frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 13 February 2023
DOI 10.3389/fmars.2023.1074340

Check for updates

OPEN ACCESS

EDITED BY
Steven Mackinson,
Scottish Pelagic Fishermen's Association,
United Kingdom

REVIEWED BY
Tiago Veiga-Malta,
Technical University of Denmark, Denmark
Alain Henri
Fonteneau, Saint Malo, France

*CORRESPONDENCE
Jefferson Murua
jmurua@azti.es

SPECIALTY SECTION
This article was submitted to
Marine Fisheries, Aquaculture and Living
Resources,
a section of the journal
Frontiers in Marine Science

RECEIVED 19 October 2022
ACCEPTED 16 January 2023
PUBLISHED 13 February 2023

CITATION
Murua J, Moreno G, Dagorn L, Itano D,
Hall M, Murua H and Restrepo V (2023)
Improving sustainable practices in tuna
purse seine fish aggregating device (FAD)
fisheries worldwide through continued
collaboration with fishers.
Front. Mar. Sci. 10:1074340.
doi: 10.3389/fmars.2023.1074340

Improving sustainable practices in tuna purse seine fish aggregating device (FAD) fisheries worldwide through continued collaboration with fishers

Jefferson Murua[1]*, Gala Moreno[2], Laurent Dagorn[3], David Itano[4], Martin Hall[5], Hilario Murua[2] and Victor Restrepo[2]

[1]Sustainable Fisheries Management Tuna Department, AZTI-Tecnalia, Sukarrieta, Spain, [2]International Seafood Sustainability Foundation, Pittsburgh, PA, United States, [3]Marine Biodiversity, Exploitation and Conservation (MARBEC), University of Montpellier, Centre National de la Recherche Scientifique (CNRS), Ifremer, Institut de Recherche pour le Développement (IRD), Sète, France, [4]Opah Consulting, Honolulu, Hawaii, HI, United States, [5]RedCID Red para el estudio de capturas incidentales y Descartes, San Diego, CA, United States

More than a decade of bottom-up collaborative workshops and research with fishers from the principal tropical tuna purse seine fleets to reduce ecological impacts associated with the use of fish aggregating devices (FADs) has yielded novel improved sustainable fishing practices in all oceans. This integrative effort is founded on participatory knowledge-exchange workshops organized by the International Seafood Sustainability Foundation (ISSF), referred to as "ISSF Skippers Workshops", where scientists, fishers, and key stakeholders examine and develop together ways and tools to minimize fishery impacts. Workshops organized since 2010 have reached fleet members in 23 countries across Asia, Africa, the Americas, Europe, and Oceania, with over 4,000 attendances, mostly skippers and crew, operating in the Indian, Atlantic, and Pacific oceans. Structured and continued open transparent discussions on ocean-specific options to minimize FAD associated bycatch, ghost fishing and marine pollution have produced an array of novel co-constructed solutions and a better understanding of ecosystem and fishery dynamics. Dedicated at sea research cruises in commercial purse seiners have enabled testing some of the ideas proposed in workshops. Results obtained were then communicated back to fishers for a double loop learning system resulting in solution refinement and/or adoption. Furthermore, fishers' increased trust and stewardship have stimulated unprecedented large-scale science-industry research projects across oceans, such as multi-fleet biodegradable FAD trials, the adoption and widespread use of non-entangling FADs, and the development and adoption of best practices for the safe handling and release of vulnerable bycatch. This model of collaborative research is broadly applicable to other natural resource conservation fields. Support for long-term inclusive programs enabling harvesters to proactively collaborate in impact mitigation research contributes to improved scientific advice, voluntary compliance, and adaptive management for lasting sustainability trajectories.

KEYWORDS

participatory approach, fishers ecological knowledge, tuna fisheries, bycatch mitigation, fish aggregated devices (FADs), co-management, elasmobranch conservation, purse seiners

1 Introduction

Marine ecosystems worldwide are affected by fishery impacts including overfishing, bycatch, marine pollution, and ghost fishing (Kelleher, 2005; Dagorn et al., 2012; Hall et al., 2013; Komoroske and Lewison, 2015; Pauly and Zeller, 2016; Stelfox et al., 2016; Strain et al., 2022). Minimizing these fishery impacts has long been a primary focus on fisheries management, but conservation measures have frequently failed to deliver expected outcomes (Chapin et al., 2009; Gilman et al., 2014). Many attribute this shortfall to bottlenecks arising from poor understanding of fishery system complexities, particularly fishers' dynamic behaviours and strategies towards resource exploitation and regulatory frameworks (Hilborn, 1985; Nielsen and Vedsmand, 1999; Salas and Gaertner, 2004; Leslie and McLeod, 2007; Iwane et al., 2021). As McGrath and Castello (2015) pointed out, it is increasingly apparent that fisheries management is not about managing fish but fishers and understanding the social and economic circumstances driving their behaviours. Highly centralized management approaches have been criticized for institutionalised inertia and stakeholder exclusion leading to polarization and poor compliance associated with illegitimacy perceptions by fishers (Nielsen and Holm, 2007; Rohe et al., 2017; Oyanedel et al., 2020; Guirkinger et al., 2021). Therefore, designing technically sound conservation management measures does not ensure effective implementation as, if these are considered unfair by fishers, they will find ways to circumvent such measures (e.g., "fishing the line"), especially in the absence of strong monitoring, control and surveillance systems (Horta e Costa et al., 2013; Guirkinger et al., 2021).

While top-down fisheries management remains the prevalent *status quo*, in recent years several national and international fisheries bodies have attempted greater stakeholder integration (e.g., Canada's Pacific Integrated Commercial Fisheries Initiative, European Union's Long Distance Fleet Advisory Council, etc.) (Stephenson et al., 2016; Holm et al., 2020). However, most inclusive research and cooperative management initiatives have been based on small-scale artisanal fisheries, possibly due to their simpler stakeholder structure and reduced geographical scope facilitating co-management approaches (Carr and Heyman, 2012; Trimble and Berkes, 2013; Saavedra-Diaz et al., 2015; Karr et al., 2017; Chuenpagdee and Jentoft, 2018; d'Armengol et al., 2018; Garza-Gil et al., 2020). In large-scale transoceanic fisheries, achieving representative fisher participation is substantially more challenging due to their widespread distribution, long periods at sea and multiple fleet nationalities and strategies with competing objectives (Torres-Irineo et al., 2014; Tickler et al., 2018). In general, international governance bodies employ industry associations to make participation numbers manageable and facilitate consensus reaching (Mackinson et al., 2020). For example, in tuna regional fisheries management organizations (tRFMOs), which oversee multiple fleet nationalities and various fishing gears (e.g., longline, pole and line, purse seine, handline, driftnets, recreational, etc.), it is often centralised ship-owner associations who represent industry and interact with policymakers. However, tuna fishers' views and interests are wide-ranging and can often differ from other industry stakeholders such as ship-owners, producers, or retailers (Sampedro et al., 2017; Airaud et al., 2020). Thus, so-called bottom-up approaches in fishery governance would be better defined as "middle-up" processes, due to the absence of direct fisher involvement (e.g., captains, navigators, deck crew). This widespread exclusion of fishers from decision-making processes generates a profound sense of disempowerment and mistrust towards fisheries managers and scientists and potentially foments lower compliance of regulations from which they feel disconnected (Dorner et al., 2015; Linke et al., 2020). Conservation measures are only as effective as their correct day-to-day implementation at sea, which ultimately rests in the hands of fishers. Developing long-lasting conservation solutions requires well thought mitigation strategies, but perhaps more importantly a more inclusive decision-making process which prevents conflict between players and increases voluntary compliance through a sense of fairness and stewardship (Mackinson et al., 2011; Hansen, 2014; Chapin et al., 2015; Aswani et al., 2018; Mackinson and Middleton, 2018; West et al., 2018; Mathevet et al., 2018; Rudolph et al., 2020).

In addition, the exchange of knowledge between fishers and scientists is known to significantly contribute to a deeper understanding of complex and dynamic fishery-ecosystem interactions (Johannes et al., 2000; Branch et al., 2006; Field et al., 2013; Giareta et al., 2021; Leduc et al., 2021). Fishers' inputs can provide timely and accurate fleet dynamics explanations to alterations in catch rates to inform stock status, including adoption of new fishing technologies and strategies in reaction to competitors and regulations (Moreno et al., 2007a; Moreno et al., 2007b; Carruthers and Neis (2011); Lopez et al., 2014; Torres-Irineo et al., 2014; Jaiteh et al., 2016; Sampedro et al., 2017). Furthermore, experienced fishers have valuable empirical knowledge on historical species distribution and abundances, and fishing technology evolution, which can help better characterize long and short-term population changes and effort creep, respectively. This non-official source of information is not only very useful in poorly monitored small scale artisanal fisheries

(Johannes, 1998; Saldana-Ruiz et al., 2017; Alfaro-Shigueto et al., 2018; Berkstrom et al., 2019; Hunnam et al., 2021), but also in data-rich industrial fisheries with rapid technological shifts and complex fleet tactics (Moreno et al., 2007a; Moreno et al., 2007b; Carruthers and Neis, 2011; Lopez et al., 2014; Macusi et al., 2017; Torres-Irineo et al., 2017). Furthermore, fishers' deep practical understanding of how fishing gear works and interacts with different species, gained through years of conducting fishing operations under varying conditions, is extremely valuable to improve selective fishing gear and practices (Hall, 2007; Jenkins, 2010; Poisson et al., 2014; Da Veiga Malta et al., 2019). This in-depth technical knowledge of gear and fishing strategy is often difficult to find among researchers, as most current scientific disciplines focus on other aspects (e.g., fish biology, population dynamics, oceanography). Even studies by fisheries technologists on industrial purse seine fishing gear are scarce and mostly theoretical (Kim and Park, 2009; Zhou et al., 2019), which warrants more cooperative work with fishers for access to at-sea gear trials. These exchanges of knowledge from fishers to scientists and vice versa are also an excellent way of establishing mutual respect, by highlighting the additive value of connecting both kinds of expertise (Mackinson, 2001; Wedemeyer-Strombel et al., 2019; Pereyra et al., 2021).

In past decades, the few cooperative approaches involving direct fisher participation in tuna industrial-scale fisheries were often a last-resource reaction to crisis events (Joseph, 1994; Roheim and Sutinen, 2006). For example, in the 1970s after strong public pressure to reduce dolphin mortality in the Eastern Pacific Ocean purse seine tuna fishery, fishers engaged with the Inter American Tropical Tuna Commission (IATTC) scientists in participatory workshops to co-create novel dolphin-safe gear (e.g., the Medina panel, named after the inventor captain Harold Medina) and release techniques (e.g., backdown procedure) (Hall, 1998; Hall, 2007). Since 1992 the Agreement of the International Dolphin Conservation Program (AIDCP) ensures that every new skipper in the IATTC intending to perform sets on dolphin-tuna aggregations completes training in best dolphin-safe practices to ensure the application of correct mitigation procedures, backed up by a penalty system for vessels exceeding dolphin mortality limits (Hall, 1998). Today dolphin mortality has been dramatically reduced in the fishery (Hall, 2007; Ballance et al., 2021). Despite the remarkable success of this sustained collaborative approach, surprisingly the AIDCP remains the only tuna RFMO that integrates a long-term program with captains and crew for best practice training.

In tropical tuna fisheries around 5 million tonnes were caught in 2020, of which 66 percent of the total catch is made by purse seiners with 36 percent deriving from sets on fish aggregating devices (FADs), 27 percent from unassociated sets and 3 percent from dolphin sets, which are only observed in the Eastern Pacific (ISSF, 2022). Both artisanal and industrial tuna fisheries have employed for decades FADs because they attract diverse species of fish, including tunas (Taquet et al., 2007), but their numbers and catches have rapidly increased in recent decades (Fonteneau et al., 2013; Hall and Roman, 2013; Maufroy et al., 2016; Dupaix et al., 2021). Initially these FADs were fixed in space i.e., anchored FADs (aFADs), but with the advent of radio tracking buoys and later GPS-geolocating buoys, enabling fishers to accurately track FAD position, man-made drifting FADs (dFADs) grew in number and efficiency (Lopez et al., 2014; Wain et al., 2021). Traditionally dFADs were built with durable and cheap reused materials such as plastic net corks for floatation and old purse seine net panels hanging under the water's surface to slow down drift and provide shade, both characteristics considered by fishers helpful to encourage tuna aggregation (Itano et al., 2004; Moreno et al., 2022). Because FAD fishing has been associated with several ecological impacts such as increases in juvenile tuna catch, vulnerable species bycatch, marine pollution and potential ecological traps (Marsac et al., 2000; Hallier and Gaertner, 2008; Dagorn et al., 2012), pressure by environmental non-government organizations (ENGOs) grew to advocate for improved FADs management in recent years. In addition to a greater number of RFMO conservation measures to limit FAD effects (e.g., FAD closures, FAD limits), this elicited a reactive response by the tuna retailers and industry to reduce FAD fishery impacts. Science-industry partnerships, such as the International Seafood Sustainability Foundation (ISSF), were borne around this time to address these and other sustainability concerns in tuna fisheries (e.g., IUU fishing, overcapacity, etc.) through the support of high-quality research and direct collaboration with tuna fleets to provide science-based solutions. In 2010 ISSF launched the Bycatch Project to develop best practices in tuna purse seine fisheries operating with FADs to mitigate ecosystem impacts. This was articulated through cooperative research actions with fishers, with the hope of reaching practical and effective solutions quickly. Also, measures developed jointly by fishers and scientists would presumably improve their implementation. At the base of this scientific research was a series of participatory workshops, referred to as "ISSF Skippers Workshops", in which tuna purse seine fishers and other key fishery stakeholders engaged with scientists and contributed their knowledge and perspectives to find corrective protocols and technology to reduce unwanted ecological impacts. The workshops were viewed as a scientist-fisher integrative global effort that reached the principal tropical tuna regions and international purse seine fleets. In this paper, we describe the process, lessons learned, and progress made in tuna fisheries to improve sustainable practices through this multi-ocean international collaborative research action program with fishers started in 2010 and still ongoing as of 2022.

