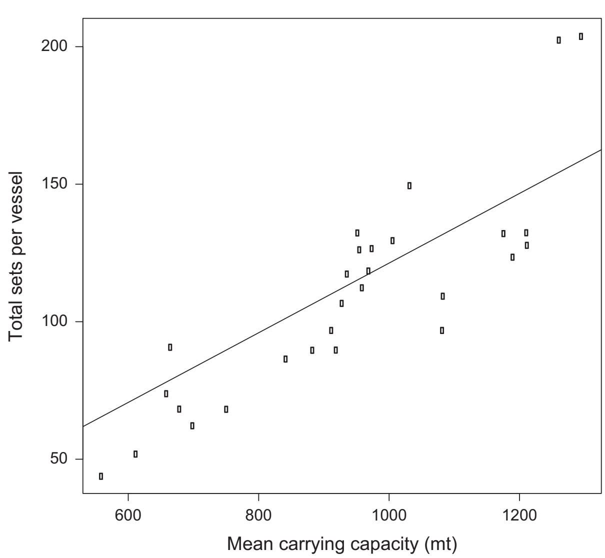

Fig. 3. Relationship between number sets of floating objects per vessels per year and mean annual carrying capacity over the period 1984–2011. Pearson product–moment correlation, $P<0.001$, $r=0.86$, $n=28$. Data from [4].

During this period fishing companies moved vessels into the Indian Ocean from the Atlantic to capitalise on this boom (J.J. Areso, Spanish fleet representative, personal communication), temporarily increasing both the total capacity of the fleet [4] and also the relative proportion of free schools sets (Fig. 2b).

In the late 2000s there was a sharp increase in the number of floating object sets per vessel (Fig. 2b) attributed largely to the impact of piracy on purse seine operations. In 2008–2010, approximately a third of the fleet, mainly comparatively smaller French vessels, moved from the Indian Ocean to the Atlantic due to the threat of piracy [4,34], leaving behind larger vessels predisposed to target mainly FADs due to their size. Furthermore, these vessels were restricted in their activity through the requirement to carry security personnel on board (and for a short while, in the case of the French fleet, vessels were also required to fish in pairs), making it more difficult to search for free schooling tunas and ultimately increasing effort on FADs [34].

Interestingly, the relative price of skipjack, the main species caught on FADs, appears to have had little influence on the propensity of the fleet to fish on FADs. In a study of what makes a 'FAD-fisher', Guillotreau et al. [33] found that knowledge of yellowfin and skipjack price had little influence on a skipper's decision making. Instead, skippers generally aimed to fill their fish-wells as quickly and as full as possible regardless of the species.

3.3. Variation in FAD fishing between fleets

In the Indian Ocean there is some variation in the FAD fishing activity of the two major nationalities operating purse seine vessels in the fishery, France and Spain, largely due to different strategic standpoints regarding the use of FADs since the 1990s [29,33] and the physical characteristics of their vessels, with Spanish vessels typically being much larger than those in the French fleet (e.g. 30% larger in 2008; see [32]). This is apparent in the number of individual FADs deployed and monitored by the two fleets, with Spanish vessels deploying a greater number of FADs than French vessels (~100 versus ~30 per vessel respectively; [33]). Furthermore, although FADs generally 'belong' to an individual skipper (i.e. only they can track a particular buoy), in the Spanish fleet skippers may pool FADs and thus increase their overall opportunity to fish on floating objects [29].

