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Bycatch governance and best practice mitigation technology in global tuna fisheries

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ABSTRACT

Overexploitation of bycatch and target species in marine capture fisheries is the most widespread and direct driver of change and loss of global marine biodiversity. Bycatch in purse seine and pelagic longline tuna fisheries, the two primary gear types for catching tunas, is a primary mortality source of some populations of seabirds, sea turtles, marine mammals and sharks. Bycatch of juvenile tunas and unmarketable species and sizes of other fish in purse seine fisheries, and juvenile swordfish in longline fisheries, contributes to the overexploitation of some stocks, and is an allocation issue. There has been substantial progress in identifying gear technology solutions to seabird and sea turtle bycatch on longlines and to direct dolphin mortality in purse seines. Given sufficient investment, gear technology solutions are probably feasible for the remaining bycatch problems. More comprehensive consideration across species groups is needed to identify conflicts as well as mutual benefits from mitigation methods. Fishery-specific bycatch assessments are necessary to determine the efficacy, economic viability, practicality and safety of alternative mitigation methods. While support for gear technology research and development has generally been strong, political will to achieve broad uptake of best practices has been lacking. The five Regional Fisheries Management Organizations have achieved mixed progress mitigating bycatch. Large gaps remain in both knowledge of ecological risks and governance of bycatch. Most binding conservation and management measures fall short of gear technology best practice. A lack of performance standards, in combination with an inadequate observer coverage for all but large Pacific purse seiners, and incomplete data collection, hinders assessing measures' efficacy. Compliance is probably low due to inadequate surveillance and enforcement. Illegal, unreported and unregulated tuna fishing hampers governance efforts. Replacing consensus-based decision-making and eliminating opt-out provisions would help. Instituting rights-based management measures could elicit improved bycatch mitigation practices. While gradual improvements in an international governance of bycatch can be expected, market-based mechanisms, including retailers and their suppliers working with fisheries to gradually improve practices and governance, promise to be expeditious and effective.

1. Introduction

Responsible fisheries conduct requires effective governance of all sources of fishing mortality, including from retained target catch, both retained and discarded bycatch, and unobserved mortalities [1–6]. Under the 1982 Law of the Sea Convention, States are obligated to protect and preserve the marine environment (Article 192), and consider the effects of fishing on species associated with or dependent upon commercially exploited species (Article 119) [2]. This is elaborated further in the 1995 Fish Stocks Agreement, which obligates States to minimize bycatch and impacts on associated and dependent species (Article 5(f)) [3], and additionally is addressed in the 1995 Food and Agriculture Organization of the United Nations' Code of Conduct for Responsible Fisheries, calling on States and ocean users to develop and apply environmentally safe and selective fishing gear and practices, minimize waste, and minimize bycatch and impacts on associated or dependent species (Sections 6.5–6.8) [4]. An integral component of implementing the ecosystem approach to fisheries [1], this is necessary to contribute to maintaining marine biodiversity, ecosystem structure, processes, and services, including sustainable fishery resources [5,6].

While used inconsistently, the term bycatch can be defined as consisting of: (i) retained catch of non-targeted, but commercially valuable species, referred to as 'incidental catch' or 'byproduct'; (ii) discarded catch, whether the reason for non-retention is economic or regulatory; plus (iii) unobserved mortalities [5–9]. Sources of unobserved mortality include catch that is depredated or dies and falls from the gear before the gear retrieval, ghost

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fishing from lost or abandoned gear, and post-release mortality of catch that escapes or is released alive but in poor condition [10–14]. Large errors can result when stock assessments and population models do not correctly account for unobserved mortality levels. Regardless of the definition employed, reporting and managing ecological risks from all fishing mortality is critical for effective fisheries governance.

Bycatch may contain a variety of species, from marine megafauna to lower trophic-level species, critical for the maintenance of the structure and functioning of marine ecosystems, and the continued provision of marine ecosystem services. Vulnerable species groups subject to bycatch include seabirds, sea turtles, marine mammals, elasmobranchs (sharks, skates, and rays) and other fish species. Populations of these species are particularly vulnerable to overexploitation of older age classes, can decline over short temporal scales (decades and shorter), and are slow to recover from large declines due to their K-selected life-history strategy, characterized by long life spans, slow growth, delayed sexual maturity, low fecundity, and low natural mortality rates of older individuals [5,10–12,15–23]. Discarded catch, offal from processing fish at sea, and discarded and lost bait all raise an ecological concern due to changes in the foraging behavior and natural diet of marine species, for instance, by scavenging seabirds, marine mammals, sharks, and benthic species, and may also cause localized anoxia of the seabed [1,11,14,18,24].