2 Methods

2.1 ISSF bycatch project

The ISSF Bycatch Project is based on three interconnected pillars: (1) a Bycatch Committee (BC) formed by a team of experienced fisheries scientists with transdisciplinary expertise (i.e., ecology, animal behaviour, fishing technology, stock assessment, fish biology, etc.), (2) bycatch mitigation workshops with fishers and other stakeholders (i.e., ISSF Skippers Workshops), and (3) scientific research cruises onboard vessels to test impact mitigation ideas proposed by BC members and fishers.

Interactions between these three elements yielded a number of positive outcomes (Figure 1). Initially, impact mitigation research options favoured by the BC were presented to fishers in the workshops and their acceptance level recorded. Mitigatory options were categorized by scientists according to species group and time of

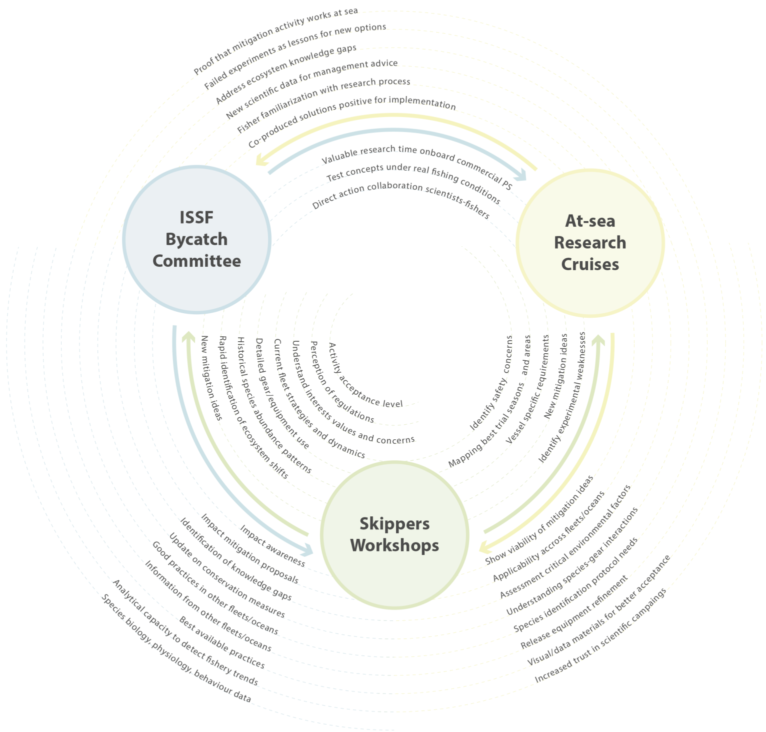

FIGURE 1
Flow chart between the three elements of the ISSF Bycatch Project: (1) Scientific Bycatch Committee, (2) Skippers Workshops, and (3) research cruises.

execution during the purse seine fishing operation (e.g., before, during or after the set) (Table 1). Fishers could propose improvements to these proposals or suggest new options to be tested. After the fishers' feedback, BC scientists regrouped and decided which mitigation actions to test in the research cruises. At sea mitigation activity trial results were communicated back to fishers in subsequent workshops to propose their adoption if successful, refine solutions if needed, or discard if clearly ineffective.

2.2 ISSF skippers workshops

The participatory workshops covered information on global tuna fisheries statistics and management, biology of species and a range of fishery mitigation topics including endangered, threatened, and protected (ETP) species bycatch mitigation, juvenile yellowfin and bigeye tuna catch reduction, FAD ghost fishing prevention, and marine pollution reduction. In addition, related RFMO conservation measures and their alignment with current fishing strategies were discussed, including opinions on the efficiency of regulations such as FAD closures and limits. Also, some bycatch related conservation measure infractions were mentioned in the workshops (e.g., the illegality and penalties for shark finning). However, in general, the workshops were not about dealing with IUU practices (e.g., transhipment issues, seeding FADs in unauthorized EEZs), as otherwise fishers could misunderstand the purpose of the meeting and become highly defensive. These matters are better left to monitoring and management agencies who can track these illegal practices through observer reports or dFAD buoy data and apply the corresponding penalties. Additionally, the growing market demand for sustainable fish sources (e.g., eco-certified fisheries) was discussed at workshops to raise fisher awareness on this subject.

A presentation helped guide the meetings, in which technical scientific jargon was avoided, instead focusing on clear language and visual user-friendly materials (e.g., maps, photos, illustrations, videos) showing examples of best practices and trial results. Presentations were regularly updated, including the latest findings from ISSF's own research cruises, other scientific groups elsewhere, the peer-reviewed literature and good practices learned during exchanges with fishers from different fleets.

Invitation to the workshops was often coordinated with help of the different local purse seine associations and tried to target locations and times favourable for higher fisher presence. This included workshops during unloading peak seasons at major tuna fishing ports such as Majuro (Republic of the Marshall Islands), Pohnpei (Federated States of Micronesia), Tema (Ghana), Jakarta (Indonesia) or Port Victoria (Seychelles), and in well-known purse seine fishers' hometowns during FAD fishery closures when many returned home, including Bermeo (Spain), Concarneau (France), Manta (Ecuador), Busan (South Korea), Shanghai (Peoples Republic of China), Madeira (Portugal) or Zadar (Croatia). Note that Portugal and Croatia do not have a tropical tuna purse seine fleet *per se*, but many fishers from these countries have been working on vessels of the Pacific Ocean since the 1960s. Meanwhile countries like Peru are rebuilding their tuna fishery (i.e., 14 purse seiners as of 2022) and raising bycatch mitigation awareness in this fleet is especially critical due to their rich waters being among the most important hotspots for sharks and rays worldwide (Lezama-Ochoa et al., 2019; Gonzalez-Pestana et al., 2021). Additional to the ISSF Skipper Workshops other parallel sustainability initiatives (e.g.,

TABLE 1 ISSF Skippers Workshops 2010- 2019 by location and participant number by work occupational group.

Continent	Location	No. WS	Skippers	Crew	Ship-owners	Fleet Mangs.	Fleet Reps	Gov. Mangs.	Scientists	Total participations
Africa	Ghana (Accra, Tema)	9	108	95	25	43	131	33	9	444
	Mauritius (Port Louis)	1	5	3	0	0	1	0	0	9
	Senegal (Dakar)	1	4	3	0	3	3	3	2	18
	Seychelles (Mahe)	1	6	2	0	0	0	1	0	9
Europe	Croatia (Zadar)	1	8	0	0	0	0	0	1	9
	France (Concarneau)	4	67	16	0	8	8	0	8	107
	Portugal (Madeira)	1	4	19	0	0	2	0	1	26
	Spain (Sukarrieta, Bermeo, Cangas, Vigo)	15	587	238	10	14	45	2	19	915
America	Ecuador (Manta, Posorja)	12	546	292	10	24	42	4	14	932
	Mexico (Mazatlan, Manzanillo)	3	110	71	1	3	5	8	2	200
	Panama (Panama City)	3	14	6	3	1	9	6	14	53
	Peru (Lima)	4	41	18	3	5	49	15	40	171
	USA (San Diego)	3	21	1	5	5	9	1	1	43
Asia	Indonesia (Bitung, Kendari, Benoa Jakarta, Sibolga, Banda Aceh, Prigi, Pekalongan, Makasar, Manado,Ambon)	24	512	145	4	20	30	92	42	845
	Japan (Yaizu)	1	1	0	0	0	17	0	11	29
	Philippines (General Santos)	3	58	13	2	5	15	4	24	121
	People's Republic of China (Shangai, Zhousan)	2	18	1	0	10	13	0	9	51
	South Korea (Busan)	2	16	9	0	2	18	5	37	87
	Taiwan (Kaoshioung)	1	1	0	0	6	12	0	0	19
	Vietnam (Quy Nohn)	1	42	0	0	0	13	0	3	58
Oceania	American Samoa (Pago Pago)	3	13	3	2	1	11	3	5	38
	Federated States of Micronesia (Ponphei)	2	10	5	1	0	4	0	0	20
	Republic of the Marshall Islands (Majuro)	4	27	11	0	3	7	2	1	51
Total		101	2219	951	66	153	444	179	243	4255

observer training programs, deck crew trainings, biodegradable FAD projects) coordinated by other scientific teams have complemented mitigation training needs in several regions.

Workshop duration was usually 4-5 hours maximum, as fishers are not used to long meetings and have busy schedules. Workshop organization was usually coordinated with help from ship owners, purse seine fleet associations and other key industry contacts. In some workshops interpreters were hired for translation. While the primary target audience was fishers including captains, navigators, chief engineers, officers, deck bosses and deck crew, the workshops were also open, free of charge, to all fishery stakeholders such as ship-owners, fleet managers, local fisheries scientists, fisheries managers, conservation group members, etc who voluntarily participated. The workshops have been financially supported up to now by ISSF and various funders (see Acknowledgments).

Most workshops were presented by two tuna fisheries scientists, one being an expert in a particular region (e.g., Indian, Atlantic, Eastern Pacific or Western and Central Pacific Oceans), the other being the workshop program coordinator, who was present in practically all workshops worldwide. The scientific coordinator figure ensured workshop harmonization across regions and direct collection and transference of knowledge gained between the different workshops. Importantly, fishers in a given region would always interact with the same two scientists (i.e., regional expert and workshop coordinator), year-after-year, thus gradually building a relationship of trust and mutual understanding.

During each fleet's workshops, the degree of acceptance level of proposed impact mitigation activities was recorded. Acceptance levels were usually based on participants' perceptions of the probability of success at sea and on how they viewed these approaches affecting their daily fishing routines (i.e., efficiency and practicality) and catches. For example, if an activity could result in a significant detriment to fishers, such as high risk of target catch loss or physical danger to crew, it would usually receive poor acceptance even if it was technically efficient at reducing an environmental impact. Categories of acceptance were scored as low, mid, and high, or a combination of these, based on the comments and feedback by workshop participants. For example, when most fishers in a workshop supported an activity (i.e., > 70%), it was considered high acceptance, but if many fishers provided negative comments, it was scored as low acceptance (i.e., < 50%). When only part of the fishers in the workshops viewed an activity as positive (i.e., 50-70%) or thought that more work was necessary to better develop a practice, then a medium acceptance score was assigned. This may not necessarily represent all opinions across a given fleet but served as a useful indicator to guide scientists on which activities would be easier to find support from fishers to test cooperatively, versus other options which would encounter strong industry opposition and be less likely voluntarily adopted. After each workshop, scientists produced a standardized report for the BC describing key points and acceptance levels by each fleet.

During the workshop, a voluntary anonymous multiple-choice questionnaire with different options around fishery practices covering a range of mitigation subjects was completed by participants. Questions were regularly reviewed and updated to collect useful information on topics of interest (e.g., adoption of best release practices, characteristics of FADs used, evolving fishing strategies, echo-sounder buoys employed, etc.). The questionnaire allowed quantifying fishers' responses and provided them a chance to contribute with their knowledge and perspectives, especially for those fishers that due to their character were more reserved during plenary discussions.

In addition to the standard ISSF Skippers Workshops, ISSF has also organized participatory workshops with purse seine fishers but focusing on a particular topic of interest such as FAD retrieval, biodegradable FADs, etc. at locations including Spain, Philippines, Federated States of Micronesia, and Papua New Guinea (Moreno et al., 2016; Moreno et al., 2018). These workshops are not counted in the results section because they did not cover the full range of impact mitigation subjects of the standard workshops.

For those tuna fishers not able to attend particular workshops, ISSF has produced free online training tools. ISSF provides fishers with easily accessible downloadable best practice guidebooks (http://www.issfguidebooks.org/) and pre-recorded workshop videos in English and with subtitles in various languages (https://www.youtube.com/watch?v=hXlgHWhIAeQ). In addition, ISSF websites offer free access to other instructional materials, such as research reports, guides on species identification, etc.

2.3 Train-the-trainer programs

Some tuna fleets in developing countries despite being primarily composed of artisanal purse seiners, due to the sheer number of vessels and rich fishing grounds, represent a significant portion of global catches. For example, Indonesia provides over 15 percent of the world's tuna supply, being the top tuna producing country in the world. These fleets are often widely distributed across numerous small ports. Reaching a representative proportion of fishers to raise awareness is logistically very challenging. Furthermore, many of these fishers may be affected by illiteracy and lower access to online training tools.

To address these training difficulties a train-the-trainer program was set up in the Indonesian archipelago, in which a group of experienced tuna scientists from the Indonesian Centre for Fisheries Research and Development (CFRD) were trained to conduct workshops with fishers during their regular trips to many fishing ports. This helped reach a larger number of fishers through in-person workshops during opportunistic and planned port visits.

Recently, ISSF started expanding their train-the-trainer program to other tuna fishing gears such as longline. Again, longline fishers are difficult to reach at one given time and location. To increase chances of engagement with longline fishers, in-port stationed personnel from several fishing companies have been trained by scientists to show fishers best mitigation practices and collect feedback opportunistically when vessels arrive to unload the fish. These workshops are not computed in the results section as they began in 2020.