In addition to the greater number of FADs available there is also a suggestion that skippers in the Spanish fleet are generally 'better' at fishing on FADs [29]. While fleets made approximately the same number of sets on floating objects per vessel (despite differences in the number of FADs deployed), the Spanish fleet had a higher catch rate using this fishing practice, which was particularly pronounced during the 1990s (Fig. 4). This is largely due to operational differences between the fleets. Firstly, the Spanish fleet typically deploys satellite and sonar buoys (as opposed to GPS buoys) which have no antenna and as a consequence are harder to find by chance by competing vessels . Secondly, unlike the French fleet, many Spanish vessels are assisted by supply vessels that deploy, maintain, check and often guard FADs until the catcher vessel arrives [35], considerably improving the efficiency of FAD fishing for these vessels. Lastly, as FAD and free school fishing require different knowledge and skill sets there is some suggestion that a skipper effect explains the difference between the fleet activities, with Spanish skippers appearing to have more developed FAD fishing skills [29,33].

4. Management of FAD fishing

4.1. Generating more data

Much of the concern surrounding FAD fishing stems from uncertainty around their ecological impacts. In order to quantitatively assess

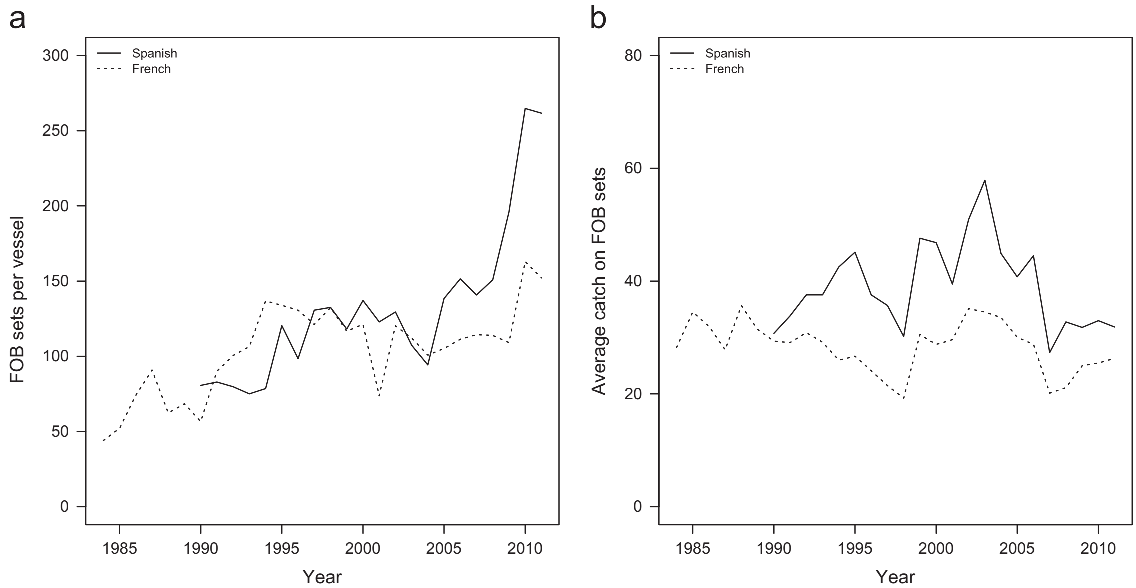

Fig. 4. Trends in (a) the number of sets on floating objects (FOB) per vessel by the French and Spanish fleet and (b) average catch per vessel on floating object sets by fleet nationality over the history of the tuna purse seine fishery in the Indian Ocean. Data from [4].

the impact of FADs and to consider potential management options, it is necessary to generate more data on how, where and why they are used. This urgent need for more data on the use of FADs in purse seine fisheries in all oceans was highlighted at the most recent joint meeting of the tRFMOs (Kobe III) in La Jolla 2011, with two types of information on FADs considered to be pertinent; an inventory and activity record of FADs ('FAD logbook') and a record of encounters with FADs by fishing and supply vessels ('fishing logbook'). In recognition of this need for better data, IOTC has recently revised and improved its reporting requirements for FADs under Resolution 10/02, which were previously considered ambiguous and insufficient to comprehensively record the practise of FAD fishing. These new and more detailed requirements include reporting the unique identifier, position, type and construction of the FAD fished on. The use of supply vessels, including the number of associated catcher vessels and number of days at sea, must also be reported. In addition, in 2012 IOTC adopted a entirely new resolution (Resolution 12/08; http://www.iotc.org/English/resolutions.php; accessed 1st June 2013) setting out the requirement for fleets to develop and submit FAD Management Plans by late 2013. This resolution, which again not only requires fishing companies to provide highly detailed information on their use of FADs but also apportions responsibility in managing their use, represents an important step towards regulating the practise of FAD fishing in the IOTC convention area, although it falls short of outlining any restrictions on their use.

