Reducing mortality of bigeye tuna during purse-seine fishing
A research agenda

Johann Bell, Jonathan Peacey and Kevin Stokes

Betty and Gordon Moore Center for Science and Oceans, Conservation International

2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA

CONSERVATION INTERNATIONAL

Preferred citation
Bell J., Peacey J. and Stokes K. 2015. Reducing Mortality of Bigeye Tuna during Purse-seine Fishing: A Research Agenda. Conservation International, Arlington, USA.

Cover photo
Bigeye, yellowfin and skipjack tuna mixed together inside a purse-seine net
(Photo: ISSF/Fabian Forget)

Contents

Page

Executive summary

Progressive expansion of purse-seine fishing for tuna in the Western and Central Pacific Ocean (WCPO), and continued longline fishing, has resulted in the spawning biomass of bigeye tuna in the WCPO falling below the limit reference point agreed by the Western and Central Pacific Fisheries Commission (WCPFC). The problem has arisen because much of the recent purse-seine fishing in the WCPO has been for tuna associated with drifting fish aggregating devices (FADs), and because most bigeye tuna caught by purse seine are taken around FADs.

Conservation and management measures introduced by WCPFC to reduce the mortality of bigeye tuna – banning the setting of purse-seine nets around FADs for several months each year; closing the high seas pockets to purse-seine fishing; prohibiting the discarding of small tuna at sea; placing observers on all purse-seine vessels and imposing annual catch limits for bigeye tuna in the longline fishery – have not had the desired effect. The total number of FAD sets has not declined and large catches of bigeye tuna continue to be taken by purse-seine vessels in the WCPO, with catches in 2013 and 2014 among the highest on record.

The high mortality of bigeye tuna due to purse-seine fishing is now preventing entry of FAD-caught tuna into some markets. The capture of bigeye tuna around FADs is also affecting the aspirations of Pacific Island countries to derive greater economic benefits from tuna resources because it does not maximise yield-per-recruit.

Proposals by some members of the WCPFC to further reduce the number of months that FADs can be used each year to help address the high fishing mortality of bigeye tuna was the subject of intense debate at the 11th Regular Session of the WCPFC in Apia, Samoa, in December 2014. Increasing the duration of FAD closures met with opposition because it would result in a disproportionate burden for some of the smaller States. WCPFC failed to reach consensus at the 11th Regular Session on a plan of action to end overfishing of bigeye tuna in the WCPO.

Other ways that have been proposed to reduce the fishing mortality of bigeye tuna by purse-seine vessels include temporal-spatial closures, vessel catch limits and increases in fees for vessels using FADs. However, implementation of such measures in the EEZs of Pacific Island nations and on the high seas is likely to be protracted because WCPFC is comprised of >30 members and operates mostly by consensus. There is also the challenge of harmonising management measures for bigeye tuna between the two regional fisheries management organizations (RFMOs) in the Pacific, the WCPFC and the Inter-American Tropical Tuna Commission (IATTC) (responsible for management east of 150°W).

The various issues and constraints involved in managing the purse-seine fishery to reduce the fishing mortality of bigeye tuna would be largely removed if practical methods could be developed to maintain high catch rates of skipjack tuna from FAD fishing while reducing the bigeye tuna catch. This has been recognised for some time and possible solutions have been investigated by several organisations, such as the International Sustainable Seafood Foundation (ISSF). It is also a requirement of a recent WCPFC Conservation

and Management Measure (CMM 2014-01), which states that "the Commission shall promote and encourage research to identify ways for vessels to avoid the capture of juvenile bigeye and yellowfin tuna during FAD sets". This report outlines a research agenda to achieve this goal. It describes:

1) Previous and existing initiatives to reduce the catch of bigeye tuna around FADs;
2) Additional research to determine whether practical methods for reducing the catch of bigeye tuna around FADs can be developed; and
3) Ways of supporting and stimulating such research.

Previous research has demonstrated that four solutions proposed to reduce the fishing mortality of bigeye tuna during purse-seining operations – reducing the depth of purse-seine nets, inserting sorting grids into nets to allow bigeye tuna to escape, setting on tuna aggregations associated with FADs at a different time of day and targeting skipjack schools that break away from FADs – all appear impractical. This is because for each of these proposed solutions there is considerable overlap in the distribution and behaviour of skipjack and bigeye tuna.

The most promising areas of research for reducing the fishing mortality of bigeye tuna by purse-seine fishing fall into two main categories. First, detecting the relative abundance of the different species of tuna associated with FADs, enabling vessel captains to avoid setting nets around FADs in areas with large quantities of bigeye tuna. Second, identifying stimuli that could be used to attract or repel either bigeye or skipjack tuna, creating opportunities to separate the species prior to setting the net.

Research in the first category needs to focus on developing improved acoustic, sonar and visual systems that would enable fishing vessels to remotely estimate the quantities of tuna species beneath a FAD. Provided there is variability in the percentage of bigeye tuna associated with FADs, improved detection methods represent the most straightforward way of reducing the fishing mortality of bigeye tuna.

For the second category of research, possible stimuli for attracting or repelling the different species of tuna include light, sound, depth of FAD material, shading, surface water spraying and bubble curtains. Application of these stimuli would depend on use of the double FAD systems under investigation by ISSF. Double FADs can be split apart before the purse-seine net is set, making it theoretically possible to set mainly on skipjack tuna if most bigeye tuna remain associated with only one of the FADs. Use of dead bait should also be included in the possible stimuli because it may have potential to lead bigeye tuna away from a FAD prior to setting. If so, double FAD technology would not be required.

Priority investments to develop the desired new fishing technology are:

1) Support for gear technologists and scientists, including the costs involved in chartering purse-seine vessels to conduct experiments; and
2) Incentives for vessel owners, and manufacturers of acoustic and optical equipment for discriminating species, to engage in the necessary research.

One way of providing an appropriate incentive is organising a competition for a substantial prize for the first vessel or fleet to consistently achieve large reductions in the catch of bigeye tuna using new technology.

The potential benefits of investments in developing purse-seine fishing methods that reduce the catch of bigeye tuna are far reaching, and include:

1) Paving the way to rebuild bigeye tuna stocks without eroding the value of the skipjack fishery;
2) Releasing some States from the disproportionate conservation burden they are currently shouldering to reduce the fishing mortality of bigeye associated with FADs;
3) Increasing yield-per-recruit for bigeye tuna by making a greater proportion of the stock available for capture at a larger size by the longline fishery;
4) Improving consumer acceptance of FAD-caught tuna products; and
5) Enabling managers to focus on reducing non-tuna catch associated with FADs, e.g. sharks.

New fishing technology alone will not necessarily solve all the problems, however. If practical methods can be developed to largely avoid capturing bigeye tuna during purse-seining operations, management measures (e.g., vessel catch limits) or market-driven incentives, will still be required to ensure that fleets use them.

The research agenda described here should also assist purse-seine vessels targeting skipjack tuna around FADs in other oceans to reduce the catch of bigeye tuna.

A purse-seine vessel (Photo: ISSF - David Itano)

1. The problem

Progressive expansion of purse-seine fishing for tunas across the Pacific since the early 1990s, coupled with continued longline fishing (Figure 1), has resulted in the spawning biomass of bigeye tuna in the Western and Central Pacific Ocean (WCPO) falling below the limit reference point of 20% of unfished spawning biomass ($SB_{F=0}$) agreed at the 9th Regular Session of Western and Central Pacific Fisheries Commission (WCPFC)[1]. [See Harley et al. (2014) for the details of the stock assessment underpinning the limit reference point for the bigeye stock in the WCPO]. Regular stock assessments of bigeye tuna in the Eastern Pacific Ocean (EPO) by the Inter-American Tropical Tuna Commission (IATTC) suggest that bigeye tuna spawning biomass is currently above the level required for maximum sustainable yield, and that overfishing of bigeye tuna is not occurring in the EPO (IATTC, 2015). However, some assumptions made about bigeye tuna in the EPO assessment model are less conservative than those made about bigeye in the WCPO assessment model.

The problem in the WCPO has arisen because a significant amount of the purse-seine fishing in recent years has targeted skipjack tuna associated with drifting fish aggregating devices (FADs) (Williams and Terawasi, 2015), and because bigeye tuna are commonly associated with these FADs (Leroy et al., 2013). As a result, larger catches of bigeye are being caught by purse-seine vessels in the WCPO, mainly around FADs (Williams and Terawasi, 2015).