2.4 In port vessel visits

For workshops taking place at key ports, typically ISSF scientists made visits to available vessels. During ISSF Skippers Workshops contact was made with ship-owners and fishers who had vessels in port to arrange visits to their vessels. Those visits helped scientists to learn first-hand about the fishing technology on the bridge, types of FADs, and the equipment employed on the deck. This was especially helpful in semi-industrial fleets, like the Indonesian or Vietnamese, for which detailed vessel technology and FAD design is sparce. Also, those visits allowed for a more personalised and informal interaction with fishers to review the topics addressed during the workshop (Figure 2). Visits also show fishers that scientists are interested in learning about the vessels they work in and particular circumstances that might affect the application of mitigation options.

2.5 ISSF research cruises

At sea trials were conducted to examine the viability of several mitigation actions proposed by fishers and scientists. The majority of research cruises involved testing the efficacy of novel developments in technology or operational protocols in large-scale purse seiners (e.g., 800-2500 GT). In particular instances, field work was also carried out on smaller scale research vessels. Both purse seine and small vessel research cruises were either fully chartered for dedicated ISSF Bycatch Project research or alternatively scientists embarked opportunistically. For opportunistic research on commercial purse seine fishing trips, ISSF arranged several meetings to pre-establish and agree with ship-owners and fishers the mitigation activities to be tested and under which conditions. Those meetings were key to solve concerns and make sure that everyone understood the work to be done onboard. This was often reflected in contracts signed between the parties involved.

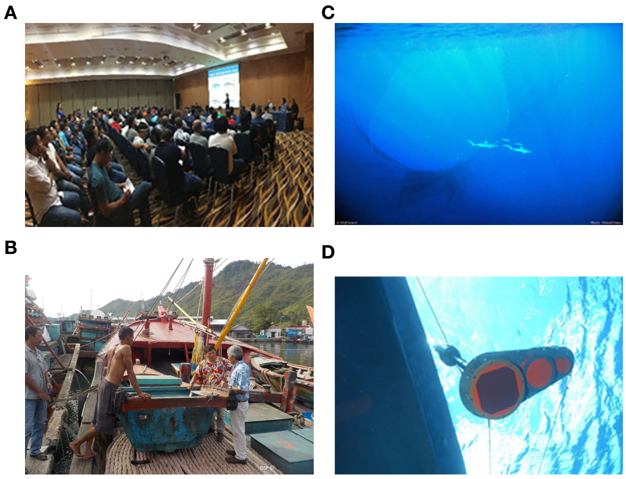

FIGURE 2
ISSF scientists and fishers **(A)** in a large-scale workshop at Manta (Ecuador), **(B)** during a visit to a small-scale purse seiner in Sibolga (Indonesia), **(C)** trials with shark escape windows in the net in the Western Pacific Ocean, and **(D)** multi-frequency echosounder transducers to improve tuna species discrimination in FADs tested during research cruises.

From the outset, the plan was to conduct research cruises in different types of vessels and in fishing areas to cross-examine the efficacy and implementability of mitigation activities in different oceanic regions. Also, fishers of the different flags involved in opportunistic research cruises contributed fleet- and ocean-specific knowledge to improve the studies. For some of the activities in recent years, especially non-entangling and biodegradable FAD trials, voluntary opportunistic research scaled up from work on single vessels to whole fishing company or even fleet level.

Complimentary to the research on vessels, a series of experimental works were undertaken in controlled scenarios such as laboratories, in offshore fish cages or marine protected coastal areas, to investigate parameters of interest such as characterizing the rate of erosion of biodegradable FAD materials or determining the acoustic signature of different tuna species and sizes to study acoustic discrimination.

2.6 Proactive vessel register

In 2012, ISSF created the Proactive Vessel Register (PVR) which enabled tuna vessel owners to identify themselves as active participants in meaningful sustainability efforts, such as implementing specific best practices. Participating vessels are regularly audited by independent accredited consultants (e.g., MRAG-Americas) to verify these sustainable actions. Tuna purchasers and other stakeholders can easily check the freely available online PVR information on hundreds of vessels worldwide (https://iss-foundation.org/knowledge-tools/databases/proactive-vessel-register/) and make informed decisions for sustainable tuna sourcing. For example, tuna traders and processor members of the International Seafood Sustainability Association (ISSA) committed to purchasing tuna only from vessels that comply with certain ISSF Conservation Measures and the PVR is a platform that tracks whether vessels are complying with them. Thus, adhering to sustainability requirements should favor market accessibility for PVR members. As of the 24th August 2022, 1,410 tuna vessels are registered, of which 489 are large-scale tropical tuna purse seiners, representing three-quarters of the large-scale tuna purse seiners worldwide (Justel-Rubio and Recio, 2022).

One of the sustainability actions reflected in the PVR is having the skippers of purse seine listed vessels trained in best mitigation practices. Skippers can become certified in best practices by attending in-person ISSF Skippers Workshops or completing the online Skipper Guidebooks. Skippers benefit from having the PVR certification as many fishing companies request it when recruiting personnel.

3 Results

3.1 ISSF Skippers workshop locations and participation

Participatory workshops have been attended by members of the principal tropical tuna purse seine fleets operating in the Indian, Atlantic, Eastern Pacific and Western and Central Pacific Oceans. Between 2009-2019 a total of 101 ISSF Skippers Workshops were conducted in 23 countries, reaching a total of 4,255 participations (Table 1). In some instances, certain fishers would repeat participation in workshops for a given location over the years. By continent, Asia was the region with more workshops (34%), mostly due to the strong effort in the Indonesian aFAD fishery with the train-the-trainer program delivering 24 workshops. North and South America yielded 25% of the global workshops, in which Ecuador, with 12 workshops, was the primary country due to its importance as the largest tuna purse seiner fleet in the Eastern Pacific Ocean. About 20% of workshops were conducted in Europe, mostly in Spain (15), as its associated vessels operate in all tropical tuna RMFO regions and amount 10% of global catches, followed by France with 4 workshops. In the African continent 12 workshops were organized, most taking place in Ghana (9) due to the importance of this fleet in the Eastern

Atlantic Ocean. Finally, 9 workshops were conducted in Oceania, targeting key island nation ports like Pago Pago (American Samoa), Majuro (Republic of the Marshall Islands) and Pohnpei (Federated States of Micronesia) where a variety of domestic or domestically based and distant water fishing (DWF) fleets operate year-round.

Overall, workshop composition by working occupation was dominated by fishers, skippers being the largest group of attendants (53%), followed by fishers occupying other crew positions (e.g., deck bosses, deck crew, chief engineers, officers) (22%). In the non-fisher professions, the largest group was fleet representatives (e.g., fleet managers, vessel inspectors, operations managers, assistant managers) (14%), followed by fisheries scientists (6%), governmental agency fisheries managers (4%), and ship-owners (1%). Note that some fishers and other stakeholders have participated in several workshops over the years, thus the total number of unique participants would be lower than the number of participations. Nevertheless, given the workshops' geographical scope and continued interactions over time significant portions of fishers in various fleets were reached. This is especially true in locations such as Ecuador (932 participations), Spain (915), Indonesia (845), or Ghana (444), where workshops were held almost yearly.

3.2 Acceptance level for impact mitigation activities

Several mitigatory activities for different animal groups were openly talked about with fishers in the workshops (Table 2). Due to the short duration of the workshops not all actions were presented in each workshop, but usually the principal topics were discussed (e.g., non-entangling and biodegradable FADs, vulnerable species best

TABLE 2 ISSF Bycatch Project mitigation activities discussed between scientist and fishers during the ISSF Skippers Workshops, by species groups and time in the fishing operation (1) before, (2) during and (3) after the set.

Species Group	Activity	Description
Sharks & Rays	(1) Shift effort from FADs to free schools	In most regions sharks are found in higher numbers in FAD sets compared to free school sets
	(1) Set time on FADs	Find times of the day to set when sharks move away from FADs and tunas are still aggregated
	(1) FAD designs to reduce entanglement	Modification of FAD construction and design to minimize opportunity of accidental entanglement
	(1) Time/area closures	Examine area and season hotspots for specific elasmobranch species and temporarily restrict sets
	(1) Attracting sharks away from FADs	Attract sharks with chum or other positive stimuli away from the FAD before the set or use double FADs moving away one FAD with the sharks and setting on the other FAD with the tuna.
	(2) Release sharks from net	Using shark release windows in the net, fishing sharks with hook and line and releasing outside of net, backdown maneuver for sharks, or release maneuver over the net's corkline with whale sharks
	(3) Live release from deck	Develop best practices to release sharks and rays once arriving on deck, including bycatch release devices to assist with safer manipulation
	(3) Prohibiting finning	Minimize incentive for fishers to carry out shark finning though penalty systems for vessels involved
Turtles	(1) FAD designs to reduce entanglement	Modification of FAD construction and design to minimize opportunity of accidental entanglement
	(1) Biodegradable FAD designs	Utilization of biodegradable materials so that if FADs accidentally end up beaching in turtle habitats, the structure will quickly degrade
	(3) Live release from deck	Develop best practices to release turtles once arriving on deck, including protocols to avoid accidental injuries
Undesired catches of yellowfin and bigeye tuna	(1) Shift some effort to free schools or reduce number of FAD sets	In some regions BET and/or YFT need to be protected due to their stocks being overfished. The juvenile sizes of these species appear mostly in floating object sets
	(1) Setting catch limits by gear and enforcing them	Set TACs for the different gears that catch juvenile yellowfin and bigeye tuna.
	(1) Selective fishing using acoustics	Use echo-sounders from vessels and buoys to discriminate tuna species and select FADs with fewer proportion of undesired tuna species.
	(1) Time/area closures	Examine area and season hotspots for undesired catches of small yellowfin or bigeye tuna and temporarily restrict sets
	(1) Set time	Find times of day when species of tunas that need to be protected are less aggregated to FADs
	(1) Net depth and FAD depth	In areas where yellowfin and bigeye tuna are deeper in the water column than skipjack, by using shallower purse seine nets and FADs, their catches could be reduced
Bony fish	(3) Live release from deck	Develop methods and tools to ensure fast release of live finfish from deck
	(3) Retention and utilization	Already requested by the four tuna RFMOs to avoid wasteful discards
Impact on coastal and benthic ecosystems	(1) Biodegradable FAD designs	Utilization of biodegradable materials so that when FADs are abandoned or lost the structure will quickly degrade

release methods, acoustic discrimination). Also, each topic presented was dynamic, changing over time as new experimental results emerged in the research cruises and fleet level trials (e.g., designs of non-entangling FADs have been evolving from simple modifications of traditional FADs with purse seine net tied in bundles to FADs with no net material nowadays).

A pattern emerged during fleet consultations in workshops in which activities that were strongly rejected initially by fishers, continued to be consistently dismissed in following years (Tables 3A, B). Fishers considered these options presented by scientists as operationally unviable or poorly aligned with the reality of their fishing strategies (e.g., shark escape panels in the purse seine net, avoidance of small FAD sets to reduce bycatch rates, or trying to catch skipjack when schools move away from the FAD). Instead, other activities which initially received mid to high range scores, gradually increased to highest acceptance levels in following years (Tables 3C–F). This well-received category included activities such as moving to non-entangling and biodegradable FADs, development of protocols and tools for best practices on safe deck release for vulnerable bycatch and advances in acoustic discrimination of tuna species found at FADs to increase selectivity. Other topics were also consulted in the meetings or questionnaires, such as the potential of FADs to act as ecological traps (i.e., changing tuna movement patterns, reducing feeding and condition factors, etc.). However, fishers generally either did not believe or due to lack of conclusive evidence were unsure whether such FAD-derived phenomenon was taking place. This is in line with the prevailing current scientific view that there is inadequate scientific information to conclude if deployments of dFADs function as ecological traps for tunas. Also, fishers were questioned in some workshops about further limiting the number of FADs as an alternative to reduce impacts. This option received good to mid-level acceptances in fleets with lower reliance on FAD sets (e.g., some Western and Central Pacific Ocean fleets with higher free school set rates) but was poorly valued by other fleets with stronger FAD use (e.g., some fleets in the Indian, Atlantic and Eastern Pacific Oceans). Such lower acceptance by the latter sector was to be expected as their competitive catch performance relies on more intensive FAD exploitation strategies.

The general tendency of acceptance levels was similar among most fleets, but in some cases certain fleets showed different patterns for particular measures. These divergences were associated with different fishers' perspectives (e.g., more traditional, less open to new practices), or particular circumstances in those fleets. For example, while most fleets showed mid-high acceptance for non-entangling and biodegradable FADs, the Chinese showed low-mid acceptance. This might be related to fishers in this fleet being very attached to their traditional FADs, having low expectations for alternative FAD designs working properly and/or other factors such as the higher costs of biodegradable materials and the difficulty of accessing high-quality biodegradable materials in their region.

3.3 At sea research cruises

Most research activities at sea focused on how to minimize FAD related impacts (e.g., shark bycatch reduction, lowering FAD structure impacts, juvenile tuna avoidance). In the early stages of the ISSF Bycatch Project the plan was to fully charter large-scale purse seiners for research work, with scientists having a high degree of control over when and how to perform fishing activities for experimental purposes. For example, during a set scientists could choose to delay the fishing operation for several hours so that they could dive in the net or introduce remotely operated vehicle (ROV) to observe and film the behavior of tunas and bycatch species. However, given the exceedingly high costs of renting these large-scale vessels for a one-month trip (e.g., over 1 million USD per trip), the strategy quickly shifted to conducting opportunistic work on purse seiners, which involved a small team of scientists onboard (e.g., 2-4 persons) focusing on a number of pre-agreed and selected activities with the ship-owner and skipper.