Fishing mortality from bycatch also contributes to the broader issue of overexploitation [25–31], currently the largest driver of change and loss of global marine biodiversity [32]. Primarily species with a K-selected life-history strategy, endemics with restricted ranges, and species with sporadic recruitment are at risk; however, even highly fecund species and those with broad distributions can be unsustainably exploited [16,18,28,33–35]. Marine capture fisheries have reduced the abundance of affected populations, and in some ecosystems have fished down food webs as targeted species have gradually been from declining mean trophic levels [16,18,27]. Fisheries overexploitation also reduces the availability of natural prey to marine mammals, seabirds, sea turtles and elasmobranchs, through direct removal of prey species and trophic cascades [16,18,27,28,36,38–41], compounding the direct adverse effects of bycatch fishing mortality.

Marine fisheries have altered marine biodiversity, from genetic diversity to ecosystem integrity, in complex ways that are not completely understood. For example, despite international obligations to maximize fisheries selectivity, concentrating bycatch and target fishing mortality on a narrow subset of an ecosystem's components can reduce genetic diversity [18,37]. As a result of fishing gear selecting for large individuals and species, marine capture fishing has altered the distribution of fish sizes, fish mature earlier and at a smaller size, causing reduced reproductive potential, where the proportion of large species and large, fast-growing individuals has declined, which may have caused irreversible changes in the gene pool, altering the evolutionary characteristics of populations [18,28,36–40]. Bycatch mortality of phylogenetically distinct species is another mechanism for reducing genetic diversity, where the loss of entire higher taxonomic groups and evolutionary lineages from marine fisheries and other anthropogenic stressors could alter the evolutionary processes of affected coastal and marine ecosystems [18,37]. Unsustainable bycatch fishing mortality of keystone and foundation species that play critical roles in regulating an ecosystem's processes and structure can cause extinction cascades, alter trophic interactions, simplify food webs, and change ecosystem structure and functioning, including reduced ecosystem resistance and resilience to environmental fluctuations, and possibly exceeding tipping points, where permanent regime shifts occur, or otherwise causing slowly reversible change [18,28,36–40].

Unsustainable levels of bycatch also have negative socioeconomic consequences for fishing communities, as an incidental catch is an important income source and contribution to food supply in some fisheries and countries [6,42]. Overexploitation of incidental species, including bycatch of juveniles of a commercial species, can cause growth and recruitment overfishing, adversely affect future catch levels, and result in allocation issues between fisheries [5,15,43]. Furthermore, discarded bycatch raises a social issue over waste, representing a threat to the long-term capacity to provide food and a source of livelihood [8,42]. Despite international obligations [1–4], from 1992 to 2001, an average of 7.3 million tons of fish were annually discarded, representing 8% of the world catch [8]. There have been substantial reductions in discard levels in recent years, in part, due to an increased retention as new markets for previously discarded species and sizes have developed, but also from an increased gear selectivity [8,15].

In this paper, bycatch problems in tuna fisheries are described, and best practice gear technology solutions, involving changes in fishing gear designs and methods, are identified. Building on previous studies that designed and assessed Regional Fisheries Management Organizations (RFMOs) against general best practice criteria [43–45], progress in international governance of bycatch in tuna fisheries is assessed, including the adoption and implementation of best practice gear technology mitigation methods. Key considerations for bycatch mitigation through gear technology approaches are also identified.

2. Tuna Fisheries

2.1. Main gear types and targets

Purse seine, pelagic longline and pole-and-line fisheries are the primary commercial fishing methods for catching tunas [15,46]. Large longline vessels generally catch older age classes of bigeye tuna (*Thunnus obesus*) and bluefin tunas (*Thunnus maccoyii* [southern], *Thunnus orientalis* [Pacific] and *Thunnus thynnus* [Atlantic]) for the *sashimi* market and some longline fleets target albacore (*Thunnus alalunga*) for canning. Purse seine vessels target younger age classes of skipjack (*Katsuwonus pelamis*) and yellowfin (*Thunnus albacares*) tuna for canning with an incidental catch of bigeye tuna [46]. A small volume of bluefin is caught by purse seiners for tuna ranching [47]. Pole-and-line vessels catch mostly skipjack and small/juvenile yellowfin, albacore, and bluefin, primarily for canning [46]. Of globally traded seafood commodities, tuna products have the third highest value [42,48]. Demand for both canned and fresh tuna has been rapidly increasing: the reported landings of the principal market species of tunas increased from <0.2 million ton in the early 1950s to a peak of 6.4 million ton in 2006, largely due to an increased catch of tropical skipjack tuna by purse seiners [42,46,49]. About 10%, 23%, and 66% of the catch of principal market species of tunas are from the Atlantic, Indian, and Pacific Oceans, respectively [49].