The European tuna purse seine fishing industry appears to have a proactive attitude towards developing management plans and generating additional data on the use of FADs. Since the mid-2000s French and Spanish fishing organisations and have been working in collaboration with their respective national scientific institutes (and independently with organisations such as the International Seafood Sustainability Foundation, ISSF) to improve the data available on FAD fishing and to also innovate FAD technologies. In particular, the European purse seine industry has been constructive in developing and deploying so-called 'eco-FADs', which are designed using rolled nets or ropes rather than open mesh panels to minimise entanglement of sharks and turtles [5]. This cooperation by the industry is likely to be inspired in part by the desire to improve the public perception of purse seine fishing, with environmental organisations generally interpreting a lack of data as bad news. There has been strong pressure applied on seafood brands by the environmental lobby to source from non-FAD fisheries and several of the major seafood suppliers have already begun to move in this direction (see http://www.greenpeace.org.uk/tunaleaguetable for a league table of suppliers). Furthermore, improving data collection and adopting technical measures like eco-FADs has been relatively painless to the fishing industry and is likely to have negligible financial cost. It is assumed that fishing companies prefer these soft measures that will improve understanding of the impact of FADs over more restrictive management measures.

4.2. Existing management measures

Given the uncertainty surrounding the ecological impacts of FADs there is a reasonable argument for tRFMOs to take a precautionary approach and make moves to manage the use of FADs more strictly. Whilst improvements in the design and construction of FADs can certainly play a role in reducing ghost fishing and bycatch [21], other measures that control fishery input are necessary to reduce the total catch taken by the purse seine fleet on FADs [36]. These measures might potentially include effort controls such as area closures, limits on the number of monitored buoys or limits on the total number of sets on FADs, although to date only area closures have been widely implemented [37]. However, a major management challenge is to achieve meaningful reductions in bycatch and catches of tuna species thought to be vulnerable to overfishing (i.e. bigeye and yellowfin tunas) whilst not significantly reducing catches of skipjack, which are not currently considered overfished.

In the Indian Ocean the most significant restriction on FAD fishing has been a time-area closure, implemented in November 2011 and again in 2012, with the objective to reduce the mortality of juvenile bigeye and yellowfin tunas (Resolution 10/01; http://www.iotc.org/English/resolutions.php; accessed 1st June 2013). This no-take area covered a large proportion of the northwest Somali Basin region towards the end of the FAD-fishing season. However, a preliminary evaluation of the first year of this closure using the IOTC catch data, presented in Table 1, suggests that it had mixed results in reducing total annual catches of bigeye and yellowfin on FADs. Taking into account the reduced total fishing effort in 2011, catches of bigeye tuna on floating objects were reduced by only a small amount during the

Table 1
Comparison of catches of the three principal target species taken on floating object sets during the closure period and the whole year when the closure was implemented compared to the reference period 2009–2010. Catches are expressed as catch per fishing day to account for changes in total effort. Data from the IOTC catch and effort database.