The ISSF Bycatch Project aimed at organizing at least two research cruises per year, spreading out trials in a balanced way between the various regions of the Indian, Atlantic and Pacific Oceans to check if proposed mitigation options could be generally applied or only in zones with certain environmental conditions (e.g., high underwater visibility, slow currents, certain water temperature, calm waters, deep thermoclines, etc.). For example, the Western Pacific offers potential for mitigation options taking advantage of the spatial separation between sharks and tunas inside the net thanks to the deep thermocline. However, such options are less viable in shallow thermocline regions like the Eastern Atlantic Ocean where species groups are closer in the net. Between four and five at sea research trials were conducted in each ocean (Table 4), in collaboration with vessels from different fleets (e.g., Ecuador, Spain, Ghana, USA, France, etc.). This enabled cross examination of mitigation activity performance under different fishing strategies and vessel types. For example, in the Ghanaian vessels limited acoustic equipment prevented high-tech species discrimination trials or the USA fleet vessels worked with bycatch release devices on deck (e.g., hoppers) while other fleets do not.

In some instances, trials were conducted at multi-vessel level, with all purse seine vessels in particular companies or fleets cooperating in a research study. This was the case for example with non-entangling biodegradable FADs projects in the Indian Ocean (European Union fleet BIOFAD project, Murua et al., 2023), the Ghanaian fleet in the Atlantic or the Ecuadorian fleet in the Eastern Pacific (IATTC project). Due to the high proportion of FAD loss or change of hands, a high number of experimental FADs was necessary to obtain meaningful statistical results. By sharing experimental trial efforts among all vessels in a fleet, this strategy requires that each vessel only deploys a small number of experimental FADs (e.g., < 5% of its annual FAD limit), thus reducing the risk of negative economic impacts per purse seiner if prototypes perform poorly (e.g., degrade too quickly or are inefficient at attracting tuna).

In some instances, for particular activities such as tuna and bycatch species´ tagging at FADs for behavioural studies, smaller scale research vessels were employed. These were either chartered vessels or again opportunistic work on other experimental vessels (e.g., Secretariat of the Pacific Community's Tuna Tagging Program). In addition, other complementary experimental activities have been conducted in near-shore facilities to monitor performance of biodegradable materials and tuna acoustic identification developments under controlled marine conditions (Table 5).

TABLE 3 Evolution of ISSF Skippers Workshop impact mitigation activity acceptance by fishers for (A) avoidance of small FAD sets, (B) shark escape panel, (C) non-entangling FADs, (D) biodegradable FADs, (E) best bycatch release practices from deck, and (F) echo-sounder buoy selectivity.

FLEET	ACCEPTANCE LEVEL							
	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
(A) AVOIDANCE SMALL SETS								
A	–	–	LOW-MID	–	LOW	–	–	–
B	–	–	–	LOW	–	–	–	–
C	–	–	–	–	–	–	–	–
D	–	–	–	–	–	–	–	–
E	–	–	MID-HIGH	LOW	–	–	–	–
F	–	–	LOW	LOW	LOW	–	–	–
G	–	–	LOW	–	–	–	–	–
H	–	–	–	–	–	–	–	–
I	–	–	LOW	–	–	–	–	–
J	LOW	–	–		–	–	–	–
K	–	LOW-MID	LOW	LOW	LOW	–	–	–
L	LOW	LOW	LOW-MID	LOW	LOW	–	–	–
M	–	–	–	–	LOW	–	–	–
N	–	–	–	–	LOW	–	–	–
O	–	–	–	–	LOW	–	–	–
(B) SHARK ESCAPE PANEL								
A	MID	MID	LOW	LOW	LOW-MID	LOW-MID	–	–
B	–	–	–	MID	–	–	–	–
C	–	MID	–	LOW	–	LOW-MID	–	–
D	–	MID	–	–	–	–	–	–
E	LOW-MID	–	MID-HIGH	LOW-MID	–	LOW-MID	–	–
F	–	–	NA	NA	NA	NA	–	–
G	–	–	MID	LOW	–	–	–	–
H	LOW	–	LOW	–	–	–	–	–
I	–	–	MID	–	–	–	–	–
J	–	–	LOW	–	–	LOW-MID	–	–
K	LOW	MID	–	LOW	–	–	–	–
L	LOW	LOW	LOW-MID	LOW-MID	LOW	–	–	–
M	LOW	LOW	LOW	LOW-MID	LOW	–	–	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	LOW	–	–	–
(C) NON-ENTANGLING FADS								
A	MID	MID-HIGH	MID-HIGH	MID-HIGH	HIGH	HIGH	HIGH	HIGH
B	–	–	–	HIGH	–	–	–	–
C	–	MID	–	MID-HIGH	–	HIGH	HIGH	–
D	–	MID-HIGH	–	–	–	–	–	–
E	HIGH	–	MID-HIGH	MID-HIGH	–	LOW-MID	–	–

(Continued)

TABLE 3 Continued

FLEET	ACCEPTANCE LEVEL							
	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
F	–	–	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
G	–	–	HIGH	MID-HIGH	–	–	–	–
H	MID-HIGH	–	MID-HIGH	MID-HIGH	–	–	–	–
I	–	–	MID-HIGH	–	–	–	–	–
J	HIGH	–	–	HIGH	–	HIGH	–	HIGH
K	MID-HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
L	LOW-MID	MID	MID	MID-HIGH	MID-HIGH	MID-HIGH	MID-HIGH	–
M	–	–	–	–	HIGH	–	–	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	MID	MID	–	–
(D) BIODEGRADABLE FADS								
A	MID	–	MID	MID-HIGH	MID-HIGH	HIGH	MID-HIGH	HIGH
B	–	–	–	MID	–	–	–	–
C	–	–	MID	MID-HIGH	–	HIGH	MID-HIGH	–
D	MID	–	MID-HIGH	–	–	–	MID-HIGH	–
E	MID	MID	–	–	–	MID	MID-HIGH	–
F	–	MID-HIGH	–	HIGH	HIGH	HIGH	MID-HIGH	MID-HIGH
G	–	–	–	MID-HIGH	–	–	–	–
H	–	–	–	MID-HIGH	–	–	–	MID-HIGH
I	–	–	–	–		MID	MID-HIGH	–
J	LOW-MID	MID	–	–	–	–	–	–
K	–	MID	MID	MID-HIGH	–	HIGH	–	HIGH
L	LOW-MID	MID	LOW-MID	MID	MID-HIGH	HIGH	HIGH	HIGH
M	–	–	–	–	MID	MID-HIGH	HIGH	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	LOW-MID	LOW-MID	–	–
(E) SHARK & RAY BEST RELEASE PRACTICES								
A	MID	MID-HIGH	HIGH	MID-HIGH	HIGH	HIGH	–	HIGH
B	–	–	–	HIGH	–	–	–	–
C	–	MID-HIGH	–	MID-HIGH	–	MID	–	–
D	–	MID-HIGH	–	–	–	–	–	–
E	MID-HIGH	–	MID-HIGH	HIGH	–	MID-HIGH	HIGH	HIGH
F	–	–	LOW	LOW-MID	MID	HIGH	HIGH	–
G	–	–	MID-HIGH	MID-HIGH	–	–	HIGH	–
H	MID	–	MID	–	–	–	–	–
I		–	MID-HIGH	–	–	–	MID-HIGH	–
J	MID	–	–	MID	–	MID	–	–
K	MID	MID-HIGH	HIGH	HIGH	HIGH	MID-HIGH	–	HIGH
L	MID	MID	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH

(Continued)

 10.3389/fmars.2023.1074340

TABLE 3 Continued

FLEET	ACCEPTANCE LEVEL							
	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19
M	–	–	–	–	HIGH	LOW	–	MID-HIGH
N	–	–	–	–	MID	–	–	–
O	–	–	–	–	LOW-MID	–	–	–
(F) ECHO-SOUNDER SELECTIVITY								
A	MID	MID	HIGH	MID-HIGH	MID-HIGH	HIGH	HIGH	HIGH
B	–	–	–	MID	–	–	–	–
C	–	MID	–	MID	–	–	HIGH	–
D	–	MID	–	–	–	–	–	–
E	MID	–	MID	MID	–	MID-HIGH	–	HIGH
F	–	–	NA	NA	NA	NA	NA	NA
G	–	–	MID	HIGH	–	–	–	–
H	LOW	–	MID	–	MID-HIGH	–	MID-HIGH	–
I	–	–	MID	–	–	HIGH	HIGH	–
J	MID	–	–	–	–	–	–	HIGH
K	MID	MID	MID	HIGH	HIGH	HIGH	HIGH	HIGH
L	LOW	MID	MID	MID	MID	–	–	–
M	–	–	–	–	HIGH	–	–	–
N	–	–	–	–	NA	–	–	–
O	–	–	–	–	MID	–	–	–

Acceptance levels ranging from low to high for best received options.
NA, Not Applicable.

Describing the extensive series of experimental results obtained during the years in ISSF research trials is beyond the scope of this article, but Restrepo et al. (2018) provide a summary of outcomes of such field-based investigations and references to more detailed documents. Overall, trial results showed that several theoretically possible mitigation actions did not work as predicted in practice (e.g., catching skipjack when moving away from the FAD, shark escape windows, sort tail FADs to attract less bigeye tuna) as suggested by fishers at skipper workshops. Other trials yielded promising results but require further refinement (e.g., fishing sharks in the net, echo-sounder buoys with acoustic discrimination, biodegradable FADs). In general, even experiments that have proven successful such as non-entangling FADs or new bycatch release devices (e.g., hoppers with ramps, mobulid sorting grids), have required trial-and-error processes of several years of adjusting protocols and designs to meet functional requirements that integrate well with the whole fishing operation.

4 Discussion

A decade of collaborative research to mitigate FAD related impacts between scientists and fishers from tropical tuna purse seine fleets across the world is advancing marine conservation practices as demonstrated by the general move to non-entangling FADs and improved bycatch release methods. This truly international network of participatory ISSF Skippers Workshops and research cruises has reduced gaps between tuna fishers and scientists by providing a stable platform where both can express their views, concerns, and develop preferred options to mitigate fishery impacts. This program is an important opportunity to move away from traditional hierarchical decision-making structures, by giving fishers a voice to directly contribute towards improved impact mitigation options. The sense of stewardship gained by fishers through participation in research decisions and actions is promoting the voluntary adoption of best practices. In recent years, many tuna fishing companies have obtained, or are in advanced assessment stages for, Marine Stewardship Council (MSC) eco-certification, where Principle 2 on minimizing environmental impacts is scored. Without recently improved RFMO management measures (e.g., FAD limits, higher observer coverage) and the significant corrective actions developed through science-fisher research cooperation in the last decade, it would have been unlikely for companies using FADs to achieve eco-certification status.

Lessons gained from this multinational tuna purse seine industry inclusive approach are widely transferrable to other fisheries. In fact, ISSF has recently started to conduct ISSF Skippers Workshops with tuna longline fisheries (e.g., Fiji, Taiwan, etc.), with views to expanding this program across key fleets. Similarly, this participatory program model could be easily adapted and exported

TABLE 4 Tuna purse seine fishery ISSF-related research cruises testing mitigation activities between 2011-2020, namely (1) non-entangling FAD designs, (2) deployment and data collection of non-entangling biodegradable FADs, (3) deployment and data collection of shallow vs deep FADs to study effect on bigeye tuna catches, (4) behavior of tunas and other species around FADs, (5) behavior of tunas and other species in the net, (6) improving pre-set estimation of species, sizes and quantities associated to FADs with acoustics, (7) avoiding catch of sharks before setting, (8) releasing sharks and other vulnerable species from the net, (9) releasing undesirable sizes of yellowfin and bigeye tuna from the net, (10) releasing sharks and other vulnerable species from onboard the vessel, (11) post-release survival of vulnerable species, (12) improving monitoring capabilities onboard, (13) fundamental biology research of FAD aggregated species.

Ocean	Vessel	Researched activities	Year
Eastern Pacific Ocean	F/V Yolanda L*	1, 3, 6, 11	2011
	F/V *Via* Simoun*	11	2012
	Nirsa fleet*	3	2015-17
	F/V Ljubica*	8	2016
	Ecuadorian fleet (with IATTC)*	2	2020
Western and Central Pacific Ocean	F/V Cape Finisterre*	4, 5, 6, 8, 9, 11, 12	2012
	F/V Cape Finisterre*	8, 11, 13	2013
	Albatun Tres*	6, 8, 9, 13	2014
	CP-10,11,12 (with SPC)**	4	2014-2016
	CFC fleet*	2	2020
Indian Ocean	MV Maya's Dugong**	3, 7	2011
	F/V Torre Giulia*	1, 4, 6, 7, 8, 11, 13	2012
	Inpesca fleet*	2	2017
	EU/Seychelles/Mauritius fleet (BIOFAD project)*	2	2019-20
Atlantic Ocean	F/V Cap Lopez*	1, 8, 11	2015
	Sea Dragon**	1,4	2015
	F/V Mar de Sergio*	5, 6, 8	2016
	F/V Pacific Star*	8, 10, 11	2018
	Ghana fleet*	2	2020

IATTC, Inter-American Tropical Tuna Commission; SPC, The Pacific Community.
*Large-scale purse seine vessels, **small research vessels.

to many different fishery scales (e.g., local, regional, international) and gears (e.g., static, demersal, pelagic) if the same guiding principles are applied.