The need to reduce the fishing mortality of bigeye tuna in the WCPO was recognised several years ago (WCPFC, 2008; 2009), when the spawning biomass was estimated to be about 30% of $SB_{F=0}$. A series of conservation

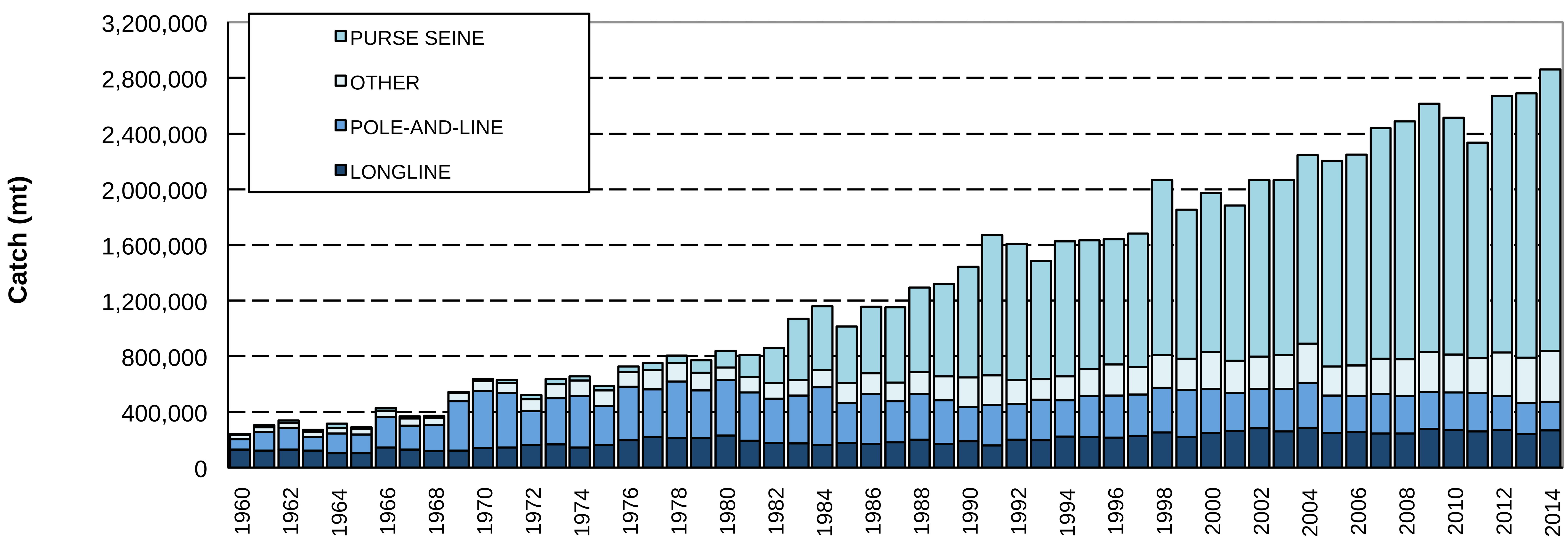

Figure 1. Total catch (mt) of all tuna species combined from the Western and Central Pacific Ocean by fishing method since 1960 (source: Williams and Terawasi, 2015).

[1] www.wcpfc.int/system/files/WCPFC9-Summary-Report-final.pdf

and management measures were subsequently introduced to reduce the mortality of bigeye tuna. These measures progressively included prohibiting the use of FADs for two, then three, and now up to four months per year; closing the high seas pockets to purse-seine fishing; banning the discarding of small tuna at sea; and placing observers on all purse-seine vessels. The measures also established annual bigeye catch limits in the longline fishery. For the six countries with the largest catches, there are country-specific limits based on historical catch levels; the sum of the limits declines each year to 55,687 tonnes in 2017. For members that caught less than 2,000 tonnes in 2004, the measures impose annual country-specific limits of 2,000 tonnes.

Regrettably, these measures have not had the desired effect – the total number of sets made by purse-seine vessels around FADs each year has not declined and catches of bigeye tuna have continued to increase (Williams and Terawasi, 2015). In 2013, the 82,151 mt of bigeye tuna caught by purse-seine nets in the WCPO was the highest on record, exceeding the longline catch for the first time. The purse-seine catch of bigeye tuna in 2014 was also among the highest on record (Figure 2).

A drifting fish aggregating device (FAD) (Photo: Fadio/IRD-Ifremer/Marc Taquet)

The effects of FAD fishing on bigeye tuna (and on other non-tuna species) associated with the devices is now preventing entry of some of the FAD-caught tuna into more lucrative markets because an increasing number of retailers are striving to promote ecologically sustainable products and refusing to purchase, or pay premium prices for, tuna captured around FADs (Anon., 2015).

Catching bigeye tuna around FADs by purse seine also falls well short of the aspirations of Pacific Island countries to maximise the economic benefits from tuna resources. In particular, purse-seine fishing does not maximise yield-per-recruit; the average size of bigeye tuna caught by purse-seine vessels is ~5 kg (~60 cm), whereas the average size of fish caught by longline is >40 kg (~130 cm) (Williams and Terawasi, 2015) (Figure 3). In addition, the average price for bigeye tuna landed by purse-seine vessels is the same as for skipjack tuna (i.e., ~$1.50 per kg), whereas larger bigeye tuna caught by longline are valued at around $9 per kg (Williams and Terawasi, 2015).

Proposals by some members of the WCPFC to further reduce the number of months that FADs may be used each year to help address the high fishing mortality for bigeye tuna have met with opposition by smaller states in the central and eastern WCPO, such as Tuvalu and Tokelau. These states rely heavily on access fees paid by foreign purse-seine fleets for government revenue. They are concerned that such vessels will be reluctant to fish in their waters if further restrictions are placed on the use of FADs. This concern arises because fleets targeting skipjack tuna in the eastern part of the WCPO rely on the use of FADs to operate efficiently (Williams and Terawasi, 2015). The small states are particularly concerned that they will bear a disproportionate burden for the conservation of bigeye tuna if further FAD restrictions are introduced.

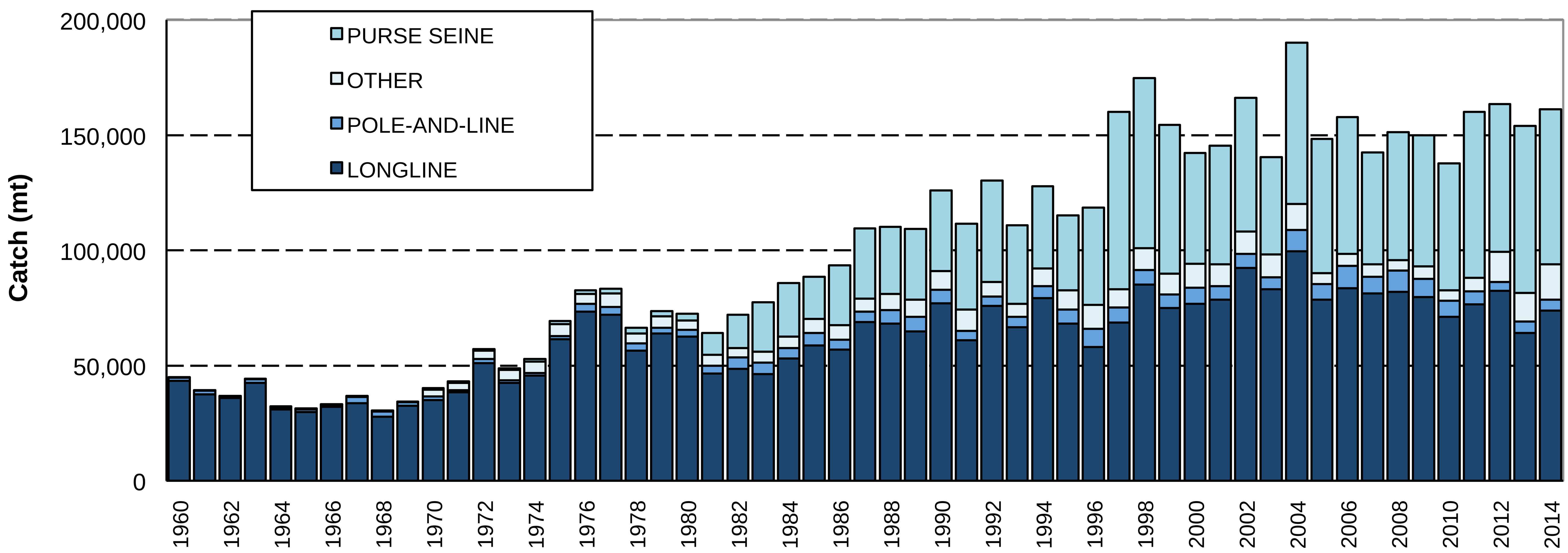

Figure 2. Catch (mt) of bigeye tuna from the Western and Central Pacific Ocean by fishing method since 1960 (source: Williams and Terawasi, 2015).

This issue was the subject of intense debate at the 11th Regular Session of the WCPFC in Apia, Samoa, in December 2014. Unfortunately, members of WCPFC failed to reach consensus on a plan of action to end overfishing of bigeye tuna in the WCPO.

The issue of bigeye tuna capture in purse-seine fisheries remains a major concern, however, and other ways to reduce the fishing mortality of bigeye tuna by purse-seine vessels were discussed at a recent workshop organised by the United States Western Pacific Regional Fishery Management Council (WPRFMC 2015). These measures are summarised briefly below.

Temporal-spatial closures. The IATTC has reduced the fishing mortality of bigeye tuna in the EPO by introducing a total closure of the tuna fishery for two months each year (either from 29 July to 28 September or 18 November to 18 January). For the WCPO, a relatively long total closure of the purse-seine fishery would be needed to reduce the fishing mortality of bigeye tuna by 50% (WPRFMC, 2015). However, a shorter closure would be required to limit the opportunity cost of a lower skipjack tuna catch. A shorter closure would need to be accompanied by additional measures to reduce the catch of bigeye tuna by purse-seine fleets.