Despite their high fecundity and wide distribution, most tuna stocks are fully exploited, and some are overfished or even depleted. Of the 20 tuna stocks for which the status is known, at least five are 'overfished' (albacore in the North Atlantic, bigeye in the Atlantic, bluefin in the East and West Atlantic, and southern bluefin) [46,49]. Furthermore, western and central Pacific bigeye is approaching an overfished state, and may already be overfished [50]. 'Overfishing' is occurring for at least an additional four stocks (bigeye in the East and western central Pacific, yellowfin in the Indian Ocean, and bluefin in the Pacific) [46,49–54]. While fishing mortality and biomass were determined to be within MSY-based reference points, the most recent stock assessment for western and central Pacific yellowfin predicted biomass declines in the equatorial subregion of the western central Pacific, where almost all yellowfin is caught in this region [53]. Despite there being skipjack stocks in the Pacific and Indian Oceans, and albacore in the South Atlantic and South Pacific that are only moderately exploited [46,49,55,56], because these species are caught primarily in purse seine fisheries, it is not presently possible to sustainably increase catches of these stocks without increasing bycatch levels of other tuna species, including small bigeye and yellowfin tunas primarily in purse seine sets on fish aggregating devices (FADs) and other floating objects. For example, Fonteneau et al. [57] estimated that bigeye tuna comprises around 12% of the total of global purse seine FAD catches, while An et al. [58] found that bigeye comprised 1.7% of purse seine sets on FADs by the Korean fleet operating in the western and central Pacific Ocean in 2008. Increased purse seine catches of the moderately exploited stocks might be sustainable if sets were restricted to being made on unassociated (free swimming) schools. Increased longline and pole-and-line catches of moderately exploited albacore stocks might also be sustainable.

2.2. Bycatch

Table 1 describes the bycatch of sea turtles, seabirds, marine mammals, sharks and juvenile and unmarketable finfish in pelagic longline and purse seine fisheries. There are extremely low bycatch levels in pole-and-line fisheries, where bycatch, that does occur generally, consists of juvenile kawakawa tuna (*Euthynnus affinis*), frigate mackerel (*Auxis rochei*), mahimahi (*Coryphaena hippurus*), and rainbow runner (*Elagatis bupinnulata*). Discards are believed to have high post release survival rates, due to the use of barbless hooks and flick-off practices [59]. However, concern over bycatch of reef fish and juvenile classes of target species in baitfish fisheries that supply live bait to pole-and-line fisheries has been raised, as have other ecological issues (ecosystem effects of removal of baitfish species, overexploitation of target baitfish species, and habitat degradation) and socioeconomic issues (food security impacts with coastal communities) [60,61].

3. Best practice gear technology solutions

This section summarizes the state of knowledge for mitigating bycatch in pelagic longline and purse seine tuna fisheries via gear technology approaches. Where progress is lacking, research and development priorities are identified.

3.1. Gear technology methods for mitigating bycatch in pelagic longline fisheries

- **Seabirds**: effective employment of combinations of certain seabird avoidance methods can nearly eliminate seabird interactions [10,111–114]. A large and growing number of effective seabird bycatch avoidance methods exist, including measures to: (i) avoid peak periods of seabird foraging via night setting; (ii) reduce seabirds' detection of baited books through blue-dyed bait, shielded deck lights, underwater setting devices, retention of offal and other discards, and an artificial bait; (iii) limit bird access to baited hooks through underwater setting devices, side setting, increased weighting near hooks, thawed bait, bait casting machine, and setting terminal tackle and mainlines outside of the propeller turbulence; and (iv) deter birds from taking baited hooks through bird-scaring 'tori' lines, towed objects, water cannons, and acoustic deterrents [10,19,62,111–114].
- **Sea turtles**: the best practice for reducing sea turtle bycatch and injury in pelagic longline fisheries, without adversely affecting an economic viability, is to employ wide circle hooks in combination with large whole fish bait. When this combination of hook and bait is used in place of using narrower J-shaped J and tuna hooks with squid bait, it has significantly reduced sea turtle catch rates by 55–90% and significantly reduced the proportion of caught turtles that swallow hooks vs. being hooked in the mouth or body or entangled, hypothesized to increase the likelihood of survival [21,22,67,115–119].