4.1 Raising awareness on the need for sustainable fishing

During the first round of ISSF Skippers Workshops in 2010, most fishers, some with over 30-years' experience in the tuna fishery, stated that was their first direct interaction with fisheries scientists. In early workshops fishers had limited awareness on the extent of impacts caused by their fishery (e.g., degree of shark entanglement mortality in FADs, the low survival rate of bycaught elasmobranchs, effects of juvenile tuna catch on stocks). Similarly, many scientists working for decades in tuna fisheries knew few fishers personally prior to these workshops. This illustrates the little direct interaction takes place between fishers and scientists in some fisheries, especially in long-distance fleets where fishers operate very far away from their national scientific institutions.

In general, fishers also had little understanding of the growing importance of consumer demands for sustainable fish and therefore

TABLE 5 ISSF-related FAD impact mitigation research activities conducted in near-shore facilities in collaboration with other scientific institutions.

Location	Experimental Tests	Year
Oahu, Hawaii	Biodegradable FAD materials (with University of Hawaii)	2015
Achotines, Panama	Tropical Tuna species acoustic discrimination (with IATTC)	2016-2022
Maniyafushi, Maldives	Biodegradable FAD materials (with IPNLF)	2016
Barcelona, Spain	Oceanographic biodegradable FAD designs (with ICM-CSIC)	2019-2022

IPNLF, International Pole and Line Foundation; ICM-CSIC, Instituto de Ciencias del Mar.

retailers' necessity of sourcing seafood from environmentally friendly fisheries. Usually, fishers' primary objective is to obtain the highest possible catches because their income and job security depend on it. However, the risk of tuna sale restrictions if their catches are unsustainably harvested, should serve as a motivation for fishing companies to find and implement better practices. It is key that ship-owners reassure fishers about the importance of applying best practices and provide the necessary means, such as biodegradable materials or bycatch release equipment, to enable their application.

In the knowledge exchanges with scientists the fishers learn also about tuna and bycatch species biology, ecology and fishery management which is essential for a better understanding of the functioning of marine ecosystems and conservation (Silva et al., 2021). For example, fishers learning about the slow life histories of sharks and mobulid rays making them more vulnerable to fishing mortality can help raise awareness to apply survival enhancing practices. Fishers must also be aware about the full range of potential negative consequences associated with environmental impacts. For example, impacts on elasmobranch populations could lead to spatio-temporal fishing closures, difficulty to obtain eco-certifications, fines for captains accidentally capturing them, etc. Thus, increased environmental and market awareness, through a deeper understanding of the reasons and consequences associated with applying best practices, plays a critical role in fishers' motivation to voluntarily implement changes.

4.2 Fisher-scientists interaction strategies

Motivation and accountability in purse seiner fleets is also achieved through fisher inclusivity in solution development, especially if involved from the early decision stages. In the first workshop rounds, fishers were somewhat skeptical and reluctant to share their views with unfamiliar scientists. Important to the workshops' dynamics was the strategy of maintaining over the years the same scientific personnel. Facilitating scientists avoided judgmental attitudes, which often contribute towards stereotypical roles and communication blockages. By having the workshops focusing only on technical aspects to reduce fishery impacts, rather than on ideological or political issues, fishers viewed the meeting as more objective and unbiased. An open-minded approach that empathized with fishers' concerns prevailed when trying to discuss impact mitigation options. In this way, over multiple interactions, fishers developed a personal trust relationship with these scientists. This promoted greater exchange of opinions and feedback by fishers, even on the more sensitive topics (e.g., FAD numbers, fishing strategies).

Workshop participant number varied between locations from small (e.g., < 10 participants) to large groups (e.g., >100). In small workshops communication usually was more distended, while in larger workshops often few more outspoken fishers mainly intervened. However, large meetings allowed greater outreach by significantly engaging with a representative section of a fleet. In all workshops fishers completed an anonymous questionnaire on key aspects of the FAD fishery, which allowed all participants to provide their input on mitigation practices. Meanwhile, port visits to speak with fishers onboard their vessels allowed for more informal conversations, and in addition, enabled close examination of fishing equipment and FADs employed. The workshops and vessel visits were a very effective method for scientists to learn the latest fishing strategies and fishing technologies being adopted in each ocean. These tuna fleets have a dynamic behavior, often adapting their strategies to other competitors, new technologies and regulations. Keeping close track of such changes, and understanding the driving forces behind them, is paramount to plan effective conservation measures.

Most fishers engaged in the workshops belonged to fleets with large-scale vessels employing dFADs. However, some key purse seine fleets like the Indonesian, operate with small-scale vessels (e.g., 10-250 GT) on aFADs. Due to the semi-artisanal nature of these vessels, with limited space and fishing technologies (e.g., no modern hauling equipment or echo-sounder buoys), and man-made anchored floating objects (see Murua et al., 2018), their impacts are somewhat different to dFADs and adapted mitigation strategies were necessary. The train-the-trainer program with local scientists resulted in a greater number of workshop trainers and trainees in the local language across the multiple fishing ports. Thanks to this approach Indonesia was the fleet with the most ports visited and highest overall fisher participations in the whole ISSF Skipper Workshop program. Didactic materials (e.g., species ID and best release practice posters) were also widely distributed among purse seine vessels to ensure fishers had access to this information. While this was the most visited fleet, this does not necessarily imply it is the one that has advanced the most in the last 12 years. Many other factors come into play when trying to explain sustainability improvement rates in different fleets, including the baseline level of their practices when the program started, fishers' socio-economic circumstances, resources available to implement better practices, effective science-based management programs, etc. Outreach efforts need to be maintained with the Indonesian and other small-scale vessel fleets in developing nations (e.g., Vietnam, Philippines) due to the large number of fishers requiring training and limited surveillance, monitor and control systems in place to ensure best practices.

The international aspect of the collaborative program played an important role in fishers perceiving with a sense of fairness the adoption of best developed practices, as other competing purse seine fleets had also to comply with the same rules (e.g., PVR conservation measures). Fishers' pretext of "why do we have to carry out these conservation efforts when other fleets are not?" disappears under this overarching global approach. Furthermore, as fishing companies learn about competing industry members taking steps towards sustainable practices, the general reaction has been to improve their standards to avoid being left behind. The strategy of involving purse seiners from various fleets in research not only helped to share the risks and responsibilities associated with the trials, but also the chance to showcase the commitment of fishers from different nationalities towards sustainable fishing.

4.3 Selecting impact mitigation solutions

For true deliberation and innovation processes both scientists and fishers must aim to be honest and willing to reach agreements. For ISSF scientists making fishers aware from the start that research activities are frequently based on slow trial-and-error processes was key. Patience and perseverance are required in many instances when developing novel alternatives, often undergoing failures and numerous iterations before solutions become functional. For example, biodegradable FADs continue to evolve since tested first in the early 2010s, still trying to find better designs and materials to enable their commercial implementation. The workshops provided scientists with a platform to discuss with fishers in detail and face-to-face why some experiments have not performed as expected. Even failed experiments can contribute important new understanding of challenging factors and provide insights into which steps to follow next. Fishers, and scientists, must be prepared to encounter research bottlenecks (e.g., finding ways to deter sharks from FADs) as otherwise they can become frustrated and lose motivation.

The workshops assisted scientists with the identification of fishers showing greater interest for exploring mitigatory solutions. These fishers, referred to by Jenkins (2010) as having a “fisher-inventor profile”, due to their problem-solving and experimental attitudes, are a great asset when developing selective technologies and practices. Their positive mindset towards research helps motivate other fishers to join these efforts, having a pronounced positive effect on their local fishery or fleet. Throughout the years of workshops, ISSF scientists have built close alliances with these proactive fishers. For example, when planning research cruises, trying to develop new bycatch release devices, or organizing specialized workshops, ISSF scientists often reach out to these strategic fishers first for collaboration.

Measures poorly aligned with fishers’ views, are less likely to be applied unless strong monitoring and enforcement exist, and even then, fishers might try to find ways to circumvent them. Therefore, carefully considering fishers’ essential needs when developing new solutions is critical. Fishers often raised practical common-sense concerns, such as requesting that if alternative non-entangling and biodegradable FAD designs were implemented, they should still attract tuna effectively. Similarly, they ask that if they must release dangerous vulnerable bycatch species from deck (e.g., large sharks), the methods proposed should not compromise their personal safety. Conservation activities which result in lower trade-offs for fishers (i.e., minimal loss of target catch or time) are more likely to be successfully adopted. Even easier to implement are win-win activities, in which fishers gain a competitive or safety advantage (e.g., bycatch reduction devices (BRDs) that minimize handling risks of hazardous species like elasmobranchs). Some advances are occurring this way, such as the development of novel or adapted BRDs based on fishers’ ideas provided at workshops (Murua et al., 2021a; Murua et al., 2021b). However, BDR prototypes need further testing and refinement to be widely adopted by different fleets. To assess improvements in the application of vulnerable species bycatch release practices, whether manual or BDR-assisted, in recent years high quality observer data should be carefully collected. Preliminary observer data analysis for some fleets seem to indicate improvements in bycatch release times from deck in recent years (Grande et al., 2019), but this can be species or size specific (Maufroy et al., 2020). Therefore, this is still work in progress and multi-ocean fleet trends should be evaluated in more detail. Furthermore, the evolution in the condition at release and survival rates of sharks and mobulids (e.g., using vitality indexes, lactate levels or with pop-up satellite tagging) should be examined by scientists over time to measure the efficiency of different release methods in purse seiners (Filmalter et al., 2015).

Levels of support for some activities were not always equal across the board given the great variety of fleets and their associated beliefs, fishing technology, and strategies. Fishing industry has often been described as a traditional sector and incorporating new practices can be a slow process. Therefore, during initial research stages it made sense to collaborate in actions perceived as more viable or beneficial by fishers, as they will be more willing to participate in trials. The acceptance levels at workshops were not static and fishers’ opinions on some activities change over time. Many new mitigation ideas presented by scientists in the early workshop rounds were totally new to fishers. Often repeated interaction with fishers to cross-exchange ideas and get familiarized with novel concepts was necessary. In several activities fishers support increased from medium to high levels consistently across many fleets from the first workshop rounds onwards. Presentation during successive workshop rounds of data and videos from at-sea trials and progress by other fleets demonstrating how some activities were viable in purse seiners like theirs was a powerful tool to increase fishers’ acceptance and assist to increase their application in commercial fishing trips.

Fishers’ feedback in the workshops yielded important savings in research time at sea and costs by learning about best areas and seasons to target mitigation activities and by identifying ways to avoid experimental protocol caveats. Some activities proposed by scientists in the workshops consistently received low scores over the years, often because fishers thought experimental trials would not work (e.g., catching skipjack away from the FAD, double-FADs) or because required tasks would go against their fishing strategies (e.g., avoidance of small FAD sets). Bycatch scientists did not always follow fishers’ recommendations and tried some of the activities with lower acceptance levels (e.g., fishing skipjack away from the FAD, shark escape windows). It is worth pointing out that various activities accepted by scientists and fishers did not fully work (e.g., attracting sharks away from the FAD with bait). Some experiments if tested more thoroughly could have potential for more positive results (e.g., utilization of more attractive bait alternatives for sharks) as underlying mechanisms of the differential sensory capacities (e.g., vision, smell, earing) of FAD associated species like tunas and elasmobranchs are still poorly understood.

4.4 Research cruises to test mitigatory activities

Mitigatory research at sea in open ocean dFAD tuna fisheries, like in many other industrial-scale pelagic fisheries, is incredibly expensive. Hence, many studies in tuna fisheries prior to the ISSF Bycatch Project have been conducted on aFADs closer to shore, in laboratories, or desk-top studies based on logbook and observer data. Initial dedicated chartering of large purse seiners by ISSF for research cruises proved too costly and was not a long-term viable option. Thus, opportunistic scientific work on cooperating commercial purse seiners was adopted as an alternative. While fishing companies can be interested in supporting scientific work, they also want assurances that the experiments performed will not impact negatively on their activity. The considerable time and resources invested in these complex negotiations to reach agreements between both parties are often overlooked in the chronograms and budgets of scientific programs. However, this preparatory process is an essential step for fishers and scientists to fully clarify and understand their respective roles and responsibilities in research campaigns. In some cases, during negotiations scientists had to compromise for less complex or risky trials, to ensure ship-owners approve the experimental protocols to be conducted on their vessels.

From the beginning ISSF scientists understood that the efficiency of impact mitigation options needed testing in multiple fleets across oceans, and preferably also in different areas and seasons within each ocean. For example, due to predominant oceanographic currents non-entangling FAD designs with simple submerged structures worked well in the Indian Ocean (e.g., rope or coiled netting tails) but not in the Pacific and Atlantic, where adjustments were required. Furthermore, tuna purse seiner vessels come in a wide range of sizes (e.g., 10-2500 GT) and equipment configurations. Thus, in most cases newly created best practices, such as bycatch reduction devices (BRDs) or net modifications, were carefully customized to each situation for effective results. During the first years of at sea trials research was predominantly executed at a single vessel level (i.e., one research trip on a particular purse seiner). However, after initial cruises yielding positive results, the rest of the purse seine industry increasingly joined research actions as a form to advance faster towards better practices. Also, tuna companies saw in cooperative research an opportunity to prepare for possible future regulatory measures (e.g., biodegradable FADs) and a way to influence their requirements. This change towards a more proactive vision has led to a rapid increase in collaborations; especially in the last five years, with several voluntary trials of unprecedented scale in terms of numbers of vessels involved. In fact, most of these large-scale FAD research efforts now co-funded by industry and different agencies (e.g., RFMOs, EU, ENGOs) are being conducted by some of the fleets with the highest frequency of workshops (e.g., EU, Ecuador, Ghana) in projects mostly coordinated by those same scientists involved in the workshops. Perhaps not surprisingly, some of the fleets most actively engaged in the ISSF Skippers Workshops have pioneered the voluntary adoption of codes of best practices programs which go beyond RFMO requirements. Meanwhile, several fleets also started to voluntarily share fishing buoy data (e.g., FAD echo-sounder buoy data), as recommended during the ISSF Skipper Workshops, useful for scientists to improve stock assessments and ecosystem monitoring (Moreno et al., 2016; Santiago et al., 2020). These sources of information are of great value for ecosystem-based fisheries management (EBFM) purposes.