Decisions about the scope for spatial closures to reduce the fishing mortality of bigeye tuna would need to be made in the context of total bigeye tuna catch, catch-per-unit-effort (CPUE) for bigeye tuna, and the proportion of bigeye tuna per set. Although CPUE and proportion per set are much greater in the central and eastern WCPO, the greatest catches of bigeye tuna are made in the western WCPO because that is where most sets are made (Harley et al., 2015). The reality is that spatial closures within either part of the region are unlikely to be endorsed by WCPFC – closures in the west would reduce

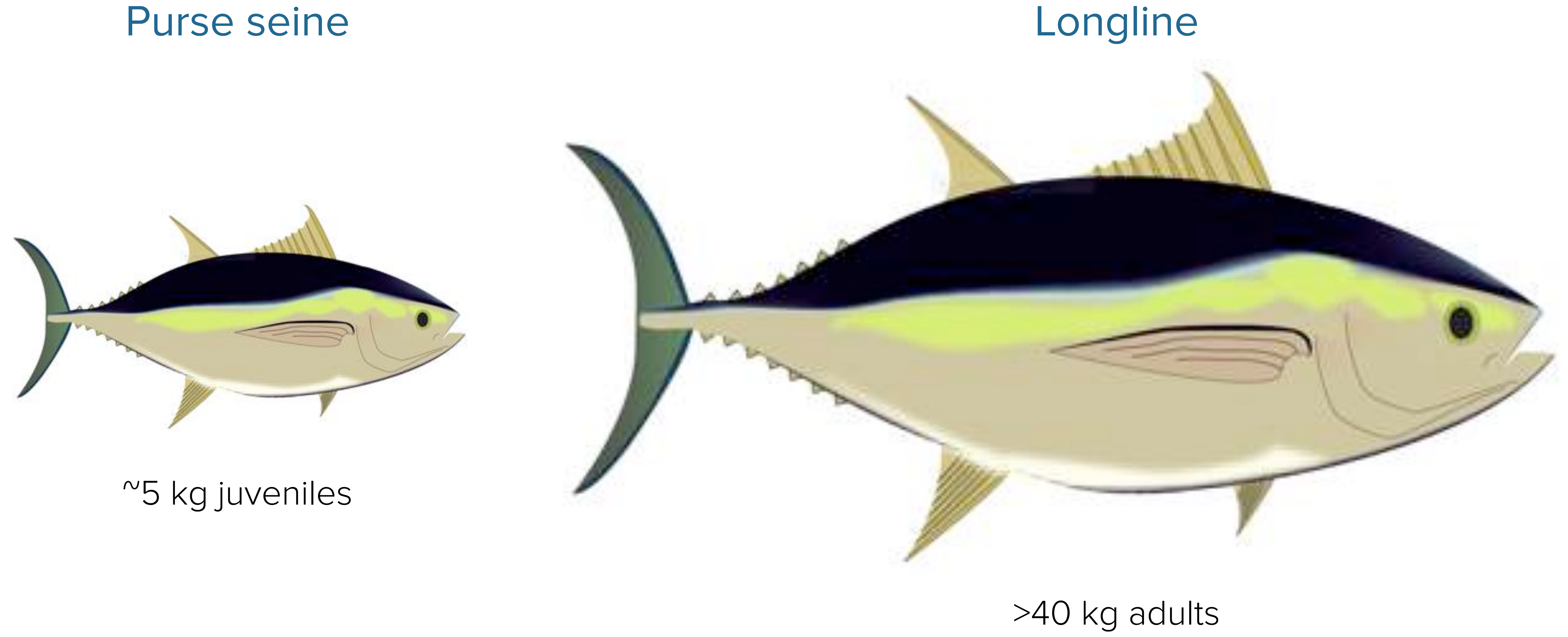

Figure 3. The striking difference in average size of bigeye tuna caught by purse-seine and longline vessels. See Williams and Terawasi (2015) for size-frequency distributions of bigeye tuna caught by purse-seine and longline vessels.

skipjack catches significantly, closures in the EEZs of smaller Pacific Island countries in the central and eastern WCPO would cause a disproportionate burden, and distant water fishing nations would object to closures of high seas areas in the east.

Catch limits for bigeye tuna. Recent analyses by Harley et al. (2015) have shown large differences in the catch of bigeye tuna among purse-seine vessels. Establishment of individual catch limits for purse-seine vessels within the WCPFC would directly address fishing mortality of bigeye tuna and create a disincentive that could change fishers' behaviour. This measure depends on development of efficient and reliable systems to estimate the proportion of bigeye tuna in purse-seine catches, either on board, during transhipping operations or at canneries.

Reducing FAD use through pricing. This management measure is based on the premise that the cost of a FAD set can be expected to influence fishing behaviour – as costs increase there should be a progressive decline in use of FADs. The Vessel Day Scheme (VDS) operated by the Parties to the Nauru Agreement Office (PNAO) provides mechanisms to introduce an additional daily fee for FAD sets. The fee per FAD set could then be adjusted to reduce FAD use to the recommended level. Another advantage of FAD pricing is that the additional revenue generated could be allocated to addressing the disproportionate burden incurred by small states as a result of reduced FAD use.

An important consideration, however, is that introduction of FAD pricing by PNAO would address only some of the bigeye tuna mortality (WPRFMC, 2015). The WCPFC would need to agree to compatible measures for the high seas, reform of the longline fishery, and develop measures for the non-PNA EEZs (e.g., Philippines and Indonesia). Registering and monitoring the large number of existing FADs would also be difficult.

1.1 Other considerations

The International Sustainable Seafood Foundation (ISSF) together with the World Wildlife Fund (WWF) and Pew Charitable Trusts, are advocating mandatory provision of data on industrial FAD fishing (e.g., design and numbers of FADs deployed, FAD usage patterns) to facilitate evidence-based decisions for introducing the types of management measures outlined above. The call for this information was also supported by WPRFMC (2015) and PNAO will require access to information from buoys attached to all FADs deployed in its waters from 2016.

However, because any management measures for bigeye tuna in the WCPO need to be approved by WCPFC, and because WCPFC operates by consensus, it is likely to take a considerable time to achieve the necessary reductions in mortality of bigeye tuna in the EEZs of Pacific Island nations and on the high seas based on the options outlined above.

There is also the challenge of harmonising management measures for bigeye tuna between the WCPO and EPO. Although bigeye tuna tagging information indicates that most bigeye tuna remain predominantly in the equatorial EPO (east of 120°W) and WCPO (west of 180°) there is considerable mixing between

120°W and 180° across the convention boundary (Schaefer et al., 2015). Until additional research required to define the stock structure of bigeye tuna throughout the Pacific Ocean with higher confidence has been completed, WCPFC and IATTC should continue to explore effective companion stock assessments for bigeye tuna (McKechnie et al., 2015).

1.2 A way forward

The existing impediments to reducing the fishing mortality of bigeye tuna during purse-seining operations, and optimising government revenue from the purse-seine fishery for small island states, would be removed if practical methods could be developed to fish around FADs that resulted in substantial reductions in the catch of bigeye tuna (WPRFMC, 2015).

Purse-seine fleets in the EPO have demonstrated that it is possible to modify fishing procedures to reduce impacts on other species associated with skipjack and yellowfin tuna (i.e., dolphins). The development of those methods resolved a controversy that threatened the viability of the fishery (Joseph, 1994). The new fishing practices and policies were subsequently adopted by IATTC, and enshrined in an international agreement between fishing states (Wright, 2000; Hedley, 2001).

The idea of developing purse-seine methods for fishing around FADs without catching bigeye tuna is not new – it has been promoted by tuna RFMOs, ISSF, and other NGOs for some time. It is also a requirement of a recent WCPFC Conservation and Management Measure (CMM 2014-01)[2], which states that "the Commission shall promote and encourage research to identify ways for vessels to avoid the capture of juvenile bigeye and yellowfin tuna during FAD sets".

This report describes:

1. The previous and existing initiatives to reduce the catch of bigeye tuna around drifting FADs;
2. The additional research needed to determine whether practical methods for reducing the catch of bigeye tuna around FADs can be developed; and
3. Ways of stimulating and supporting such research.

The emphasis of this report – a proposed research agenda to reduce fishing mortality of bigeye tuna during purse-seining operations – does not imply that new fishing technology alone will solve the problems. If practical methods can be developed to largely avoid capturing bigeye tuna during purse-seining operations, management measures, such as vessel catch limits, will still be required to ensure that fleets use them. Market forces also have a role to play in providing additional incentives to apply the new technology (Anon., 2015; WPRFMC, 2015). If canneries stopped buying bigeye tuna or payed a greatly reduced price, purse-seine vessels would be quick to develop FAD-fishing technology to reduce the percentage of bigeye in catches and/or fish in areas with lower abundance of bigeye tuna.

Although the focus is on the WCPO, the research agenda outlined here should also assist purse-seine vessels targeting skipjack tuna around FADs in other oceans to reduce the catch of bigeye tuna.

[2] www.wcpfc.int/conservation-and-management-measures

2. Previous and existing initiatives

A number of attempts have already been made to reduce catch of bigeye tuna during purse-seine operations targeting skipjack tuna (Itano, 2005; Morgan, 2011; Hall and Roman, 2013; Restrepo, 2014). These initiatives are summarised below.