	Fishing effort (days)	Catch rate by species (t day^{-1})		
		Bigeye	Yellowfin	Skipjack
Closure period (November 2011)				
2008–2010	798	1.7	6.0	13.2
2011	666	1.3	8.3	11.3
Difference		−0.4%	2.3%	−2.0%
Full year (2011)				
2008–2010	10,419	1.7	5.0	12.4
2011	9718	1.6	7.8	12.4
Difference		−0.2%	2.8%	0.0%

period of closure and over the whole year, compared to the period 2008–2010, whereas catches of object-associated yellowfin actually increased. Catches of skipjack were reduced slightly during the closure period but there was no overall reduction in the annual catch (Table 1). This limited effect of area closure on catches of yellowfin and bigeye tunas was largely due to the reallocation of fishing effort into adjacent areas to the south and east of the closure where the fleet could continue to fish with reasonable efficiency using FADs. Furthermore, in the month following the closure the fleet moved back into the area and reported higher catch rates on floating objects than usual for December (15.8 versus 11.0 t fishing day^{-1} for the same period in 2008–2011; IOTC data). There is insufficient data available to evaluate the effect of this closure in terms of a reduction in bycatch, although the closure area is a hotspot for bycatch of silky sharks [38].

The displacement of effort around the boundaries of closed areas, often termed 'fishing the line', is a common harvesting tactic in many fisheries (e.g. [39,40]) and in this instance the purse seine fleet could still access much of the seasonal fishing ground. As such the closure appeared to simply displace the issues associated with FAD fishing. In order to produce meaningful reductions in the catches of juvenile yellowfin and bigeye tunas using an area closure, it would probably be necessary to implement closures considerably larger (and longer) than those that have been implemented to date [41]. The creation of a massive closure in the main FAD fishing region is likely to have a disproportionate effect on catches, as it is unlikely that the fleet would be able to recoup its losses through the reallocation of effort elsewhere due to the relatively poor fishing in other regions during this season. Whilst this conservation measure would be expected to reduce overall catches of small yellowfin and bigeye tunas, it would also result in a significant reduction in catches of skipjack tuna. This loss in catches of what is currently a healthy stock would probably be an unacceptable penalty to the purse seine industry and would also have a major impact on the processing industry in Indian Ocean states, realistically limiting the possibility of such a dramatic conservation measure ever being adopted by the IOTC.

4.3. *Potential management options*

The known location of FADs is an important information in determining where a skipper will choose to fish and in general a larger number of monitored FADs improves both search efficiency and the fishing capacity [2]. A limit on the number of deployed or monitored FADs would thus curb search efficiency and decrease (or maintain, depending on where limits are set) the total number of sets made, although it is important to note the distinction between the number of FADs deployed and the number monitored; the former is relevant to modification of the pelagic habitat (and issues related to their effect on tuna biology) whereas the latter is relevant to fishing capacity and efficiency. A challenge for implementing both the measures is setting an appropriate limit without a well defined reference point, which is yet to be calculated by the IOTC. Nevertheless, at least some of the industry appears to have introduced a ceiling on the use of FADs, with French fishing companies recently choosing to limit the number of FAD monitored by their vessels at any time to 150 [5]. Whilst this is probably close to the number of FADs French skippers have monitored in recent years [29], and is therefore unlikely to reflect a reduction in effort by the French fleet, it might represent a future reduction when considering the increasing trend in FAD use.

A precautionary upper limit on the number of monitored FADs would go some way towards controlling fishing mortality on FADs, although this depends largely on whether a limit was set on the total number monitored or the total number monitored *at any given time* (i.e. allowing for cycling between buoys). There is some evidence that older FADs that have been in the water for a longer period and have been colonised by other pelagic species are better at attracting tuna schools [5]. As a result, the ability to fish on a FAD that had been 'hidden' for a period of several months, assuming it has not been fished by another vessel, might lead to larger catches on a smaller number of sets and diminish any overall reduction in the total catch on floating objects. Furthermore, as skippers would be permitted to fish on any floating object they encounter opportunistically, it might be considered advantageous to deploy a greater number of FADs, with or without buoys.