Similarly, the wide diversity of workshop locations assisted in characterizing the large variety of fishing strategies employed (e.g., anchored FADs vs drifting FADs; FAD vs free school fishing; company vessels working individually or in groups; vessels unassisted vs vessels aided by supply vessels, helicopters, etc.) and vessel types and equipment (e.g., large industrial vs small scale purse seiners; use of echo-sounder buoys vs non-use; small vs large sized nets) in these fisheries. Tactics employed by fishers are quite dynamic and may change in a relatively short time due to technological advances or in response to legislative measures. Regular meetings with individual fleets helped track up to date fishing strategy changes such as rates of adoption of echo-sounder buoy technology, fishers' shift to working in coordinated company vessel groups, adaptations to FAD closures and limits, and so on. Understanding the motivations driving these behavioral and technical changes is essential for adaptive management policies. For instance, this information is of great interest to scientists and managers to accurately estimate relative abundance indices to inform stock status (e.g., effort creep) and devise effective conservation measures in a timely manner. Furthermore, many fishers attending the workshops had decades of experience in their fishery and have been able to assist with historical and more recent information for scientific studies, including endangered species observation rates over the years or contrast observations on tuna population behavior. Part of this information was obtained through the anonymous questionnaires filled in by participants and covering various topics (e.g., types of FADs used, fishing strategies, vessel and FAD equipment, bycatch release methods, etc.).

4.5 Non entangling FADs case study

One of the most illustrating examples of the fisher-scientists solution development process and voluntary implementation was the shift from entangling to non-entangling FADs. At the beginning of the workshops in 2010 the idea of non-entangling FADs was totally alien to fishers, as they had been working with the traditional entangling FAD designs for over 30 years. However, a study by Filmalter et al. (2013) in the Indian Ocean revealed that the rate of shark entanglement in FADs was much higher than previously thought (Figure 3). Additionally, turtles were sometimes entangled in FADs, especially near or on top of the raft when climbing to rest on them. This information was shared at the workshops, helping raise awareness among fishers about the need to replace traditional FAD designs. Through repeated exposure to the non-entangling FAD concept fleets became familiar to the idea. In addition, it was important to let fishers to provide their input in the non-entangling FAD designs from the beginning of the experimental process and by 2012 some vessels started testing them voluntarily. At times, flexibility and adaptability on both parts were necessary to accommodate demands from each party. Initially scientists wanted to construct non-entangling FADs with zero netting, but this drastic change would have been rejected by fleets as alternative materials were not globally/regionally available. Furthermore, at this early stage of the collaborative process fishers were not mentally prepared for such marked change in FAD configuration. Instead, to accelerate the transition to less entangling designs the use of small mesh and tied up mesh materials (categorized as lower entanglement risk FADs by the ISSF guide, ISSF (2012)) was allowed, as fishers were familiarized with these materials. During this whole development process, the ISSF Skippers Workshops collected updated feedback on the various non-entangling FAD trials in each fleet and served as a transmission channel showing fishers from every region the best materials and designs employed by others. This cross pollination of experiences helped speed up the development in reaching efficient non-entangling FAD designs and encouraged many companies, which had initial doubts about these FAD types (e.g., fear of new FADs yielding lower catches, being lost faster, etc.), to make the transition before their respective RFMOs required them (Murua et al., 2016). Currently there is a push to implement fully non-entangling FADs without netting, with various RFMOs having adopted conservation measures to prohibit any net material in FADs (e.g., IOTC Resolution 19/02;

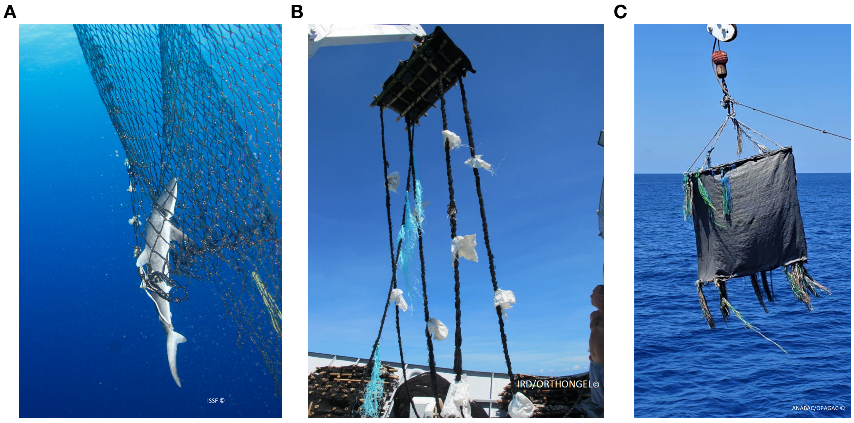

FIGURE 3
Transition process from traditional entangling dFADs to non-entangling dFADs with zero netting, **(A)** Shark entangled in the tail of a traditional high entanglement risk dFAD constructed with large mesh open panels, **(B)** dFAD prototype tested in 2013 by the French fleet with net tied up into bundles to minimize entanglement risk, **(C)** non-entangling dFAD employed in the Indian Ocean built with canvas and biodegradable rope attractors and no netting material.

WCPFC CMM 2021-01) and ISSF requesting the same by January 2024 in its conservation measure 3.7. High level of monitoring will be essential to verify to which degree this transition is being implemented, as some fishers might be reluctant to change if they feel that using small mesh netting is enough to prevent most FAD entanglements. This is an issue in which ship-owners will also need to show commitment, as they are responsible for buying and providing the materials to build FADs.

4.6 Sustained collaboration for long-lasting improvements

To build strong collaborative bridges requires a considerable effort investment which must be sustained overtime, as sporadic interventions with fishers are unlikely to yield desirable long-term benefits. Only when fishers know that their opinion and expertise will be consulted and genuinely considered on a regular basis, in a similar way fisheries management bodies consider systematically scientific committees' recommendations, will they feel part of the process as well. Otherwise, one-off meetings with scientists may not be perceived by fishers as truly collaborative processes and they might even feel used by scientists as mere data providers for academic studies. Scientists have been often criticized for being very active in requesting data from industry for their studies but have frequently failed to report back to fishers on the results and use derived from such data. This non-reciprocal behavior only helps reinforce fishers' mistrust in the scientific process. Full-circle inclusive research processes in which fishers are involved from the initial planning and design stages until the final product is achieved are necessary.

While having workshops at certain locations on an annual or biannual basis may be viewed as low frequency and short duration (e.g., 5 hours), when sustained overtime there is a cumulative long-term effect. From the workshops' experience it seems preferrable to maintain a slow but steady pace of interactions to build stable working relationships rather than putting excessive strain on fishers to collaborate. If scientists request fishers to attend several meetings per year, most likely this will backfire as there would be a burnout effect. This is because, unlike coastal fishers, large-scale tuna vessel fishers spend many months at sea away from their family and when in their free time at home often must attend not only these workshops, but other courses too (e.g., health and safety certifications, fishing technology update courses, etc.). Also, having the workshops on an annual basis, allows time for novel results from the latest experimental trials or lessons learned from other scientific groups or fleets to be incorporated in the presentation (e.g., recent research cruises, improvements in FAD designs, new trials by other fleets). In this way repeating participants can keep up to date with the latest trends in impact mitigation and learn new ways in which scientists and fishers from other fleets are addressing the same issues.

Up to 2019, the ISSF Skippers Workshops have maintained a high level of consistency, aiming at delivering around 8 to 12 workshops per year worldwide. While the program has tried to reach as many fleets as possible, some of the venues became almost fixed every year (e.g., Spain, Ecuador, Indonesia, Ghana) due to the strategic importance of these fleets in their regions and favorable access to fishers at particular times of the year (e.g., during FAD closures, fishers' holidays, etc.). Unfortunately, since 2020 due to the Covid-19 pandemic, workshops were abruptly discontinued, and only in 2022 they are slowly starting again, but this time around with several restrictions in terms of travel access to certain regions and a more limited budget. These circumstances could slow down or even revert the unprecedented high levels of cooperation achieved between tuna purse seine fishers and scientists in the last decade. It would be advisable that regional or international funding bodies (e.g., national fisheries agencies, RMFOs, ENGOs, etc.) set up or support fisher-scientist research programs that enable regular meeting opportunities to keep working on the improvement of harvesting practices. Furthermore, there is an increasing need for fishers, especially newcomers, to be well acquainted with the growing number of conservation regulations, both voluntary (e.g., Codes of Good Practices, ISSF) and obligatory (e.g., RFMOs).

5 Conclusion

The ISSF workshops and associated research cruises provide a bright spot example of how promoting a more integrated approach of fishers and industry from large-scale fisheries in impact mitigation research can yield better technical solutions for adoption of changes and gear modifications at fleet level that support sustainable best practices. Our experience also highlights the importance of building long-term collaborative bridges with fishers based on trust, mutual respect of knowledge, identification of common goals and perseverance to develop effective solutions and a sense of stewardship. In global fisheries, like the tropical tuna purse seine one, involving key fleets from all oceans has been crucial to understand the differences between each region and customize fit-for-purpose sustainable practices that consider fishers' circumstances. While the process here described is still work in progress and we fully acknowledge more actions are needed to further improve marine conservation in tuna fisheries, important advances have been achieved in a relatively short period thanks to an unprecedented scale of cooperation with hundreds of vessels taking part in research to test new FAD constructions and selective fishing protocols. It is recommended that to better assess progress in sustainable practices of these tuna fleets, or any others following cooperative models, a combination of comprehensive scientific studies, observer data, and independent audits should be employed. Collaborative fisher-scientist consultation platforms and action research programs should continue to be supported in the future to consolidate and continue the growth of sustainable fishing practices.

Recommendations

This work presents the broadest fisher-scientist research collaborative initiative ever conducted in tuna fisheries to improve sustainable practices worldwide. During the last decade scientists associated with the International Seafood Sustainability Foundation's Bycatch Project have coordinated over 100 participatory workshops in 23 countries across the Americas, Asia, Europe, Africa, and Oceania with tropical tuna purse seine fishers to address environmental impacts. Additionally, multiple research campaigns onboard large-scale tuna purse seiners in the Indian, Atlantic and Pacific Oceans have tested innovative mitigation alternatives. Research activities favoured by fishers, such as better vulnerable bycatch release methods or minimizing marine pollution, were prioritized. Critical advances including voluntary replacement of highly entangling fish aggregating devices (FADs) with non-entangling designs and improvement in bycatch release equipment, showcase the benefits of bottom-up integrative strategies. Ongoing research continues to refine other solutions such as biodegradable FADs or acoustic selectivity tools with support from industry. Important lessons learned during this process include the need to establish reliable and trustworthy fora for direct open communication with fishers that improve experimental outcomes and promote stewardship conductive to adoption of best practices. For sustainable fishery trajectories to continue advancing into the future, long-term well-funded fisher-inclusive research and awareness programs should be maintained.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials. Further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Acknowledgments

The authors would like to thank all the purse seine fishers and companies that have participated in the ISSF Skippers Workshops and associated research activities. Several scientists including Ben Ashigbui, Sven Blackenhorn, Jose Maria Ferarios, Fabien Forget, Maitane Grande, Federico Iriarte, Papa Kebe, Jon Lopez, Berry Muller, Tatsuki Oshima, Marlon Roman, Mariana Tolotti, Ignatius Tri, Anung Widodo and Dai Xiaojie assisted in the coordination and delivery of the workshops. Fleet association managers and members including Kwame Adomako, Luigi Benincasa, John Farmer, Zhao Gang, William Gibbons-Fly, Michel Goujon, Marko Kamber, Guillermo Moran, Julio Moron, Anertz Muniategi, and Rendra Purdiansa also greatly helped with workshop organization. Special thanks are also due to workshop funding bodies such as FAO Common Oceans Tuna Project, the Walton Family Foundation, the Gordon and Betty Moore Foundation and ISSF for providing financial support for the workshops and research over the years.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Airaud, M., Tezenas, L., Moreno, G., Dagorn, L., and Murua, J. (2020). "Action research in tropical tuna purse seine fisheries: thoughts and perspectives," in *Collaborative research in fisheries* (MARE publications). doi: 10.1007/978-3-030-26784-1_12

Alfaro-Shigueto, J., Mangel, J. C., Darquea, J., Donoso, M., Baquero, A., Doherty, P. D., et al. (2018). Untangling the impacts of nets in the southeastern pacific: Rapid assessment of marine turtle bycatch to set conservation priorities in small-scale fisheries. *Fish. Res.* 206, 185–192. doi: 10.1016/j.fishres.2018.04.013

Aswani, S., Basurto, X., Ferse, S., Glaser, M., Campbell, L., Cinner, J. E., et al. (2018). Marine resource management and conservation in the anthropocene. *Environ. Conserv.* 45 (2), 192–202. doi: 10.1017/s0376892917000431

Ballance, L. T., Gerrodette, T., Lennert-Cody, C., Pitman, R. L., and Squires, D. (2021). A history of the tuna-dolphin problem: Successes, failures, and lessons learned. *Front. Mar. Sci.* 8, 1700. doi: 10.3389/fmars.2021.754755

Berkstrom, C., Papadopoulos, M., Jiddawi, N. S., and Nordlund, L. M. (2019). Fishers' local ecological knowledge (LEK) on connectivity and seascape management. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00130

Branch, T. A., Hilborn, R., Haynie, A. C., Fay, G., Flynn, L., Griffiths, J., et al. (2006). Fleet dynamics and fishermen behavior: lessons for fisheries managers. *Can. J. Fish. Aquat. Sci.* 63 (7), 1647–1668. doi: 10.1139/f06-072

Carr, L. M., and Heyman, W. D. (2012). "It's about seeing what's actually out there": Quantifying fishers' ecological knowledge and biases in a small-scale commercial fishery as a path toward co-management. *Ocean Coast. Manage.* 69, 118–132. doi: 10.1016/j.ocecoaman.2012.07.018

Carruthers, E. H., and Neis, B. (2011). Bycatch mitigation in context: Using qualitative interview data to improve assessment and mitigation in a data-rich fishery. *Biol. Conserv.* 144 (9), 2289–2299. doi: 10.1016/j.biocon.2011.06.007

Chapin, F. S.III, Kofinas, G. P., Folke, C., and Chapin, M. C. (2009). *Principles of ecosystem stewardship: resilience-based natural resource management in a changing world* (Springer Science & Business Media). Available at: https://www.academia.edu/39166299/Principles_of_Ecosystem_Stewardship.