  Wider circle hooks are understood to reduce captures of hard shelled turtles, which tend to get caught by biting a baited hook, due to hooks being wider at their narrowest point. Leatherback turtles tend to get caught by becoming foul-hooked on the body and entangled; circle hooks may reduce leatherback capture due to their shape [67,68,120]. While no significant difference has been found on turtle catch rates or the location of hooking between circle hooks with a 10° offset and non-offset (i.e., with the point in the same plane as the shaft) [69,120–122], presumably there is a threshold offset angle above which the gape would be sufficiently large to cause it to hook catch similarly to J-shaped hooks.

  Turtles tend to progressively eat fish bait in small bites until they completely remove the fish from the hook, thus avoiding ingesting the hook [70,120,123]. In contrast, with squid bait, turtles tend to line the squid up with their flippers and gulp it down whole, ingesting the hook and bait together, perhaps because the squid's firm texture makes it difficult to bite off pieces [70,120,123].

  Deeper setting, to deploy hooks below 100 m, also holds promise to mitigate turtle bycatch [21,124,125]. Other promising approaches include restricting the use of lightsticks, single-hooking fish bait, reducing gear soak time and retrieval during daytime, and fishing in waters with a sea surface temperature below 20 °C [21,22,67,126,127].
- **Sharks**: best practice methods to mitigate unwanted shark bycatch include: (i) using fish instead of squid for bait; (ii) prohibiting wire leaders; (iii) avoiding hotspots; (iv) setting gear deeper; and (v) moving position when shark interaction rates are high [12,67–69,117,128–131]. Using fish instead of squid for bait causes a significant, ca. 35%, decrease in shark CPUE, while using a wider circle hook instead of a narrower J hook causes a ca. 10%, possibly significant, an increase in shark CPUE [12,67–69,117,130,132]. Deeper setting reduces catches of pelagic sharks, but likely increases catches of deeper-dwelling shark species [132–134]. Significantly lower shark catch rates occur with monofilament leaders vs. leaders of more durable material (wire, multifilament nylon) because sharks can bite through the monofilament [128,129,131]; however, terminal tackle will remain attached to the shark, with an unknown effect. There is a need to invest in continued research and development of shark deterrents, such as the development of cost-effective objects made of electropositive metals with an effective range of deterrence of pelagic sharks, which could be incorporated into terminal tackle [12,135–138].
- **Marine mammals**: best practice methods to mitigate cetacean depredation and bycatch include: (i) avoiding known hotspots; (ii) conducting fleet communication; (iii) moving when interactions occur; (iv) using circle hooks in place of J and tuna hooks, to reduce both cetacean catch rates and the proportion of those caught that are deeply hooked; and (v) using 'weak' hooks, designed so that when cetaceans are hooked, they can straighten the hooks and escape [11,139–142]. Designs for hydrophones, to detect the presence of species of echolocating cetaceans that depredate from longline gear, are in the development and testing stages [143,144]. Methods to encapsulate caught fish, and adding hardware to physically protect baited hooks, are also in the concept or research and development

Table 1
Bycatch problems in pelagic longline and purse seine fisheries.