Limiting the total number of sets allowed to be made by an individual vessel on floating objects (including FADs) might have a more direct effect on the practice of FAD fishing. Skippers usually fish on any floating object they come across, particularly in the absence of other opportunities, even if the associated school is relatively small. Thus, placing a finite limit on the number of FADs that can be fished might incentivise skippers to be more discriminatory on the objects they fished on, presumably by choosing to fish on objects with large associated schools. This would be possible in practice due to the increasing use of buoys fitted with echosounders, which gives an idea of the size of the school associated with the FAD. As an additional effect to regulating effort, this selective fishing behaviour might also reduce the ecological impacts of FAD fishing on the basis that the ratio of bycatch to target catch is generally lower for larger set sizes [42].

A potential challenge in implementing either quota options is the variation in the importance of FAD fishing at different times of the year and also to different components of the fleet. For instance, restriction on the use of FADs may limit the ability of fleets to cushion the economic impact of poor free school opportunities at certain times of the year or during anomalous climatic events (see [43]). A blanket quota on FAD use may also be perceived as discriminatory against larger vessels that are reliant on FADs to maintain a profitable operation, and compromise in negotiations on FAD limits within the IOTC might result in high and potentially ineffectual limits. It should also be noted that to effectively implement controls on the total number of FADs fished on or deployed it would be necessary to ensure compliance with effort limits using measures such as closed circuit television or on-board observers.

5. The future of the fishery

In the past two decades the use of FADs has reshaped the dynamics of purse seine fleets, particularly in the Indian Ocean. The improved catch levels made possible by this fishing practice facilitated a rapid growth of the fishery, and the subsequent development of the fleet, in particular the Spanish component, has largely been based around the use of FADs. Thus, with the use of FADs being increasingly vital to the fishing operations of many vessels, their use is not expected to decline under a business-as-usual scenario, potentially rekindling the excess capacity observed in the fishery in the past [36]. However, any increase in the use of FADs would not necessarily mean a uniform increase in fishing effort throughout the western Indian Ocean, but rather increased intensity of effort in the main FAD fishing regions. The fishery and ecological effects of such a change in the spatial dynamics of effort are not well understood, although recent modelling work suggests that an increase in the number of FADs in a region would probably result in smaller schools distributed between greater number of objects. Thus search costs and bycatch might increase, rather than catches [44].

A number of external pressures might also be expected to change the face of FAD fishing in the future, although conflicting pressures have the potential to push the industry in different directions. Purse seine fishing has become an increasingly expensive operation over the past decade, particularly for the largest and most powerful vessels, due to rising fuel prices and increased fishing effort [3]. This has reduced profit margins and potentially increased the fisheries′ economic vulnerability to poor fishing seasons and environmental or economic shocks. Given the past trends it might be reasonable to assume that this situation would provoke an even stronger reliance on FADs, especially for those vessels that still target a relatively large proportion of free schools. Again, this might result in the saturation of the FAD fishery, potentially leading to increased costs, lower catches but high total extraction rates.

In contrast, market pressures might result in reduced effort on FADs. The majority of the skipjack caught in the Indian Ocean purse seine fishery is of canning grade and destined for markets in the European Community countries [32]. Here consumer pressure for sustainably sourced fish is strong and seafood certification schemes, such as that of the Marine Stewardship Council (MSC), are popular [45]. To date, one purse seine fishery in the Western and Central Pacific convention area has been awarded certification by the MSC, although this has been exclusively for skipjack tuna caught in free school sets (http://www.msc.org/track-a-fishery/fisheries-in-the-program/certified/pacific/pna_western_central_pacific_skipjack_tuna; accessed 25th July 2013). If this sets a precedent for certification of purse seine fisheries this may mark a move away from FAD fishing with renewed focus on pursuing free schools.

6. Final remarks

The increase in the use of FADs over the past two decades has given rise to concern over their associated ecological impacts, yet management of FAD fishing is complicated by the compromise between achieving a reduction in these impacts and allowing the sustainable exploitation of healthy tuna stocks, namely skipjack tuna. This is complicated further by the current reliance of the purse seine fishery on this highly efficient fishing practice, which is likely to only increase further under a business-as-usual scenario as fishing operations become more expensive and shrinking profit margins require an ever greater use of FADs. However, continued growth in FAD fishing might be expected to result in diminishing returns as the relative benefit of each FAD in the fishery is diluted.