2.1 Methods with limited potential

2.1.1 Reducing depth of purse-seine nets

Based on observations that bigeye tuna sometimes occur at greater depths than skipjack tuna below FADs, limiting the depth of purse-seine nets has been proposed as a way of reducing the bigeye catch (Matsumoto et al., 2006; Leroy et al., 2009). However, this is not a practical solution because bigeye tuna are also found close to the surface at night and so have overlapping depth distributions with skipjack and yellowfin tuna around FADs prior to dawn (Schaefer and Fuller, 2005; 2013), when most sets occur. Thus, bigeye would still be vulnerable to shallower nets (Opnai, 2002; Itano, 2005; Leroy et al., 2010; Delgado de Molina et al., 2010). Also, it is probably impractical to make purse-seine nets shallower because such modifications may permit skipjack tuna to escape.

2.1.2 Sorting grids

The limited trials involving insertion of solid or flexible panels of larger mesh within purse-seine nets to facilitate escape of juvenile bigeye tuna (Hall and Roman, 2013) have not proven to be effective in the EPO (Nelson, 2004) or the WCPO (Nasegawa et al., 2010). Further research on sorting grids is not generally considered to be worthwhile because there is little consistency in size differences between skipjack and bigeye tuna species in FAD sets (Hall and Roman, 2013). In fact, juvenile bigeye tuna are often larger than the skipjack tuna targeted. Hall and Roman (2013) and WPRFMC (2015) outline some factors that may allow bigeye to be separated from skipjack tuna within purse-seine nets but any such measures have the disadvantage of dealing with fish within nets under greater stress, increasing the probability of mortality even if the bigeye tuna are assisted to escape before brailing[3] occurs.

2.1.3 Setting nets at a different time of day

Potential differences in the time of day that the three main tuna species associate with FADs were investigated by Forget et al. (2015) using acoustic tagging. The investigations showed that there is little scope for reducing bigeye catch (without adversely affecting the catch of skipjack tuna) by adjusting the time purse-seine nets are set around FADs. The times of day that bigeye tuna are most closely associated with FADs are very similar to those for skipjack and yellowfin tuna (Figure 4).

[3] Brailing is the process of transferring fish in the purse-seine net to the vessel once the large net is alongside the boat. The brail net used for this purpose usually holds around 5 tonnes of fish. It is used to scoop fish from the purse-seine net and is hoisted on board with the use of ropes and derrick.

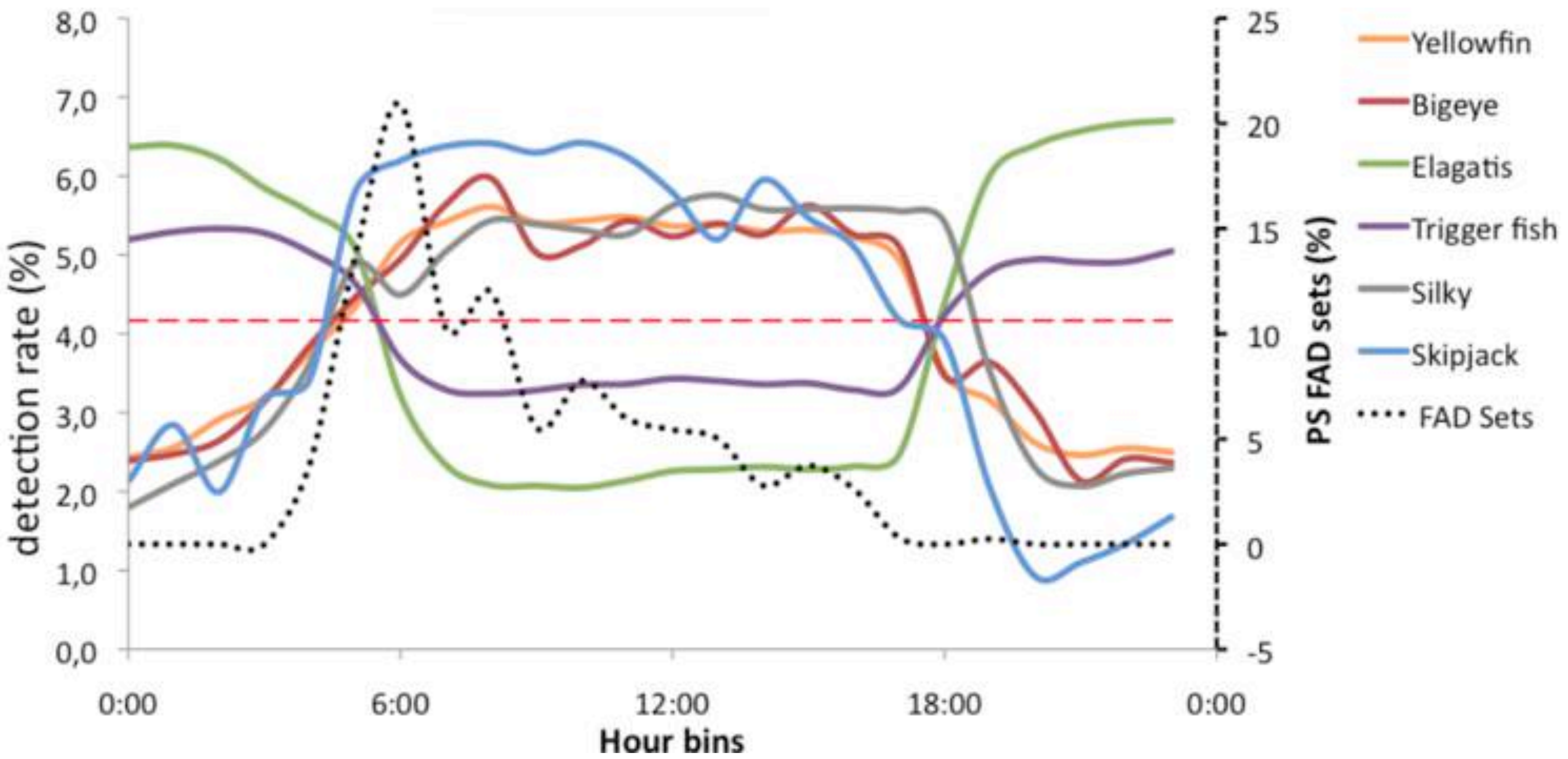

Figure 4. Detection of three species of tuna, and other fish species, near FADs in the Western Indian Ocean over the 24 hour cycle using acoustic tags (after Forget et al. 2015).

2.1.4 Targeting schools that break away from FADs

Targeting mono-specific skipjack schools (or sub-schools) when they move away from drifting FADs does not appear to be a feasible option for reducing fishing mortality of bigeye tuna. The main problems are that schools of skipjack tuna which separate from drifting FADs are only a portion of the total skipjack present at a FAD, and those sub-schools are difficult to catch (Schaefer and Fuller, 2013).

2.2 Ongoing initiatives

ISSF (Restrepo et al., 2014) and the Fishery Research Agency of Japan (Satoh et al., 2012) are currently pursuing three other lines of research to reduce the catch of bigeye tuna. These initiatives are summarised below.

2.2.1 Assessing bigeye tuna around FADs prior to setting

Current acoustic technology cannot yet reliably determine the relative abundance of tuna species associated with FADs. Most FADs now have attached echo-sounder buoys that provide information on the relative abundance of all fish to the vessel. However, they do not have the ability to discriminate among tuna species, or sizes (Delgado de Molina et al., 2005). Nor do they provide information consistent with that available from echo sounders on vessels (Lopez et al. 2010). Buoys attached to FADs that can remotely report the species, size distributions and relative abundances of species (Moreno et al., 2005; 2007; Miquel et al., 2006; Morón, 2008, Dagorn et al. 2009), and minimise the effects of sea conditions and thermocline depth on interpretation of acoustic data (Durand and Delcroix, 2000; Kessler, 2006), are needed.

Provided that the acoustic technology associated with FADs can be improved substantially to allow captains and fishing masters on purse-seine vessels to remotely determine the relative abundance of bigeye and skipjack tuna around FADs, it would be possible to significantly reduce the catch of bigeye tuna. Such echo-sounder records from aggregations associated with FADs could also potentially be used to help assess the status of tuna stocks (WPRFMC, 2015).

2.2.2 Investigating whether FAD depth affects bigeye catches

This research is based on the observation that bigeye tuna sometimes aggregate below FADs at a greater depth than skipjack tuna (Matsumoto et al., 2006). ISSF and IATTC currently have a field experiment underway to evaluate the tuna species composition from sets on shallow and normal depth drifting FADs in the equatorial EPO. (See Section 3.3.1 for more details about the potential for this observation to help separate skipjack and bigeye tuna prior to setting a purse-seine net.)

2.2.3 Assessing the potential of other stimuli to segregate tuna species

This research consists of improving knowledge on the schooling behaviour of bigeye, yellowfin and skipjack tuna, the sensory abilities of each species, and their responses to different stimuli.