Species group	Pelagic longline	Purse seine
Seabirds	Problematic primarily in higher latitudes [10,62]. Primarily while gear is being set, seabirds are hooked or entangled and drown as gear sinks. Of 61 species affected by longline fisheries, 26 are threatened with an extinction, including 18 albatross species [62,63–66].	Not problematic.
Sea turtles	Problematic primarily in tropics and subtropics [21–23]. Hard shelled turtles tend to get caught by biting baited hooks; leatherbacks by foul-hooking on the body and entanglement [21,67,68,69,70]. Relative risk may be high in some areas, for some populations, but information on mortality from the full range of threats is lacking. Globally, tens of thousands to hundreds of thousands are estimated to be caught annually, extrapolated from limited data from a small number of fisheries; about 25% are dead when retrieved [21–23,71,72].	Occasionally entangled in FAD appendages and caught in pursed net [5,73–76]. An IATTC estimated sea turtle mortality by large purse seiners to be 5–172 per year for 1993–2008 [77]. Relative degree of risk is likely low. When encountered in the net, turtles are typically alive and released [21]. Mortalities result from drowning when entangled in the net or an FAD, or, in rare instances, from being crushed when the net is loaded onboard [21]. Turtle mortality also occurs through an entanglement in lost FADs [78]. Sets on FADs and logs result in an order of magnitude higher turtle catch rates than dolphin-associated and unassociated sets [5,75,79,80].
Sharks and relatives	Up to a quarter of the total catch in some pelagic longline tuna fisheries, pelagic sharks can be a target, incidental or discarded bycatch [12,81]. Global catch levels of blue sharks (*Prionace glauca*), the dominant species of shark caught in high seas pelagic longline fisheries [12,75,82], while less vulnerable to an overexploitation relative to other shark species [83], may be close to or exceeding maximum sustainable yield [81,84]. Average annual shark catch levels from 1994 to 2006 in western and central pacific pelagic longline fisheries (excluding domestic fisheries of Indonesia, Philippines, and Taiwan) were estimated at 102,000 ton, with blue sharks comprising 66% [85]. In the ICCAT area, blue shark annual catch levels from 1980 to 2006 were estimated at 50,000 ton, based on an analysis of shark fin trade data, assumed to be primarily from longline fisheries [86].	A small proportion of total catch, typically < 1%, for sets on FADs and other floating objects; shark catch rates are higher for sets on FADs, other floating objects and whales than dolphin-associated and unassociated sets [5,73,75,79,80,87–90]. Silky shark (*Carcharhinus falciformis*) is the predominant shark species, comprising up to 90% of the shark catch, followed by the oceanic white tip (*Carcharhinus longimanus*) [5,73,75,88]. The Pacific purse seine catch of silky sharks was estimated at 40,000 individuals from 1992 to 1998, and 550 ton in 1998, an order of magnitude lower than levels in longline fisheries [91]. Average annual shark catch levels from 1995 to 2007 in western and central Pacific purse seine fisheries (excluding domestic fisheries of Indonesia, Philippines, and Taiwan) have been estimated at 2000 ton, with silky sharks comprising 38% [85].
Marine mammals	Cetaceans are occasionally entangled and hooked, which can injure and kill cetaceans [11,75,92,93]. Fishers may harass and kill cetaceans to try to avoid future depredation (removal of hooked fish and bait) and gear damage. Relative degree of risk is likely low [94]. Isolated (e.g., island-associated) cetacean populations may be most at risk [95,96].	There have been 98% reductions in dolphin mortality in the eastern Pacific Ocean [51,79]. Dolphin populations have not recovered as anticipated. Stress from chronic chase and capture may be a factor. E.g., sets on dolphins have been observed to cause miscarriages or separation and loss of calves, [97,98]. Purse seining in most areas other than the Eastern Pacific typically does not involve setting around dolphins, because the tuna-dolphin association is understood to be predominant only in the Eastern Pacific; however, the association of yellowfin tuna and dolphins has been observed in other oceans [73,79]. Sets occasionally made on whale-associated tuna schools can injure and kill whales [73,75,76]. Of the 6058 observed sets by U.S. purse seine vessels in the western and central Pacific Ocean from 1997 to 2002, 40 were made on live whales [76]. There is also documented cetacean bycatch on unassociated and FAD sets [75,99]. For instance, in 27,644 observed sets in the western and central Pacific, 687 marine mammals were captured [75].
Juvenile/under-sized tunas and other unmarketable sizes and species of fish	Smaller swordfish are often discarded due to minimum size requirements or low market value [100,101]. Catch rates of swordfish and juvenile/small tunas might be higher near shallow seamounts; about 10% of the tropical Pacific tuna longline catch is taken at seamounts [102–108].	Purse seine sets on anchored and drifting FADs and natural floating objects (logs, flotsam) is widespread; about half of tropical tuna catches are from FAD sets [57]. FAD sets have high catch rates of small and juvenile bigeye and yellowfin tunas and unmarketable species and sizes of other fish species relative to unassociated sets [52,57,58,73,87,90,109,110]. Networks of thousands of artificial drifting and anchored FADs possibly act as 'ecological traps' of pelagic species by altering their natural spatial and temporal distributions, habitat associations, migration patterns, and residence times [87,163–166].