Explicit management of the use of FADs is undoubtedly a necessity to ensure future sustainability of the fishery. Whilst there are several options available to manage the use of FADs, each option is expected to produce a different response from the purse seine fleet. Time-area closures have already been implemented but with mixed success in reducing juvenile mortality due to the flexibility of the fleet in reallocating effort. Whilst larger (and longer) closures may achieve greater reductions in juvenile catch this would be at the expense of significant reductions in skipjack catch. This has major implications on the fishing and processing industries based in the Indian Ocean, with a realistic danger that many purse seiners would choose to leave the Indian Ocean altogether. On the other hand, input controls such as limiting the number of actively monitored FADs or the number of sets made on floating objects directly address concerns about FAD fishing, if designed and implemented appropriately, but are likely to be challenging to negotiate within the IOTC and difficult to enforce.

Acknowledgements

We are grateful to the Economic and Social Research Council and the Natural Environment Research Council for funding this research. This paper is a contribution from Imperial College's Grand Challenges in Ecosystems and the Environment initiative. Generous thanks are also given to J. Pearce, L. Dagorn and A. Fonteneau for informative discussion on the current and future management of FAD fishing, and to J.J. Areso, several members of staff at the Seychelles Fishing Authority and a number of anonymous skippers who gave up their time to offer invaluable insight into the practical aspects of purse seine fishing.

References

[1] Dempster T, Taquet M. Fish aggregation device (FAD) research: gaps in current knowledge and future directions for ecological studies. Rev Fish Biol Fish 2004;14(1):21–42.
[2] Fonteneau A, Pallares P, Pianet R. A worldwide review of purse seine fisheries on FADs. In: Le Gall JY, Cayre´ P, Taquet M, editors. Pêche thonière et dispositifs de concentration de poisons, 28. Actes Colloques-IFREMER; 2000. p. 15–35.
[3] Miyake MP, Guillotreau P, Sun CH, Ishimura G. Recent developments in the tuna industry: stocks, fisheries, management, processing, trade and markets. FAO fisheries and aquaculture technical paper no. 543, Rome; 2010.
[4] Floch L, Molina ADD, Assan C, Dewals P, Areso JJ, Chassot E. Statistics of the European purse seine fishing fleet and associated flags targeting tropical tunas in the Indian Ocean (1981–2011). Working document for IOTC. Indian Ocean Tuna Commission; 2012.
[5] Dagorn L, Holland KN, Restrepo V, Moreno G. 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 2012;14(3):391–415.
[6] Bromhead D, Foster J, Attard R, Findlay J, Kalish J. A review of the impacts of fish aggregating devices (FADs) on tuna fisheries. Final report to the fisheries resources research fund. Canberra: ACT, Australia: Bureau of Rural Sciences; 2003.
[7] Amandè JM, Ariz J, Chassot E, Chavance P, Delgado de Molina A, Gaertner D. et al. By-catch and discards of the European purse seine tuna fishery in the Indian Ocean: estimation and characteristics for the 2003–2007 period. Working document for IOTC. Indian Ocean Tuna Commission; 2008.
[8] Amandè MJ, Ariz J, Chassot E, De Molina AD, Gaertner D, Murua H, et al. Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003–2007 period. Aquat Living Resour 2010;23(4):353–62.
[9] Fonteneau A, Chassot E, Bodin N. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (FADs): Taking a historical perspective to inform current challenges. Aquat Living Resour 2013;26(1):37–48.
[10] Fonteneau A. Prospects for the management of FAD fisheries in the Indian Ocean. Working document for IOTC. Indian Ocean Tuna Commission; 2003.
[11] Martin S, Edwards C, Mees C. An analysis of the effects of the use of Fish Aggregating Devices on yellowfin tuna *Thunnus albacores* in the Indian Ocean. Working document for IOTC. Indian Ocean Tuna Commission; 2011.
[12] Murua H, Herrera M, Fonteneau A, Marsac, F. Evaluation of current and alternative time-area closures by catch reductions scenarios. Working document for IOTC. Indian Ocean Tuna Commission; 2012.
[13] Salas S, Gaertner D. The behavioural dynamics of fishers: management implications. Fish Fish 2004;5(2):153–67.
[14] Branch TA, Hilborn R, Haynie AC, Fay G, Flynn L, Griffiths J, et al. Fleet dynamics and fishermen behavior: lessons for fisheries managers. Can J Fish Aquat Sci 2006;63(7):1647–68.
[15] Fulton EA, Smith ADM, Smith DC, van Putten IE. Human behaviour: the key source of uncertainty in fisheries management. Fish Fish 2011;12(1):2–17.
[16] Fromentin JM, Fonteneau A. Fishing effects and life history traits: a case study comparing tropical versus temperate tunas. Fish Res 2001;53(2):133–50.
[17] Maunder MN. Updated indicators of stock status for skipjack tuna in the eastern Pacific Ocean. Unpublished IATTC report. La Jolla, USA; 2011. pp. 5.