The results of the second and third types of research above could potentially be used during fishing operations to separate bigeye tuna from skipjack tuna using the 'double FAD' technology

Netting suspended below a raft to attract tuna (Photo: ISSF-David Itano)

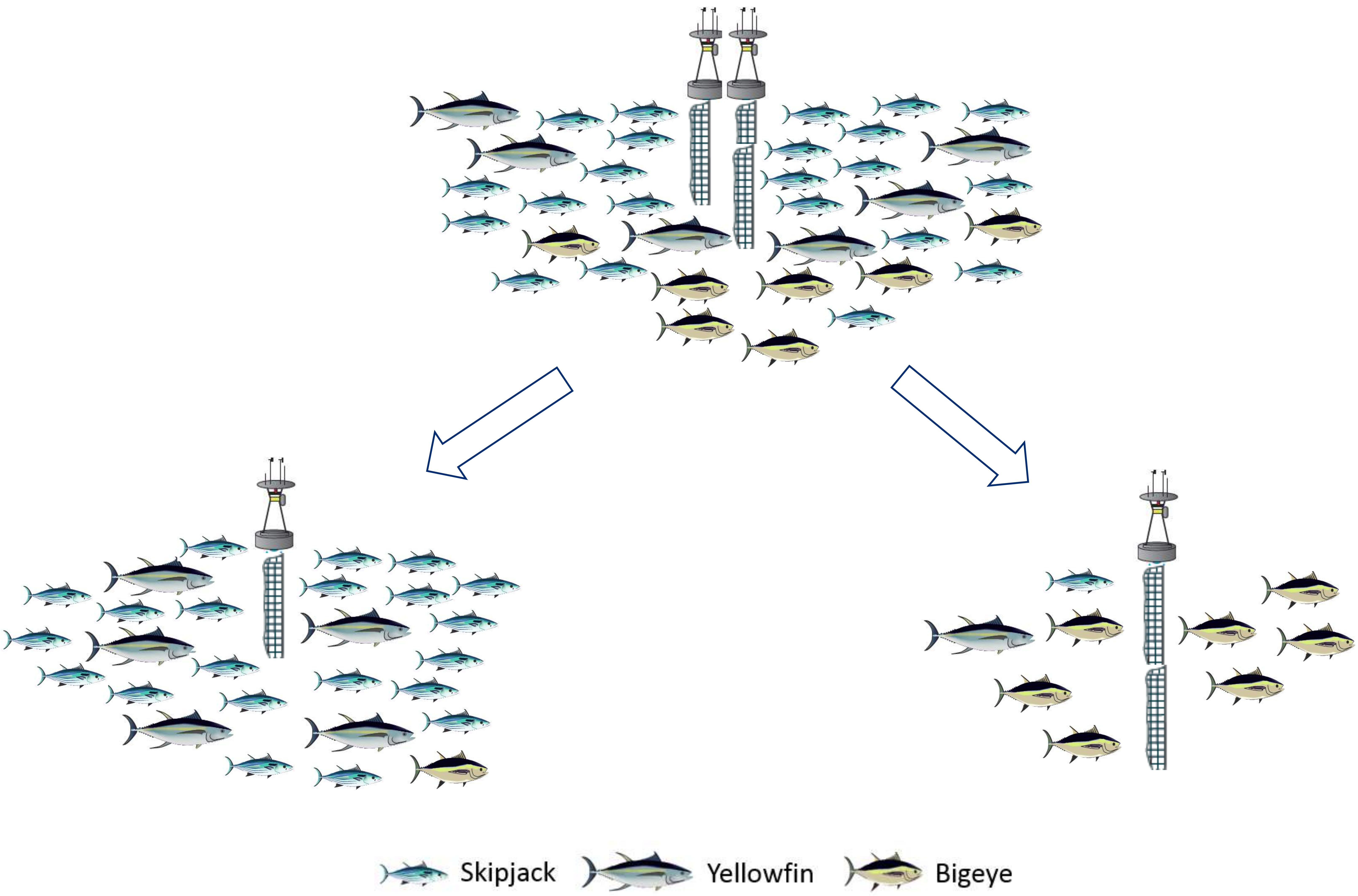

Figure 5. Double FADs – using competition between different stimuli to segregate tuna species as the two FADs are separated (after ISSF).

already under consideration by ISSF for separating bycatch species (e.g., sharks) from target species during purse-seining operations. Double FADs can be split apart before the purse-seine net is set, making it theoretically possible to set mainly on skipjack and yellowfin tuna if most bigeye tuna remain associated with only one of the FADs (Figure 5).

In theory, a purse-seine fishing method that largely avoided capturing bigeye tuna could be developed by identifying a stimulus that repelled bigeye from a single FAD but did not affect skipjack or yellowfin tuna. However, this may be difficult considering that the stimulus would have to be strong enough to overcome the attracting power of the FAD, and that any stimulus repelling bigeye tuna (presumably related to predation threat) would also presumably deter the other species of tuna as well.

The advantage of the double FAD concept is that, having attracted tuna to the floating object, it allows research to focus on second-order stimuli that may attract a given tuna species to one of the two FADs during separation, while the other species remain associated with the other FAD. In practice, the probability of attracting bigeye tuna alone to one of the FADs during separation may be low because bigeye and yellowfin tuna are closely related (both are in the genus *Thunnus*) and may have similar responses to a given stimulus.

To reduce the capture of bigeye tuna using double FAD technology, tuna could be attracted in any one of four possible combinations. These combinations, the advantages and disadvantages of each combination, and suggested priorities for research are given in Table 1.

The disadvantages of combinations 2 and 3 in Table 1, which preclude yellowfin tuna from purse-seine catches, are relatively minor because skippers often prefer to catch yellowfin tuna in free schools, which are generally comprised of larger fish that fetch a higher price than FAD-caught yellowfin (Williams and Terawasi, 2015).

Table 1. The four combinations of tuna attraction that would allow bigeye tuna to be isolated using double FAD technology, together with the advantages and disadvantages of each combination and suggested priorities for research; BET = bigeye tuna, YFT = yellowfin tuna; SKJ = skipjack tuna.

Tuna species to be attracted			Comments	Research priority
BET	YFT	SJK		
z			Ideal, if possible, because BET can be concentrated around one of the two FADs and led away, enabling vessels to set on the remaining FAD with SKJ and YFT. But might be difficult to achieve because YFT could have a similar response to BET to a given stimulus due to their close genetic relationship.	1
		X	Might be most practical because SKJ is in a different genus to BET and YFT and is the main target of the purse-seine fishery. Disadvantage is that YFT would be lost from the purse-seine catch.	2
X	X		Reasonable probability of occurring (see above). Disadvantage is that YFT will also be led away and lost from the catch when the net is set around the FAD with SJK only.	3
	X	X	Unlikely to occur because YFT and SKJ are in different genera but ideal because both SKJ and YFT would be caught.	4

2.3 Other potential methods

Bait could be used to attempt to attract bigeye tuna into deeper water prior to setting the purse-seine net. This method does not depend on double FAD technology and is based on observations by master fishermen at the Secretariat of the Pacific Community (SPC) that bigeye and yellowfin tuna (and sharks) are attracted to dead bait, whereas skipjack tuna are not. This method would involve deploying a skiff from a purse-seine vessel to manipulate a bag of chum bait near a FAD before the net is set, slowly lowering it to a depth of 300 m to attract bigeye and yellowfin tuna and sharks, and then moving the bag several hundred metres away from the FAD before the net is set around the skipjack tuna remaining there.

Yellowfin tuna (Photo: Fadio/IRD-Ifremer/Marc Taquet)

3. Additional research and development required

The key challenges involved in evaluating and developing methods for purse-seine fishing around FADs to avoid the capture of bigeye tuna involve completing and integrating the research initiated by ISSF and partners. Up to four areas of research may warrant investigation:

1. Developing 'smart' FADs with a new generation of acoustics capable of determining the relative abundances of tuna species associated with FADs;
2. Identifying cue(s) that attract or repel the different species of tuna to segregate bigeye tuna using double FAD technology;
3. Developing methods that can be used to split double FADs apart remotely and to produce the most effective stimulus for attracting particular tuna species to one of the two FADs; and
4. Determining whether baiting is a practical way of leading bigeye tuna and sharks away from FADs.

These tasks need to be tackled sequentially. If the development of acoustic methods that allow purse-seine skippers to identify FADs with few bigeye work successfully, and good catches of skipjack tuna (the target of the fishery) can still be made on FADs with few bigeye tuna, there will be no need to proceed further. However, if only a small proportion of FADs have low bigeye:skipjack biomass ratios, or if large schools of skipjack tuna are usually also associated with relatively high numbers of bigeye tuna, there will be a need to embark on the other areas of research listed above.

Details of the factors to be considered in addressing each of these lines of research are outlined below.

3.1 Determining relative abundances of tuna associated with FADs

The potential to use acoustics to help bycatch reduction is widely recognised (Simmonds and MacLennan, 2005; Lopez et al., 2010, 2014). Development of effective acoustic systems to enable fishing vessels to determine the number of bigeye around a FAD will depend on:

- Demonstrating that there is variability in the percentage of bigeye tuna in catches made around FADs (Sancristobal et al., 2014); and
- Progressing existing acoustic technology, which can already discriminate among tuna species based on known differences in acoustic target strength related to fish length, presence/absence of a swim bladder, and swim bladder volume (Arnaud and Josse, 2000; Schaefer and Fuller 2008; Imaizumi et al., 2012), to the point where it can be used to estimate the relative abundances of different tuna species in large aggregations associated with FADs.

Ultimately, the second requirement will involve verification of the pre-set estimates from acoustic information with the species and size composition data from individual sets around FADs, as done in the equatorial EPO by Fuller and Schaefer (2014).

Given the potential difficulties in discriminating between individual bigeye tuna and yellowfin tuna that have swim bladders of the same size, even though the individuals are different lengths, the focus for new acoustic technology could be on distinguishing skipjack tuna from bigeye and yellowfin tuna. Although this may ultimately result in reduced catches of yellowfin tuna around FADs, any effects on the economics of purse-seine fishing are likely to be minor because, as mentioned above, there are advantages in catching yellowfin in free schools.