Chapin, F. S., Sommerkorn, M., Robards, M. D., and Hillmer-Pegram, K. (2015). Ecosystem stewardship: A resilience framework for arctic conservation. *Global Environ. Change Human Policy Dimensions* 34, 207–217. doi: 10.1016/j.gloenvcha.2015.07.003

Chuenpagdee, R., and Jentoft, S. (2018). Transforming the governance of small-scale fisheries. *Maritime Stud.* 17 (1), 101–115. doi: 10.1007/s40152-018-0087-7

d'Armengol, L., Castillo, M. P., Ruiz-Mallen, I., and Corbera, E. (2018). A systematic review of co-managed small-scale fisheries: Social diversity and adaptive management improve outcomes. *Global Environ. Change Human Policy Dimensions* 52, 212–225. doi: 10.1016/j.gloenvcha.2018.07.009

Dagorn, L., Holland, K. N., Restrepo, V., and Moreno, G. (2012). Is it good or bad to fish with FADs? what are the real impacts of the use of drifting FADs on pelagic marine ecosystems? *Fish Fish.* 14 (3), 391–415. doi: 10.1111/j.1467-2979.2012.00478.x

Da Veiga Malta, T., Feekings, J., Herrmann, B., and Krag, L. (2019). Industry-led fishing gear development: Can it facilitate the process? *Ocean Coast. Manage.* 177, 148–155. doi: 10.1016/j.ocecoaman.2019.05.009

Dorner, H., Graham, N., Bianchi, G., Bjordal, A., Frederiksen, M., Karp, W. A., et al. (2015). From cooperative data collection to full collaboration and co-management: a synthesis of the 2014 ICES symposium on fishery-dependent information introduction. *Ices J. Mar. Sci.* 72 (4), 1133–1139. doi: 10.1093/icesjms/fsu222

Dupaix, A., Capello, M., Lett, C., Andrello, M., Barrier, N., Viennois, G., et al. (2021). Surface habitat modification through industrial tuna fishery practices. *Ices J. Mar. Sci.* 78 (9), 3075–3088. doi: 10.1093/icesjms/fsab175

Field, J. G., Attwood, C. G., Jarre, A., Sink, K., Atkinson, L. J., and Petersen, S. (2013). Cooperation between scientists, NGOs and industry in support of sustainable fisheries: the south African hake merluccius spp. trawl fishery experiencea. *J. Fish Biol.* 83 (4), 1019–1034. doi: 10.1111/jfb.12118

Filmalter, J., Capello, M., Deneubourg, J.-L., Cowley, P., and Dagorn, L. (2013). Looking behind the curtain: Quantifying massive shark mortality in fish aggregating devices. *Front. Ecol. Environ.* 11, 291–296. doi: 10.1890/130045

Filmalter, J., Hutchinson, M., Poisson, F., Eddy, W., Brill, R., Bernal., D., et al. (2015). *Global comparison of post-release survival of silky sharks caught by tropical tuna purse seine vessels. ISSF technical report 2015-10* (Washington, D.C., U.S.A: International Seafood Sustainability Foundation).

Fonteneau, A., Chassot, E., and Bodin, N. (2013). Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. *Aquat. Living Resour.* 26, 37–48. doi: 10.1051/alr/2013046

Garza-Gil, M. D., Perez-Perez, M. I., and Fernandez-Gonzalez, R. (2020). Governance in small-scale fisheries of Galicia (NW spain): Moving toward co-management? *Ocean Coast. Manage.* 184, 105013. doi: 10.1016/j.ocecoaman.2019.105013

Giareta, E. P., Prado, A. C., Leite, R. D., Padilha, E., dos Santos, I. H., Wosiak, C. D. D., et al. (2021). Fishermen's participation in research and conservation of coastal elasmobranchs. *Ocean Coast. Manage.* 199, 105421. doi: 10.1016/j.ocecoaman.2020.105421

Gilman, E., Passfield, K., and Nakamura, K. (2014). Performance of regional fisheries management organizations: ecosystem-based governance of bycatch and discards. *Fish Fish.* 15 (2), 327–351. doi: 10.1111/faf.12021

Gonzalez-Pestana, A., Mangel, J. C., Alfaro-Córdova, E., Acuña-Perales, N., Córdova-Zavaleta, F., Segura-Cobeña, E., et al. (2021). Diet, trophic interactions and possible ecological role of commercial sharks and batoids in northern Peruvian waters. *J. Fish. Biol.* 98 (3), 768–783. doi: 10.1111/jfb.14624

Guirkinger, L., Rojas-Perea, S., Ender, I., Ramsden, M., Lenton-Lyons, C., and Geldmann, J. (2021). Motivations for compliance in Peruvian manta ray fisheries. *Mar. Policy* 124, 104315. doi: 10.1016/j.marpol.2020.104315

Grande, M., Murua, J., Ruiz, J., Ferarios, J. M., Murua, H., Krug, I., et al. (2019). Bycatch mitigation actions on tropical tuna purse seiners: best practices program and bycatch releasing tools. *IATTC - 9th Meeting of the Working Group on Bycatch*. San Diego, California.

Hall, M. A. (1998). An ecological view of the tuna-dolphin problem: impacts and trade-offs. *Rev. Fish Biol. Fish.* 8 (1), 1–34. doi: 10.1023/a:1008854816580

Hall, M. A. (2007). "Working with fishers to reduce by-cathes," in *By-catch reduction in the world's fisheries. reviews: Methods and technologies in fish biology and fisheries*, vol. 7 . Ed. S. J. Kennelly (Dordrecht: Springer). doi: 10.1007/978-1-4020-6078-6_8

Hallier, J.-P., and Gaertner, D. (2008). Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. *Mar. Ecol. Prog. Ser.* 353, 255–264. doi: 10.3354/meps07180

Hall, M., and Roman, A. (2013). *Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. FAO fisheries and aquaculture technical paper no. 568* (Fish and Agriculture Organization of the United Nations). doi: 10.13140/2.1.1734.4963

Hansen, W. D. (2014). Generalizable principles for ecosystem stewardship-based management of social-ecological systems: lessons learned from Alaska. *Ecol. Soc.* 19 (4), 13. doi: 10.5751/es-06907-190413

Hilborn, R. (1985). Fleet dynamics and individual variation: Why some people catch more fish than others. *Can. J. Fish. Aquat. Sci.* 42, 2–13. doi: 10.1139/f85-001

Holm, P., Hadjimichael, M., Linke, S., and Mackinson, S. (2020). *Collaborative research in fisheries Co-creating knowledge for fisheries governance in Europe* (Cham: Springer International Publishing).

Horta e Costa, B., Batista, M. I., Gonçalves, L., Erzini, K., Caselle, J. E., Cabral, H. N., et al. (2013). Fishers' behaviour in response to the implementation of a marine protected area. *PloS One* 8 (6), e65057. doi: 10.1371/journal.pone.0065057

Hunnam, K., Carlos, I., Hammer, M. P., Dos Reis Lopes, J., Mills, D. J., and Stacey, N. (2021). Untangling tales of tropical sardines: Local knowledge from fisheries in timor-leste. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.673173

ISSF (2022). *Status of the world fisheries for tuna. Nov. 2022. ISSF Technical Report*. 2022–15 (Pittsburgh, PA, USA: International Seafood Sustainability Foundation).

Itano, D., Fukofuka, S., and Brogan, D. (2004). "The development, design, and current status of anchored and drifting FADs in the WCP," in *17th Meeting of the Standing Committee on Tuna and Billfish*, Majuro, Marshall Islands, 9-18 August 2004. 26.

Iwane, M. A., Leong, K. M., Vaughan, M., and Oleson, K. L. L. (2021). When a shark is more than a shark: A sociopolitical problem-solving approach to Fisher-shark interactions. *Front. Conserv. Sci.* 2. doi: 10.3389/fcosc.2021.669105

Jaiteh, V. F., Lindfield, S. J., Mangubhai, S., Warren, C., Fitzpatrick, B., and Loneragan, N. R. (2016). Higher abundance of marine predators and changes in fishers' behavior following spatial protection within the world's biggest shark fishery. *Front. Mar. Sci.* 3. doi: 10.3389/fmars.2016.00043

Jenkins, L. (2010). Profile and influence of the successful Fisher-inventor of marine conservation technology. *Conserv. Soc.* 8, 44–54. doi: 10.4103/0972-4923.62677

Johannes, R. E. (1998). The case for data-less marine resource management: examples from tropical nearshore finfisheries. *Trends Ecol. Evol.* 13 (6), 243–246. doi: 10.1016/s0169-5347(98)01384-6

Johannes, R. E., Freeman, M. M. R., and Hamilton, R. J. (2000). Ignore fishers' knowledge and miss the boat. *Fish Fish.* 1 (3), 257–271. doi: 10.1046/j.1467-2979.2000.00019.x

Joseph, J. (1994). The tuna-dolphin controversy in the Eastern pacific ocean: Biological, economic, and political impacts. *Ocean Dev. Int. Law* 25 (1), 1–30. doi: 10.1080/00908329409546023

Justel-Rubio, A., and Recio, L. (2022). *A snapshot of the Large-scale tropical tuna purse seine fishing fleets as of July 2022 (Version 10). ISSF technical report 2022-14* (International Seafood Sustainability Foundation). https://www.iss-foundation.org/research-advocacy-recommendations/our-scientific-program/scientific-reports/download-info/issf-2022-14-a-snapshot-of-the-large-scale-tropical-tuna-purse-seine-fishing-fleets-as-of-july-2022/

Karr, K. A., Fujita, R., Carcamo, R., Epstein, L., Foley, J. R., Fraire-Cervantes, J. A., et al. (2017). Integrating science-based Co-management, partnerships, participatory processes and stewardship incentives to improve the performance of small-scale fisheries. *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00345

Kelleher, K. (2005). "Discards in the World'S marine fisheries. an update," in *FAO fisheries technical paper 470* (Fish and Agriculture Organization of the United Nations). https://www.fao.org/3/y5936e/y5936e00.htm

Kim, Y.-H., and Park, M.-C. (2009). The simulation of the geometry of a tuna purse seine under current and drift of purse seiner. *Ocean Eng.* 36 (14), 1080–1088. doi: 10.1016/j.oceaneng.2009.06.011

Komoroske, L. M., and Lewison, R. L. (2015). Addressing fisheries bycatch in a changing world. *Front. Mar. Sci.* 2. doi: 10.3389/fmars.2015.00083

Leduc, A., De Carvalho, F. H. D., Hussey, N. E., Reis, J. A., Longo, G. O., and Lopes, P. F. M. (2021). Local ecological knowledge to assist conservation status assessments in data poor contexts: a case study with the threatened sharks of the Brazilian northeast. *Biodivers. Conserv.* 30 (3), 819–845. doi: 10.1007/s10531-021-02119-5

Leslie, H., and McLeod, K. (2007). Confronting the challenges of implementing marine ecosystem-based management. *Front. Ecol. Environ.* 5, 540–548. doi: 10.1890/1540-9295(2007)5[540:ctcoim]2.0.co;2

Lezama-Ochoa, N., Hall, M. A., Pennino, M. G., Stewart, J. D., López, J., and Murua, H. (2019). Environmental characteristics associated with the presence of the spinetail devil ray (*Mobula mobular*) in the eastern tropical pacific. *PloS One* 14 (8), e0220854. doi: 10.1371/journal.pone.0220854

Linke, S., Hadjimichael, M., Mackinson, S., and Holm, P. (2020). *Knowledge for fisheries governance: Participation, integration and institutional reform* (MARE Publications). 7–25. https://link.springer.com/chapter/10.1007/978-3-030-26784-1_2; OI: 10.1007/978-3-030-26784-1_2

Lopez, J., Moreno, G., Sancristobal, I., and Murua, J. (2014). Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and pacific oceans. *Fish. Res.* 155, 127–137. doi: 10.1016/j.fishres.2014.02.033

Mackinson, S. (2001). Integrating local and scientific knowledge: An example in fisheries science. *Environ. Manage.* 27 (4), 533–545. doi: 10.1007/s0026702366