[18] Anon. Report of the 2011 ISSF stock assessment workshop, March 14–17, Rome, Italy. ISSF technical report. International Seafood Sustainability Foundation, McLean, Virginia, USA; 2011.
[19] Hall MA. The association of tunas with floating objects and dolphins in the Eastern Pacific Ocean. Some hypotheses on the mechanisms governing the association of tunas with floating objects and dolphins. Background document for the international workshop on the ecology and fisheries for tunas associated with floating objects, La Jolla, USA; 1992.
[20] Romanov EV. Bycatch in the tuna purse-seine fisheries of the western Indian Ocean. Fish Bull 2002;100(1):90–105.
[21] Gilman EL. Bycatch governance and best practice mitigation technology in global tuna fisheries. Mar Policy 2011;35(5):590–609.
[22] Camhi MD, Fordham SV, Fowler SL, Gibson C. The conservation status of Pelagic Sharks and Rays: report of the IUCN shark specialist group Pelagic Shark red list workshop. Newbury, UK: IUCN Species Survival Commission Shark Specialist Group; 2009.
[23] Amandè MJ, Chassot E, Chavance P, Murua H, de Molina AD, Bez N. Precision in bycatch estimates: the case of tuna purse-seine fisheries in the Indian Ocean. ICES J Mar Sci: J Cons 2012;69:1501–10.
[24] Dagorn L, Fréon P. Tropical tuna associated with floating objects: a simulation study of the meeting point hypothesis. Can J Fish Aquat Sci 1999;56 (6):984–93.
[25] Marsac F, Fonteneau A, Ménard F. Drifting FADs used in tuna fisheries: an ecological trap? In: Le Gall JY, Cayre´ P, Taquet M, editors. Pêche thonière et dispositifs de concentration de poisons, 28. Actes Colloques-IFREMER; 2000. p. 15–35.
[26] Hallier JP, Gaertner D. Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. Mar Ecol Prog Ser 2008;353:255–64.
[27] Jaquemet S, Potier M, Ménard F. Do drifting and anchored fish aggregating devices (FADs) similarly influence tuna feeding habits? A case study from the western Indian Ocean Fish Res 2011;107(1):283–90.
[28] Fauvel T, Bez N, Walker E, Alicia D, Murua H, Chavance P. et al. Comparative study of the distribution of natural versus artificial drifting Fish Aggregating Devices (FADs) in the Western Indian Ocean. Working document for IOTC. Indian Ocean Tuna Commission; 2009.
[29] Moreno G, Dagorn L, Sancho G, Itano D. Fish behaviour from fishers′ knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). Can J Fish Aquat Sci 2007;64(11):1517–28.
[30] Marsac F. Outlook of ocean climate variability in the west tropical Indian Ocean, 1997–2008. Working document for IOTC. Indian Ocean Tuna Commission; 2008.
[31] Dagorn L, Bez N, Fauvel T, Walker E. How much do fish aggregating devices (FADs) modify the floating object environment in the ocean? Fish Oceanogr 2013;22(3):147–53.
[32] Campling L. The Tuna 'Commodity Frontier': business strategies and environment in the industrial tuna fisheries of the Western Indian Ocean. J Agrar Change 2012;12(July):252–78.