Experienced purse-seine skippers are adept at interpreting echo-sounder data to identify tuna species based on presence/absence of swim bladders, but interpretation is complicated in mixed species aggregations. Hall and Roman (2013) have pointed out that development of better acoustic technology would benefit from multi-frequency systems and software to discriminate species composition and sizes. They suggest that creating a library of images with data on the captures obtained in each case, would assist progressive improvements in the interpretation of acoustic data.

Other alternatives for identifying tuna species associated with FADs which have been considered are:

- multi-beam sonar (Okamoto et al., 2010); and
- underwater video systems (Itano et al., 2009).

Any alternatives used in practice will need to balance:

- effectiveness with cost of hardware, maintenance, and processing; and
- effectiveness and attractiveness of automated systems as opposed to systems using a degree of human integration.

Combined acoustic and optical systems have already been developed for fish stock assessment purposes (Macaulay et al., 2012; O'Driscoll et al., 2012) and are now being deployed by industry in some fisheries[4]. Use of such approaches elsewhere holds promise for tuna applications.

3.2 Identifying cues (stimuli) that attract or repel different tuna species

3.2.1 Potential stimuli for attracting tuna

Marine fish are known to respond to features of their environment, or behaviour of their conspecifics. Some of these features can be reproduced and magnified to potentially attract or repel particular species of tuna or stimulate behaviours that selectively separate or aggregate different species of tuna. The various stimuli, and evidence for the potential of these simulated features to affect the behaviour of tuna, are summarised below.

Sound and vibrations. Sound and vibrations are well known to influence fish behaviour (Popper and Carlson, 1998; Gabriel et al., 2005; Yan et al., 2010). The inner ear in fish has evolved to detect acoustic signals and the lateral line to detect vibrations. The larvae of a broad range of tropical marine fish species use sound as a cue for orientating towards coral reefs prior to settling from the plankton (Montgomery et al., 2006). And sound has been used to condition cultured marine fish released into the wild to gather at feeding stations (Lindell et al., 2012), where they can be recaptured.

[4] www.sealord.com/docs/default-source/News/state-of-the-art-technology-to-boost-fisheries-research-media-release-.pdf?sfvrsn=0

Tuna and non-tuna species in the purse-seine fishery are also known to respond to sound. Iverson (1967) trained captive yellowfin tuna to swim between two nets when a sound was made and to swim straight in the absence of sound. Yellowfin tuna have also been recorded making their own sounds (Allen and Demer, 2003). Silky sharks are attracted to sound and the attraction increases as the frequency spectrum decreases from 500-1000 Hz to 25-50 HZ, and pulsation increases from 1 to 20 pulses per second (Myrberg et al., 1972).

In addition, there are many anecdotal reports from fishermen that certain fishing boat designs are better for trolling for tuna than others, with the best results obtained from slower revving diesel motors that emit low frequency sound. Others report better catches in the vicinity of large cargo vessels as they pass by, apparently due to the sounds from the vessel.

There is also considerable evidence that FADs attract tuna and other species of large pelagic fish partly as a result of the sounds made by surface rafts and the vibrations made by anchor ropes (Yan et al., 2010).

The challenge is to find sounds and vibrations that are distinctly attractive to bigeye, or to skipjack tuna. Experimentation in the open ocean is not straightforward and practical rather than definitive approaches will be necessary.

Brail used to transfer tuna from the purse-seine net for storage onboard (Photo: ISSF-David Itano)

Light. Artificial light has been used to catch a wide variety of fish, both as adults (Ben-Yami, 1976) and juveniles (Doherty, 1987). Light already plays a role in tuna fisheries, where it is used to catch the baitfish for pole-and-line operations, and where chemical light sticks are used to make the dead baits on longlines more attractive to tuna and swordfish by mimicking the bioluminescence of prey organisms (Sokimi and Beverly, 2010).

There is some evidence for phototaxis (movement of an organism toward or away from a source of light) in tuna. Preliminary experiments have shown that bigeye tuna move horizontally away from a flashing light, albeit with varying responses that appear to be related to the distance of the fish from the light and the time of day (Hasegawa et al., 2010). Other species of fish are also repelled by strobe lighting (Patrick et al., 1985). Thus, because most purse-seining operations around FADs are done before dawn (ISSF, 2014), there may be scope for using artificial light to repel bigeye tuna from FADs while retaining skipjack tuna. Experiments with other species of fish in the Mediterranean (Machesan et al., 2005) have shown that light of different intensities and wavelengths affected phototaxis in most species examined.

At least one other large pelagic fish species, yellowtail amberjack (*Seriola lalandi)*, is known to be attracted to some forms of light. Commercial fishermen in NSW, Australia, have used mirrors to 'bait' pelagic fish traps for this species. The traps proved to be so efficient that they were banned (Stewart et al., 2001).

Depth of FAD material. There is some evidence from the EPO suggesting that the occurrence of bigeye tuna around drifting FADs is related to the length (depth) of material below the raft (Lennert-Cody et al., 2007). However, Sato et al. (2008) and Moon et al. (2008) found no strong evidence for such a trend in the WCPO but acknowledge that several other factors may have influenced their findings. Although there appears to be little scope for using the occasional deeper occurrence of bigeye tuna near FADs to exclude them from catches by reducing the depth of purse-seine nets (Section 2.1.1), the fact that bigeye tuna can be found in deeper water than skipjack tuna near FADs (Josse and Bertrand, 2000; Schaefer and Fuller, 2005) merits equipping one of the FADs in a double-FAD setup with deeper netting to determine whether:

1) Bigeye tuna are consistently attracted to the deeper FAD; and
2) Slow separation of the two FADs (perhaps in combination with surface sprays/bubble curtains – see below) leads most bigeye away from skipjack and yellowfin tuna.

For the reasons explained in Section 2.1.1, separation of the two FADs may need to be done during daylight hours, not prior to dawn.

Shading, spray and bubble curtains. Although shading from light can attract or repel some species of fish (Cocheret de la Moriniere et al., 2004; Verweij et al., 2006), there is little or no scope for using shading to separate species of tuna around FADs because most sets are made prior to dawn.

Spraying water on the surface is known to attract skipjack, yellowfin and bigeye tuna and has been an essential part of the pole-and-line fishing method. In conjunction with the release of live bait, spraying gives the illusion that the water surface is alive with small fish and helps keep tuna beside the fishing vessel[5]. Experimentation with water sprays around one of the two FADs during separation of double FADs would be worthwhile to see if bigeye tuna or skipjack tuna responded more strongly to that stimulus.

There are mixed reports about the effects of air bubbles on fish. Some tuna are apparently attracted to air bubbles, although it is not clear whether it is the bubbles themselves that attract the fish, or the acoustics associated with the noise produced by air bubbles (Gabriel et al., 2005). Other studies report that some species of fish are repelled by air bubbles (Patrick et al., 1985).

It is also worth noting that trolling lures for tuna and other large gamefish are often designed to create trails of air bubbles to attract these fish.

Overall, there is evidence to suggest that both spraying and air bubbles may influence the behaviour of tuna. Therefore, experiments rigging FADs with solar-powered equipment to produce surface spray and underwater curtains of air bubbles could be considered to see if these stimuli have differential effects on bigeye and skipjack tuna.

3.2.2 Applying the stimulus to FADs

Assuming that the above lines of experimentation are successful in developing a stimulus that either attracts of repels bigeye tuna, or skipjack tuna, practical methods will then need to be developed to place the equipment required to produce this species-specific stimulus by remote control on one of the two FADs within a double FAD.

3.2.3 Verifying the species composition of tuna around the target FAD

Prior to setting the purse-seine net around the selected FAD, it would be advantageous (but not always essential) to verify that the fish associated with that FAD are mainly skipjack tuna, and that very few if any bigeye tuna are present. The technology described under 3.1 could be used to do this where bigeye tuna are relatively abundant, e.g. in the central and eastern WCPO.

3.3 Developing methods for splitting double FADs

Once a technique has been developed for producing the species-specific stimulus for attracting/repelling bigeye tuna, or skipjack tuna, a practical method will be needed for separating the two parts of the double FAD.

[5] FAO Fishing methods (www.fao.org/fishery/fishtech/30/en)

3.4 Leading bigeye tuna away from FADs using bait

The key experiments here will involve identifying which baits, bait presentation methods, and bait presentation times, are most attractive to bigeye tuna. The experiments should involve testing whether low-value non-tuna species (e.g., rainbow runner) are effective baits because this would help reduce costs.

4. Possible approaches to support further research

Given the investments already made by ISSF and other agencies, it is logical to build on the initiatives already underway to develop FAD fishing methods to reduce mortality of bigeye tuna. Investments should also be made to harness the experience and expertise of purse-seine captains and fishing masters. After all, many of the most effective methods for reducing unwanted catch, e.g., dolphin-free purse-seine fishing in the EPO, have been developed by fishermen. [See examples in reviews by Glass (2000), Kennelly (2007), Jordan et al. (2013) and papers collected by the Consortium for Wildlife Bycatch Reduction[6]].

Priority investments are:

1. Support for gear technologists and scientists to do the research in the four areas described in Section 3, including the costs involved in chartering purse-seine vessels to conduct experiments; and
2. Incentives for vessel owners, and manufacturers of acoustic equipment, to develop FAD fishing methods that greatly reduce the mortality of bigeye tuna.