stages [11,145]. Moreno et al. [145] tested a device that descends over groups of hooks during gear hauling, encasing the catch, finding 83% lower cetacean depredation of caught fish when employing the device in the Chilean demersal longline fishery for Patagonian toothfish. The demersal longline gear soaks at a depth below the diving depth of cetaceans that interact with the fishery, so the encasement device only needs to work during the haul. The device is not deemed suitable for pelagic longline gear, because it does not protect caught fish during the set and soak, when cetaceans can access hooks. However, design of a device to encase caught fish in pelagic longline fisheries is in development [141] and at-sea trials are planned (Derek Hamer, Australian Marine Mammal Center, personal communication, 16 June 2010). Encasement of hooked sensitive species is a concern. Mooney et al. [146] tested a prototype acoustic device, designed to block cetacean echolocation performance, on a captive false killer whales (*Pseudorca crassidens*), finding that the device effectively disrupted echolocation, but only when in close proximity (< 30 m) to the whale, and that efficacy decreased over time, perhaps due to the whale's habituation to the device, and/or because the source sound level decreased due to power drain. 'Acoustic harassment devices' have raised concerns due to potential injury to cetaceans directly from exposure to loud noise and indirectly through altered distribution, while 'acoustic deterrence devices', which transmit a lower level of noise than harassment devices, may result in habituation by cetaceans, attracting cetaceans, and having a deterrent effect on target species [147–150]. Broadcasting killer whale vocalizations when hunting has been proposed as a possible deterrent, although cetacean habituation is likely [11]. Analysis of observer program data revealed that cetaceans avoid depredating oilfish (*Ruvettus pretiosus*) in the Hawaii pelagic longline fleet (Karin Forney, National Marine Fisheries Service, personal communication, April 2010); lacing decoy fish on the line with oilfish or isolating and using the chemical found to have the deterrent property could elicit a learned avoidance behavior by cetaceans for individual vessels employing the technique.

- **Juvenile and small billfish**: avoiding grounds with high densities of juvenile and small swordfish and other billfish, such as shallow seamounts [102–108], using circle hooks to increase the prospects of discarded billfish of surviving the interaction [100], employing gear designed to set baited hooks below 100 m [124,125], and restricting the use of lightsticks, are best practices for mitigating the bycatch of unwanted juvenile and small swordfish and other billfish in pelagic longline tuna fisheries.

3.2. Gear technology methods for mitigating bycatch in purse seine Fisheries

- **Sea turtles**: (i) restricting setting on FADs and other aggregating devices (logs, other floating debris, whales, whale sharks, and data buoys); (ii) avoiding encircling turtles; (iii) monitoring FADs and releasing entangled turtles; (iv) recovering FADs when not in use; and (v) deploying crew on boats to spot and release turtles entangled in the net are methods to reduce sea turtle bycatch [21,151]. There is a need to continue research on modified FAD designs. Chanrachkij et al. [152] suggest using relatively rigid netting material for the FAD underwater appendage to reduce the risk of turtle entanglement. Molina et al. [74] describe a prototype FAD designed to avoid turtle entanglement by using a cylindrical curtain of fabric instead of conventional netting for the FAD appendage. Designs of biodegradable FADs are being considered to address the problem of ghost fishing by discarded and lost FADs [152].
- **Sharks**: methods to avoid shark bycatch include: (i) avoiding hotspots and (ii) restricting setting on FADs and other aggregating devices [5,52,57,58,75,79,80,87]. There is a need to invest in research on shark repellents with sufficient effective range for deployment on FADs [12,137,138]. Employment of a bait station to attract sharks away from FADs has been suggested as a way to separate sharks from target species [153]. There is preliminary evidence that silky sharks make nocturnal excursions of a few hours away from FADs [154], potentially allowing for the timing of sets to coincide with periods with low shark abundance in FAD aggregations. Additional research is needed to test this hypothesis across other shark species and regions, although most FAD-caught individuals are silky sharks [5,73,75,88].
- **Marine mammals**: methods to reduce dolphin bycatch in purse seine sets on dolphins include prohibition of night sets, conducting 'backdown' after dolphins are captured (tilting down the purse seine net at one end to let encircled dolphins escape), use of a 'Medina dolphin safety panel' (named after a California skipper, a panel of fine mesh netting sewn into the purse seine net to surround the apex of the backdown area, where porpoises are most likely to come into contact with and become entangled in the net), deploying rescuers during backdown, and using dolphin safety/rescue equipment [79,153]. Restricting live whale-associated sets would avoid injury and mortality of whales.
- **Juvenile and small tunas/unmarketable sizes and/or species of fish**: restricting setting on FADs and other floating aggregating devices would reduce catches of juvenile and small bigeye and yellowfin tunas and unmarketable sizes and/or species of fish [5,52,57,58,73,75,79,80,87,90,109]. Other gear technology approaches to avoid and minimize bycatch of finfish are in the research and development or concept stages. There is a need for continued research on sorting grids, which allow unwanted species and sizes of fish to escape, but retain target species. Prototypes have shown problematic release of target skipjack, which are of similar size as the non-target small bigeye and yellowfin; they also caused injury to fish that escaped through the grid [151,155]. Use of continuous and intermittent lights inside the net to attract and repel tunas, respectively, has been suggested as a method to move non-target catch to a sorting grid, while retaining target catch [151]. The depth of the appendage hanging vertically beneath a drifting FAD has been found to be positively correlated with bycatch rates of bigeye, suggesting that reducing the appendage depth will reduce bigeye catches [156,157]. Due to differences in swim bladder volume, different fish sizes and tuna species have distinct acoustic signatures. It is therefore conceptually feasible for purse seine operators to identify the species composition of tuna schools and the average size of fish of each species in aggregations associated with floating objects. This would provide information needed to allow them to refrain from making sets when high bycatch of unwanted species and juvenile and small tunas would occur [52,158–160]. However, current echosounder designs provide imprecise differentiation between tuna species when large schools are present, and generally do not enable precise estimates of the size of schools [151]. Hydrophones incorporated into FADs might provide the capability to determine the species and size composition of aggregations, based on there being disparate and distinguishable sounds produced by different species and sizes [151]. There is qualitative evidence that towing FADs out of the seine during the set removes small fish (e.g., chubs, dolphin fish, jacks), which are closely associated with the FAD; this is the current practice for some purse seine operators [161]. Additional research is needed to determine if this practice can effectively remove small bigeye from the net. Using two FADs within close proximity, or stacking two FADs (one at the surface, a second deployed more deeply to separate out bigeye from the aggregation) are suggested methods to separate non-target and target tunas [151,161]. Aerating the water in the net and reducing the constriction of pursing the net are concepts for improved survival rates of catch that will be discarded [151]. Qualitative observations in the Eastern Pacific suggest that skipjack and bigeye tunas move away from FADs at different times of the day, potentially allowing for the timing of sets to coincide with periods of low bigeye abundance in FAD aggregations (Kurt Schaefer, Inter-American Tropical Tuna Commission, personal communication, 26 June 2010); research is needed to test the hypothesis.