[33] Guillotreau P, Salladarré F, Dewals P, Dagorn L. Fishing tuna around Fish Aggregating Devices (FADs) vs free swimming schools: skipper decision and other determining factors. Fish Res 2011;109:234–42.
[34] Chassot E, Dewals P, Floch L, Lucas V, Morales-Vargas M, Kaplan D. Analysis of the effects of Somali piracy on the European tuna purse seine fisheries of the Indian Ocean. Working document for IOTC. Indian Ocean Tuna Commission; 2010.
[35] Itano D, Fukofuka S, Brogan, D. The development, design and recent status of anchored and drifting DFADs in the WCPO. Standing Committee on Tuna and Billfish, Majuro, Republic of the Marshall Islands. Working document for WCPFC. Western and Central Indian Ocean Tuna Commission; 2004.
[36] Joseph J, Squires D, Bayliff W, Groves T. Addressing the problem of excess fishing capacity in tuna fisheries. In: Allen R, Joseph J, Squiers D, editors. Conservation and management of transnational tuna fisheries. Iowa, USA: Wiley-Blackwell; 2010.
[37] Davies TK, Martin S, Mees C, Chassot E, Kaplan, DM. A review of the conservation benefits of marine protected areas for pelagic species associated with fisheries. ISSF technical report 2012-02. International Seafood Sustainability Foundation, McLean, Virginia, USA; 2012.
[38] Amandè JM, Bez N, Konan N, Murua H, Delgado de Molina A, Chavance P. et al. Areas with high bycatch of silky sharks (*Carcharhinus falciformis*) in the Western Indian Ocean purse seine fishery. Working document for IOTC. Indian Ocean Tuna Commission; 2011.
[39] Murawski SA, Wigley SE, Fogarty MJ, Rago PJ, Mountain DG. Effort distribution and catch patterns adjacent to temperate MPAs. ICES J Mar Sci: J du Cons 2005;62(6):1150–67.
[40] Abbott JK, Haynie AC. What are we protecting? Fisher behavior and the unintended consequences of spatial closures as a fishery management tool Ecol Appl 2012;22(3):762–77.
[41] Kaplan DM, Bach P, Bonhommeau S, Chassot E, Chavance P, Dagorn L, et al. The true challenge of giant marine reserves. Science 2013;340(6134):810.
[42] Dagorn L, Filmalter JD, Forget F, Amandé JM, Hall MA, Williams P, et al. Targeting bigger schools can reduce ecosystem impacts of fisheries. Can J Fish Aquat Sci 2012;69:1463–7.
[43] Robinson J, Guillotreau P, Jiménez-Toribio R, Lantz F, Nadzon L, Dorizo J, et al. Impacts of climate variability on the tuna economy of Seychelles. Clim Res 2010;43(3):149–62.
[44] Sempo G, Dagorn L, Robert M, Deneubourg JL. Impact of increasing deployment of artificial floating objects on the spatial distribution of social fish species. J Appl Ecol 2013;50(5):1081–92.
[45] Jaffry S, Pickering H, Ghulam Y, Whitmarsh D, Wattage P. Consumer choices for quality and sustainability labelled seafood products in the UK. Food Policy 2004;29(3):215–28.