Tuna in a purse-seine net (Photo: ISSF-Jeff Muir)

[6] www.bycatch.org/publications

Pressure from tuna retailers, among other groups, is expected to provide increasingly strong incentives to develop FAD fishing methods that take few if any bigeye tuna. However, one way of providing an appropriate incentive quickly, that has proved to be effective in helping to find technical solutions to other difficult problems, is organising a competition for a substantial prize. This type of incentive leads to the formation of creative research teams and usually leverages other sources of support to help solve the problem. A pertinent example is the ANSARI X Prize[7].

5. Conclusions

The prospect of developing FAD fishing methods that capture relatively few bigeye tuna is real – continued investment in acoustics research is expected to improve the ability of vessels to identify the species composition, relative abundance and size of tuna associated with FADs, opening the way for more selective fishing.

In the event that use of more sophisticated acoustics demonstrates that it is not as profitable to fish for skipjack tuna exclusively around FADs with few bigeye, there are a number of stimuli known to attract or repel fish, including tuna, which could be manipulated to separate bigeye from skipjack tuna during FAD fishing operations. The double FAD technology already under investigation by ISSF warrants further research. Although somewhat speculative, luring bigeye tuna away from FADs with dead bait also merits research because, if successful, it would negate the need for using double FADs.

The potential benefits of investments in developing purse-seine fishing methods that reduce the catch of bigeye tuna are far reaching, and include:

1. Paving the way to restore bigeye tuna stocks without eroding the value of the skipjack fishery;
2. Releasing small island states from the disproportionate conservation burden they are currently shouldering to reduce the fishing mortality of bigeye tuna associated with FADs;
3. Increasing yield-per-recruit for bigeye tuna by making a greater proportion of the stock available for capture at a larger size by the longline fishery; adding to the volume and value of the catch and creating opportunities to charge higher fishery access fees for longline vessels;
4. Improving consumer acceptance of FAD-caught tuna products; and
5. Enabling managers to focus on reducing other bycatch associated with FADs, e.g., sharks.

Acknowledgements

The authors thank John Hampton, Shelton Harley, David Itano, Simon Nicol, Victor Restrepo, Kurt Schaefer, Peter Sharples, William Sokimi and Sebastian Troeng for useful comments on the draft text and/or helpful discussions about the proposed areas of research. We also thank Nicole Han for the graphic design and layout of this report.

[7] www.ansari.xprize.org/

References

Allen S and Demer DA (2003) Detection and characterization of yellowfin and bluefin tuna using passive-acoustical techniques. *Fisheries Research* 63, 393-403.

Anon. (2015) Value creation opportunities for WCPO island nations in the tuna industry. Conservation International, Arlington, USA.

Ben-Yami M (1976) Fishing with Light. FAO, Rome.

Bertrand A and Josse E (2000) Tuna target-strength related to fish length and swim bladder volume. *ICES Journal of Marine Science* 57, 1143-1146.

Cocheret de la Moriniere E, Nagelkerken I, van der Meij H and Van der Velde G (2004) What attracts juvenile coral reef fish to mangroves: structural complexity or shade? *Marine Biology* 144, 139-145.

Dagorn L, Robinson J, Bach P, Deneubourg JL, Morena G, Di Natale A, Tserpes G, Travassos P, Dufosse L, Taquet M, Robin JJ, Valettini B, Afonso P and Koutsikopoulos C (2009) MADE: Preliminary information on a new EC project to propose measures to mitigate adverse impacts of open ocean fisheries targeting large pelagic fish. *Collective Volume of Scientific Papers, ICCAT* 64, 2518–2533.

Delgado de Molina A, Ariz J, Pallares P, Delgado de Molina R and Deniz S (2005) Tropical Tuna Acoustic Selectivity Studies and Experimental New FADs Ecologically Designed (Reducing By-Catch) Through Experimental Cruises in Spanish Purse Seiners in the Indian Ocean. IOTC-2005-WPBy-12.

Delgado de Molina A, Ariz J, Carlos Santana and Sotillo B (2010). Analysis of the catch rate of juvenile bigeye depending on the depth of the purse-seine net used by the tropical fleet. Western and Central Pacific Fisheries Commission, WCPFC-SC6-2010/FT- WP-0

Doherty P (1987) Light-traps: selective but useful devices for quantifying the distributions and abundances of larval fishes. *Bulletin of Marine Sciences* 41, 423-431.

Durand F and Delcroix T (2000) On the variability of the tropical Pacific thermal structure during the 1979–96 period, as deduced from XBT sections. *Journal of Physical Oceanography* 30, 3261–3269.

Forget FG, Capello M, Filmalter JD, Govinden R, Soria M, Cowley PD and Dagorn L (2015) Behaviour and vulnerability of target and non-target species at drifting fish aggregating devices (FADs) in the tropical tuna purse seine fishery determined by acoustic telemetry. *Canadian Journal of Fisheries and Aquatic Sciences.* doi: 10.1139/cjfas-2014-0458

Fuller DW and Schaefer KM (2014) Evaluation of a fishing captain's ability to predict species composition, sizes, and quantities of tunas associated with drifting fish-aggregating devices in the eastern Pacific Ocean. *ICES Journal of Marine Science* 71, 1774-1780.

Gabriel O, Lange K, Dahm E and Wendt T (eds) (2005) Fish Catching Methods of the World, 4th Edition. Blackwell, Oxford.

Glass CW (2000) Conservation of fish stocks through bycatch reduction: A review. *Northeastern Naturalist* 7, 395-410.

Hall M and Roman M (2013) Bycatch and Non-Tuna Catch in the Tropical Tuna Purse Seine Fisheries of the World. FAO Fisheries and Aquaculture Technical Paper No. 568, FAO, Rome.

Harley S, Davies N, Hampton J and McKechnie S (2014) Stock assessment of bigeye tuna in the Western and Central Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC–SC10–2014/SA–WP–01.

Harley S, Tremblay-Boyer L, Williams P, Pilling G, and Hampton J (2015) Examination of purse seine catches of bigeye tuna. Western and Central Pacific Fisheries Commission, WCPFC-SC11-2015/ MI-WP-07.

Hasegawa S, Takao Y, Oshima T, Iga H, Semba Y and Okamoto H (2010) Study on the methods to reduce the bycatch of juvenile bigeye tuna by purse seine operation on FADs in the western and central Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC-SC6-2010/ FT-WP-02.

Hedley C (2001) The 1998 agreement on the international dolphin conservation program: Recent developments in the tuna-dolphin controversy in the Eastern Pacific Ocean. *Ocean Development & International Law* 32, 71-92.

IATTC (2015) Summary of the fishery and assessments of the major stocks of tuna exploited in the eastern Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC-SC11-2015/ GN-WP-02

Imaizumi T, Abe K, Wang Y, Ito M, Matsuo I, Nishimori Y, Akamatsu T (2012) Classification of three tuna species in enclosures by using target strength spectra measured by a broadband split-beam system. *Journal Acoustical Society of America* 131, 3287.

Iverson RTB (1967) Response of yellowfin tuna (*Thunnus albacares*) to underwater sound. In: Marine Bio-acoustics, Volume 2 (Tavolga WN, ed) pp. 105-109, Permagon, New York.

Itano D (2005) A summarization and discussion of technical options to mitigate the take of juvenile bigeye and yellowfin tuna and associated bycatch species found in association with floating objects. Western and Central Pacific Fisheries Commission, WCPFC-SC1 FT WP-4.

Itano D, Schaefer K and Fuller D (2009) The use of underwater video to characterize the species, size composition and vertical distribution of tunas and non-tuna bycatch around floating objects. Western and Central Pacific Fisheries Commission, WCPFC-SC5-2009/FT-WP-03.

Jordan LK, Mandelman JW, McComb DM, Fordham SV, Carlson JK and Werner TB (2013) Linking sensory biology and fisheries bycatch reduction in elasmobranch fishes: a review with new directions for research. *Conservation Physiology* doi: 10.1093/conphys/cot002

Joseph J (1994) The tuna–dolphin controversy in the Eastern Pacific Ocean: Biological, economic, and political impacts. *Ocean Development & International Law* 25, 1-30.

Josse E and Bertrand A (2000) In situ acoustic target strength measurements of tuna associated with fish aggregating device. *ICES Journal of Marine Science* 57, 11-918.

Kennelly SJ (Editor) (2007) By-catch Reduction in the World's Fisheries. Springer, New York.

Kessler WS (2006) The circulation of the eastern tropical Pacific: a review. *Progress in Oceanography* 69, 181–217.

Lennert-Cody CE, Roberts JJ, Stephenson RJ (2007) Effects of gear characteristics on the presence of bigeye tuna (*Thunnus obesus*) in the catches of the purse-seine fishery of the eastern Pacific Ocean. *ICES Journal of Marine Science* 65, 970-978.

Leroy B, Itano DG, Usu T, Nicol SJ, Holland KN and Hampton J (2009) Vertical behavior and observation of FAD effects on tropical tuna in the warm-pool of the western Pacific Ocean. In: Nielsen JL, Arrizabalaga H, Fragoso N, Hobday A, Lutcavage M, Sibert J (eds) Reviews: Methods and Technologies in Fish Biology and Fisheries, Volume 9, Tagging and Tracking of Marine Animals with Electronic Devices, pp. 161–179, Springer, Berlin,

Leroy B, Itano DG, Usu T, Nicol SJ, Holland KN and Hampton J (2010) Vertical behavior and the observation of FAD effects on tropical tuna in the warm-pool of the western Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC-SC6-2010/FT-IP-01.