Gear technology approaches to reduce problematic bycatch in purse seine sets on FADs remain in the research and development stages, but with increased investment, promise to be effective.

While restricting purse seine FAD sets would reduce bycatch [5,21,52,57,58,73–76,79,80,87,109,152], relative to unassociated sets, in terms of CPUE and fuel consumption, sets on FADs are substantially more efficient at catching skipjack. For example, over 90% of purse seine sets on FADs are successful, compared to only 50% of sets on free-schooling tuna, and the total catch of tuna in weight per set is higher in FAD sets relative to unassociated sets [57]. While profitable purse seine fisheries that target free schools of tuna exist (e.g., in 2009, Korea's western and central Pacific purse seine fleet made 80% of their sets and obtained 82% of their catch from free-swimming schools, with the remainder of an effort and catch coming from log-associated schools [162]), these produce only about half of total global purse seine tuna landings [57,58,90,109] and are likely to become progressively less economically viable as FADs continue to increase in number and density: networks of thousands of artificial drifting and anchored FADs aggregate tunas from surrounding waters, and possibly act as 'ecological traps' of pelagic species by altering their natural spatial and temporal distributions, habitat associations, migration patterns, and residence times [87,163–166].

4. Principles and approaches

Several principles and approaches require consideration when conducting fisheries bycatch assessments and identifying potential bycatch mitigation solutions appropriate for an individual fishery.