Mackinson, S., and Middleton, D. A. J. (2018). Evolving the ecosystem approach in European fisheries: Transferable lessons from new zealand's experience in strengthening stakeholder involvement. *Mar. Policy* 90, 194–202. doi: 10.1016/j.marpol.2017.12.001

Mackinson, S., Holm, P., and Hadjimichael, M. (2020). Chapter 18: Conclusion. In: *Collaborative Research in fisheries: Co-creating knowledge for fisheries governance in Europe*. Springer International Publishing Switzerland, 320p, doi: 10.1007/978-3-030-26784-1

Mackinson, S., Wilson, D. C., Galiay, P., and Deas, B. (2011). Engaging stakeholders in fisheries and marine research. *Mar. Policy* 35 (1), 18–24. doi: 10.1016/j.marpol.2010.07.003

Macusi, E. D., Abreo, N. A. S., and Babaran, R. P. (2017). Local ecological knowledge (LEK) on fish behavior around anchored FADs: the case of tuna purse seine and ringnet fishers from southern Philippines. *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00188

Marsac, F., Fonteneau, A., and Ménard, F. (2000). "Drifting FADs used in tuna fisheries: an ecological trap?" Pêche thonière et dispositifs de concentration de poissons, Caribbean-Martinique. Available at: https://scholar.google.com/citations?view_op=view_citation&hl=fr&user=Jwg4jEsAAAAJ&citation_for_view=Jwg4jEsAAAAJ:8k81kl-MbHgC

Mathevet, R., Bousquet, F., and Raymond, C. M. (2018). The concept of stewardship in sustainability science and conservation biology. *Biol. Conserv.* 217, 363–370. doi: 10.1016/j.biocon.2017.10.015

Maufroy, A., Gamon, A., Vernet, A. L., and Goujon, M. (2020). "8 years of best practices onboard French and associated flags tropical tuna purse seiners: An overview in the Atlantic and Indian oceans," in *IOTC - 16th Working Party on Ecosystems and Bycatch. IOTC-2020-WPEB16-11* 74, 215-225.

Maufroy, A., Kaplan, D. M., Bez, N., Delgado de Molina, A., Murua, H., Floch, L., et al. (2016). Massive increase in the use of drifting fish aggregating devices (dFADs) by tropical tuna purse seine fisheries in the Atlantic and Indian oceans. *ICES J. Mar. Sci*. doi: 10.1093/icesjms/fsw175

McGrath, D., and Castello, L. (2015). "Integrating fishers' ecological knowledge and the ecosystem based management of tropical inland fisheries: an Amazon case study," Fish and Agriculture Organization of the United Nations, vol. 127. https://www.fao.org/inland-fisheries/resources/detail/es/c/1149517/.

Moreno, G., Restrepo, V., Dagorn, L., Hall, M., Murua, J., Sancristobal, I., et al. (2016). Workshop on the use of biodegradable fish aggregating devices (FAD). *ISSF Technical Report 2016-18A*. Washington, D.C., USA: International Seafood Sustainability Foundation.

Moreno, G., Dagorn, L., Sancho, G., Garcia, D., and Itano, D. (2007a). Using local ecological knowledge (LEK) to provide insight on the tuna purse seine fleets of the Indian ocean useful for management. *Aquat. Living Resour.* 20 (4), 367–376. doi: 10.1051/alr:2008014

Moreno, G., Dagorn, L., Sancho, G., and Itano, D. (2007b). Fish behaviour from fishers' knowledge: the case study of tropical tuna around drifting fish aggregating devices (DFADs). *Can. J. Fish. Aquat. Sci.* 64 (11), 1517–1528. doi: 10.1139/f07-113

Moreno, G., Salvador, J., Zudaire, I., Murua, J., Pelegrí, J. L., Uranga, J., et al. (2022). The jelly-FAD: a paradigm shift in the design of biodegradable fish aggregating devices. *Mar. Policy* 174, 105352. doi: 10.1016/j.marpol.2022.105352

Moreno, G., Murua, J., Kebe, P, Scott, J., and Restrepo, V. (2018). Design workshop on the use of biodegradable fish aggregating devices in Ghanaian purse seine and pole and line tuna fleets. *ISSF Technical Report 2018-07*. Washington, D.C., USA: International Seafood Sustainability Foundation.

Murua, J., Grande, M., Onandia, M., and Santiago, J. (2021a). "Improving on deck best handling and release practices for sharks in tuna purse seiners using hopper with ramp devices," in *Seventeenth Regular Session of the Scientific Committee, WCPFC, SC17-EB-IP-13*.

Murua, J., Ferarios, J. M., Grande, M., Onandia, I., Ruiz, J., Zudaire, I., et al. (2021b). "Developing solutions to increase survival rates of vulnerable bycatch species in tuna purse seine FAD fisheries," in *IOTC - 2nd ad hoc working group on FADs. IOTC-2021-WGFAD02-11_rev1, online* (Indian Ocean Tuna Commission). Available at: https://iotc.org/documents/developing-solutions-increase-survival-rates-vulnerable-bycatch-species-tuna-purse-seine

Murua, H., Dagorn, L., Justel-Rubio, A., Moreno, G., and Restrepo, V. (2021). *Questions and Answers about FADs and Bycatch (Version 3). ISSF Technical Report 2021-11*. International Seafood Sustainability Foundation, Washington, D.C., USA.

Murua, J., Itano, D., Hall, M., Dagorn, L., Moreno, G., and Restrepo, V. (2016). "Advances in the use of entanglement-reducing drifting fish aggregating devices (DFADs) in tuna purse seine fleets," in *ISSF Technical Report 2016-08. International Seafood Sustainability Foundation*, Washington, D.C., U.S.A.

Murua, J., Itano, D., and Widodo, A. (2018). "Characterising small and medium scale tuna purse seine and ring net vessels in Indonesia," in *ISSF Technical Report 2018-06. International Seafood Sustainability Foundation*, Washington, D.C., USA.

Murua, H., Zudaire, I., Tolotti, M., Murua, J., Capello, M., Cabezas, O., et al (2023). In press. lessons learnt from the first large-scale biodegradable FAD research experiment to mitigate drifting FADs impacts on the ecosystem. *Mar. Policy*. doi: 10.1016/j.marpol.2022.105394

Nielsen, K. N., and Holm, P. (2007). A brief catalogue of failures: Framing evaluation and learning in fisheries resource management. *Mar. Policy* 31 (6), 669–680. doi: 10.1016/j.marpol.2007.03.014

Nielsen, J. R., and Vedsmand, T. (1999). User participation and institutional change in fisheries management: a viable alternative to the failures of 'top-down' driven control? *Ocean Coast. Manage.* 42 (1), 19–37. doi: 10.1016/s0964-5691(98)00085-4

Oyanedel, R., Gelcich, S., and Milner-Gulland, E. J. (2020). Motivations for (non-) compliance with conservation rules by small-scale resource users. *Conserv. Lett.* 13 (5). doi: 10.1111/conl.12725

Pauly, D., and Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* 7 (10244), 10244. doi: 10.1038/ncomms10244

Pereyra, P. E. R., Hallwass, G., Poesch, M., and Silvano, R. A. M. (2021). 'Taking fishers' knowledge to the lab': An interdisciplinary approach to understand fish trophic relationships in the Brazilian Amazon. *Front. Ecol. Evol.* 9. doi: 10.3389/fevo.2021.723026

Poisson, F., Seret, B., Vernet, A. L., Goujon, M., and Dagorn, L. (2014). Collaborative research: Development of a manual on elasmobranch handling and release best practices in tropical tuna purse-seine fisheries. *Mar. Policy* 44, 312–320. doi: 10.1016/j.marpol.2013.09.025

Restrepo, V. D. L., Moreno, G., Forget, F., Schaefer, K., Sancristobal, I., Muir, J., et al. (2018). "Compendium of ISSF At-Sea bycatch mitigation research activities as of September 2018," in *ISSF Technical Report 2018-20 International Seafood Sustainability Foundation*, Washington D.C., U.S.A.

Rohe, J. R., Aswani, S., Schluter, A., and Ferse, S. C. A. (2017). Multiple drivers of local (Non-) compliance in community-based marine resource management: Case studies from the south pacific. *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00172

Roheim, C., and Sutinen, J. (2006). Trade and marketplace measures to promote sustainable fishing practices. doi: 10.7215/nr_ip_20060501

Rudolph, T. B., Ruckelshaus, M., Swilling, M., Allison, E. H., Osterblom, H., Gelcich, S., et al. (2020). A transition to sustainable ocean governance. *Nat. Commun.* 11 (1), 3600. doi: 10.1038/s41467-020-17410-2

Saavedra-Diaz, L. M., Rosenberg, A. A., and Martin-Lopez, B. (2015). Social perceptions of Colombian small-scale marine fisheries conflicts: Insights for management. *Mar. Policy* 56, 61–70. doi: 10.1016/j.marpol.2014.11.026

Salas, S., and Gaertner, D. (2004). The behavioural dynamics of fishers: management implications. *Fish Fish.* 5 (2), 153–167. doi: 10.1111/j.1467-2979.2004.00146.x

Saldana-Ruiz, L. E., Sosa-Nishizaki, O., and Cartamil, D. (2017). Historical reconstruction of gulf of California shark fishery landings and species composition 1939-2014, in a data-poor fishery context. *Fish. Res.* 195, 116–129. doi: 10.1016/j.fishres.2017.07.011

Sampedro, P., Prellezo, R., Garcia, D., Da-Rocha, J. M., Cervino, S., Torralba, J., et al. (2017). To shape or to be shaped: engaging stakeholders in fishery management advice. *Ices J. Mar. Sci.* 74 (2), 487–498. doi: 10.1093/icesjms/fsw160

Santiago, J., Uranga, J., Quincoces, I., Orue, B., Grande, M., Murua, H., et al. (2020). *A novel index of abundance of skipjack in the Indian ocean derived from echosounder buoys*. (Indian Ocean Tuna Commision)

Silva, M.R.O., Pennino, M.G., and Lopes, P. F. M. (2021). Predicting potential compliance of small-scale fishers in Brazil: The need to increase trust to achieve fisheries management goals. *J. Env. Man.* 288, 112372. doi: 10.1016/j.jenvman.2021.112372

Stelfox, M., Hudgins, J., and Sweet, M. (2016). A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. *Mar. pollut. Bull.* 111 (1), 6–17. doi: 10.1016/j.marpolbul.2016.06.034

Stephenson, R. L., Paul, S., Pastoors, M. A., Kraan, M., Holm, P., Wiber, M., et al. (2016). Integrating fishers' knowledge research in science and management. *Ices J. Mar. Sci.* 73 (6), 1459–1465. doi: 10.1093/icesjms/fsw025

Strainn, E. M., Lai, R., White, C., Piarulli, S., Leung, K. M., Airoldi, L., et al. (2022). Editorial: Marine Pollution - Emerging Issues and Challenges. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.918984

Taquet, M., Sancho, G., Dagorn, L., Gaertner, J.-C., Itano, D., Aumeeruddy, R., et al. (2007). Characterizing fish communities associated with drifting fish aggregating devices (FADs) in the Western Indian ocean using underwater visual surveys. doi: 10.1051/alr:2008007

Torres-Irineo, E., Gaertner, D., Chassot, E., and Dreyfus-Leon, M. (2014). Changes in fishing power and fishing strategies driven by new technologies: The case of tropical tuna purse seiners in the eastern Atlantic ocean. *Fish. Res.* 155, 10–19. doi: 10.1016/j.fishres.2014.02.017

Torres-Irineo, E., Dreyfus-León, M., Gaertner, D., Salas, S., and Marchal, P. (2017). Adaptive responses of tropical tuna purse-seiners under temporal regulations. *Ambio* 46 (1), 88–97. doi: 10.1007/s13280-016-0801-x

Tickler, D., Meeuwig, J. J., Palomares, M. L., Pauly, D., and Zeller, D. (2018). Far from home: Distance patterns of global fishing fleets. *Sci Adv.* 4(8):eaar3279. doi: 10.1126/sciadv.aar3279

Trimble, M., and Berkes, F. (2013). Participatory research towards co-management: Lessons from artisanal fisheries in coastal Uruguay. *J. Environ. Manage.* 128, 768–778. doi: 10.1016/j.jenvman.2013.06.032

Wain, G., Guery, L., Kaplan, D. M., and Gaertner, D. (2021). Quantifying the increase in fishing efficiency due to the use of drifting FADs equipped with echosounders in tropical tuna purse seine fisheries. *Ices J. Mar. Sci.* 78 (1), 235–245. doi: 10.1093/icesjms/fsaa216

Wedemeyer-Strombel, K. R., Peterson, M. J., Sanchez, R. N., Chavarría, S., Valle, M., Altamirano, E., et al. (2019). Engaging fishers' ecological knowledge for endangered species conservation: Four advantages to emphasizing voice in participatory action research. *Front. Communication* 4 (30). doi: 10.3389/fcomm.2019.00030

West, S., Haider, L. J., Masterson, V., Enqvist, J. P., Svedin, U., and Tengo, M. (2018). Stewardship, care and relational values. *Curr. Opin. Environ. Sustain.* 35, 30–38. doi: 10.1016/j.cosust.2018.10.008

Zhou, C., Xu, L., Tang, H., Hu, F., He, P., Kumazawa, T., et al. (2019). Identifying the design alternatives and flow interference of tuna purse seine by the numerical modelling approach. *J. Mar. Sci. Eng.* 7 (11), 405. doi: 10.3390/jmse7110405