Leroy B, Scut-Phillips JS, Nicol S, Pilling GM, Harley S, Bromhead D, Hoyle S, Caillot S, Allain V and Hampton J (2013) A critique of the ecosystem impacts of drifting and anchored FADs use by purse-seine tuna fisheries in the Western and Central Pacific Ocean. *Aquatic Living Resources* 26, 49-61.

Lindell S, Miner S, Goudey C, Kite-Powell H and Page S (2012) Acoustic conditioning and ranching of Black Sea bass *Centropristis striata* in Massachusetts USA. *Bulletin Fisheries Research Agency* 35, 103-110.

Lopez J, Moreno G, Soria M, Cotel P and Dagorn L (2010) Remote discrimination of by-catch in purse seine fishery using fisher's echo-sounder buoys. Indian Ocean Tuna Commission, IOTC-2010-WPEB-03.

Lopez J, Moreno G, Sancristobal I and Jefferson M (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. *Fisheries Research* 155, 127-137.

Macaulay GJ, Kloser RJ and Ryan TE (2012) In situ target strength estimates of visually verified orange roughy. *ICES Journal Marine Science* 70, 215-222.

Marchesan M, Spoto M, Verginella L and Ferrero EA (2005) Behavioural effects of artificial light on fish species of commercial interest. *Fisheries Research* 73, 171-185.

Matsumoto T, Okamoto H and Toyonaga M (2006) Behavioral study of small bigeye, yellowfin and skipjack tunas associated with drifting FADs using ultrasonic coded transmitter in the central Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC-SC2-2006/FT IP-7

McKechnie S, Tremblay-Boyer L, and Harley SJ (2015) Longline CPUE indices for bigeye tuna based on the analysis of Pacific-wide operational catch and effort data. Western and Central Pacific Fisheries Commission, WCPFC-SC11-2015/SA-WP-02.

Miquel J, Delgado de Molina A, Ariz J, Delgado de Molina R, Déniz S, Díaz N, Iglesias M, Santana JC and Brehmer YP (2006) Acoustic selectivity in tropical tuna (experimental purse-seine campaign in the Indian Ocean). Indian Ocean Fisheries Commission, IOTC-2006-WPTT-06.

Montgomery JC, Jeffs A, Simpson SD, Meekan M and Tindle C (2006) Sound as an orientation cue for the pelagic larvae of reef fishes and decapod crustaceans. *Advances in Marine Biology* 51, 143-196.

Moon D-Y, An D-H, Hwang S-J and Kim S-S (2008) Preliminary information on the catch of small-sized tuna by set type of Korean tuna purse seine fishery in the WCPO. Western and Central Pacific Fisheries Commission, WCPFC-SC4-2008/FT-IP-5

Moreno G, Josse E, Brehmer P and Nøttestad L (2005) Observing tuna and their prey community around drifting FADs using a multi-frequency echosounder. 56th Tuna Conference, Lake Arrowhead, La Jolla, CA. Inter-American Tropical Tuna Commission and Southwest Fisheries Science Center.

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

Morgan AC (2011) Fish Aggregating Devices (FADs) and Tuna Impacts and Management Options. Ocean Science Series, PEW Environment Group.

Morón J (2008) Research on acoustic selectivity on FAD associated tropical purse seine fisheries. Western and Central Pacific Fisheries Commission, WCPFC-SC4-FT-SWG/WP-2.

Myrberg AA Jr, Ha SJ, Walewski S and Banbury JC (1972) Effectiveness of acoustic signals in attracting epipelagic sharks to an underwater sound source. *Bulletin of Marine Science* 22, 926-949.

Nelson P (2004) Technology related projects and proposals to mitigate bycatch levels in longline and purse seine fisheries. g) Reducing juvenile bigeye tuna mortality in FAD sets.. Inter-American Tropical Tuna Commission. 17th Standing Committee on Tuna and Billfish. FTWG-7g.

O'Driscoll RL, Oeffner J and Dunferd AJ (2012) In situ target strength estimates of optically verified southern blue whiting (*Micromesistius australis*). *ICES Journal Marine Science* doi:10.1093/icesjms/fss177

Okamoto H (2010) Application of broadband dolphin mimetic sonar for discriminating target fish species. Western and Central Pacific Fisheries Commission, WCPFC-SC6-2010/FT-WP-01.

Opnai LJ (2002) Summary of the FFC Species Working Group Meeting on options for bigeye management. SCTB 15 Working Paper FTWG-14.

Patrick PH, Christie A, Sager D, Hocutt C and Stauffer J Jr (1985) Responses of fish to a strobe light/air-bubble barrier. *Fisheries Research* 3, 157-172.

Popper AN and Carlson TJ (1998) Application of sound and other stimuli to control fish behaviour. *Transactions of the American Fisheries Society* 127, 673-707.

Restrepo V, Dagorn L, Itano D, Justel-Rubio A, Forget F and Filmalter JD (2014) A summary of bycatch issues and ISSF mitigation initiatives to-date in purse seine fisheries, with emphasis on FADs. ISSF Technical Report 2014-1, International Seafood Sustainability Foundation, Washington DC, USA.

Sancristobal I, Filmalter J, Forget F, Boyra G, Moreno G, Muir J, Dagorn L, Restrepo V (2014) International Seafood Sustainability Foundation's third bycatch mitigation research cruise in the WCPO. Western and Central Pacific Fisheries Commission, WCPFC-SC10-2014/EB-WP-08

Satoh K, Okamoto H, Takeuchi Y, Shono H, Matsumoto T, Watanabe K, Miyabe N and Honda H (2008) Effects of depth of underwater structures of FADs on catch of bigeye tuna (*Thunnus obesus*) in the tropical waters of the western Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC-SC4-2008/FT-WP-1

Satoh K, Hasegawa S, Oshima T, Inagake D, Kawamoto T et al. (2012) Review of Japan's approaches to reduce bycatch of juvenile bigeye tuna by purse seine on FADs in tropical area of the western and central Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC-SC8-2012/ EB-WP-15

Schaefer KM and Fuller DW (2005) Behavior of bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*) tunas within aggregations associated with floating objects in the equatorial eastern Pacific. *Marine Biology* 146, 781-792.

Schaefer KM and Fuller DW (2008) Acoustic imaging, visual observations, and other information used for classification of tuna aggregations associated with floating objects in the Pacific Ocean. Western and Central Pacific Fisheries Commission, WCPFC-SC4-2008/FT-IP-2.

Schaefer KM and Fuller DW (2013) Simultaneous behavior of skipjack (*Katsuwonus pelamis*), bigeye (*Thunnus obsesus*), and yellowfin (*T. albacares*) tunas, within large multi-species aggregations associated with drifting fish aggregating devices (FADs) in the equatorial eastern Pacific Ocean. *Marine Biology* 160, 3005-3014.

Schaefer K, Fuller D, Hampton J, Caillot S, Leroy B, and Itano D (2015) Movements, dispersion, and mixing of bigeye tuna (*Thunnus obesus*) tagged and released in the equatorial Central Pacific Ocean, with conventional and archival tags. *Fisheries Research* 161, 336– 355.

Simmonds EJ and MacLennan DN (2005) Fisheries Acoustics: Theory and Practice, Second Edition. Blackwell Science, London.

Sokimi W and Beverly S (2010) Small-scale Fishing Techniques Using Light: A Manual for Fishermen. Secretariat of the Pacific Community, Noumea.

Stewart J, Ferrell DJ, van der Walt B, Johnson D and Lowry M (2001) Assessment of length and age composition of commercial kingfish landings. NSW Fisheries Final Report Series, No.36, http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/545620/FFRS-36_Stewart-et-al-2001.pdf

Verweij MC, Nagelkerken I, de Graaff D, Peeters M, Bakker EJ and van der Velde G (2006) Structure, food and shade attract juvenile coral reef fish to mangrove and seagrass habitats: a field experiment. *Marine Ecology Progress Series* 306, 257-268.

WCPFC (2008) The Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean, 2008, conservation and management measure for bigeye and yellowfin tuna in the western and central Pacific Ocean., Conservation and Management Measure 2008-01 WCPFC5.

WCPFC (2009) The Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean, 2009, conservation and management measure on the application of high seas FAD closures and catch retention., Conservation and Management Measure 2009-02 WCPFC6.

WPRFMC (2015) Draft Report of the Western and Central Pacific Ocean Purse Seine Bigeye Management Workshop. Western Pacific Regional Fishery Management Council, Honolulu, Hawaii

Williams P and Terawasi P (2015) Overview of tuna fisheries in the Western and Central Pacific Ocean, including economic conditions – 2014. Western and Central Pacific Fisheries Commission, WCPFC-SC11-2015/GN WP-1

Wright BG (2000) Environmental NGOs and the dolphin–tuna case. *Environmental Politics* 9, 82-103.

Yan HY, Anraku K and Babaran RP (2010) Hearing in marine fish and its application to fisheries. In: Behaviour of Marine Fishes: Capture Processes and Conservation Challenges (He P, ed) pp. 45-64. Wiley-Blackwell, Ames, Iowa.

Back Cover Photo

Purse-seine fishing for skipjack tuna (Photo: SPC)