- **Fishery-specific solutions:** solutions to bycatch problems may be fishery-specific. For instance, while an underwater setting chute has been shown to be very effective at avoiding seabird captures in the Hawaii pelagic longline fleet [111], trials in Australia have been less promising, likely due to the seabird species complex and behavioral interactions,[1] the weighting design and the use of live bait [167]. However, there may be cases where a gear technology approach can be assumed to work similarly across fisheries, where the measure's efficacy is nominally affected by various differences between fisheries. For instance, a minimum branchline weighting design or a performance standard for baited hook sink rate, and night setting, might be globally relevant across seabird assemblages, longline fisheries, and regions to reduce the bycatch of surface diving and nocturnal-foraging seabird species, respectively [10].
- **Fishing industry direct involvement:** fishers have a large repository of knowledge, which can be tapped to contribute to finding effective and practical bycatch solutions. Several bycatch mitigation methods were developed by fishermen, including bird-scaring tori lines, and technical methods to reduce dolphin mortality for eastern Pacific purse seining [5]. Furthermore, participation of fishers can result in the fishing industry developing a sense of ownership for bycatch reduction methods.
- **Criteria for an optimal bycatch mitigation method:** an obvious filter for prioritizing bycatch mitigation methods is: (i) an efficacy at mitigating unwanted bycatch to nominal levels, through methods that, prioritized in the following order, avoid interactions; minimize catch; reduce injury via handling and release best practices; and offset mortality through compensatory mitigation [10]. Furthermore, it is critical to consider the commercial viability of bycatch solutions. Given the state of fisheries management frameworks, including limited resources for monitoring, control and surveillance, methods shown to be effective in experiments may not be employed as prescribed or at all by fishers if they are not (ii) practical, (iii) safe, and (iv) economically viable, or better yet, provide operational and economic benefits [10,111]. (v) Methods that require minimal alteration to traditional gear and practices increase the likelihood of fisher acceptance. (vi) A gear technology method must be commercially available. (vii) The cost required for uptake and continued employment is another important consideration. For example, the long-term efficacy of circle hook exchange initiatives may be compromised if the circle hooks are more expensive or are not locally available, causing vessels to revert to using J and tuna hooks when circle hooks require replacement. (viii) Another important consideration is whether or not crew behavior affects the efficacy of the measure. For example, tori line efficacy can be compromised if a crew member does not maintain streamer coverage over the area where baited hooks are being deployed. Conversely, the efficacy of prescribed hook, bait, line weighting and night setting are not subject to crew behavior. (ix) Related to the previous criterion, methods that facilitate enforcement are preferable. For example, vessel compliance with night setting can be confirmed via vessel monitoring systems. Prescribed gear designs can be confirmed via dockside inspections. Conversely, use of tori lines or blue-dyed and thawed bait to prescription is not easily enforced. (x) Measures that lend themselves to measurable performance standards without requiring analyses of observer program data, such as a weighting design that achieves a threshold baited hook sink rate, are optimal. Finally, (xi) an optimal bycatch mitigation method will not cause increased bycatch of other unwanted bycatch species/sizes, or better yet, will effectively mitigate problematic bycatch of multiple species.
- **Consideration of effects on multiple bycatch species groups:** it is critical to identify known conflicts as well as mutual benefits amongst species groups from bycatch mitigation methods. For example, use of wider circle hooks in place of narrower J and tuna hooks to reduce turtle bycatch rates and mortality in pelagic longline fisheries has also been found to reduce seabird bycatch rates by about 80%, while use of fish instead of squid for bait to reduce turtle catch rates also significantly reduces shark catch rates by about 30% [12,15,168]. However, for instance, in some regions, setting longlines at night to protect albatrosses and other diurnal foraging seabirds has led to higher bycatch of nocturnal-foraging seabirds [169]. Restrictions on purse seine sets on dolphins resulted in an increased FAD setting, which increased bycatch of juvenile/small tunas, sharks, dolphin fish, sea turtles and marine mammals [75,79,109]. Prohibiting wire leaders in longline gear to reduce shark catch rates [128,129,131] could exacerbate seabird bycatch problems: fishers may be less likely to attach weights close to hooks on branchlines lacking a wire leader due to safety concerns,[2] thus reducing the baited hook sink rate and increasing seabird catch rates [170]. Potential conflicts resulting from the uptake of alternative bycatch mitigation methods has received inadequate consideration in past initiatives, which have tended to have a single-species or a species group focus.

[1] In Australia, a deep diving shearwater brings baited hooks to the surface making them available to larger albatrosses and petrels, while deep diving seabirds rarely interact with the Hawaii fleet [167].

[2] If a longline branchline breaks during hauling, which frequently occurs when sharks are caught and bite off the terminal tackle, or if the hooks pulls free from a caught fish with the line under high tension (the fish 'throws' the hook), the weight can fly back at the vessel at high velocity, infrequently causing serious injury, and in rare cases, killing the crew [12,132].

For instance, existing species group-specific International Plans of Action (sharks, seabirds [19,20]) do not provide this more holistic assessment.

5. International governance

Five RFMOs were established to manage global fisheries for tunas and tuna-like species: Commission for the Conservation of Southern Bluefin Tuna (CCSBT), Indian Ocean Tuna Commission (IOTC); Inter-American Tropical Tuna Commission (IATTC), International Commission for the Conservation of Atlantic Tunas (ICCAT), and Western and Central Pacific Fisheries Commission (WCPFC). There are several critical deficits with tuna-RFMO governance of problematic bycatch: numerous gaps remain in adopting measures to mitigate problematic bycatch, while most existing measures deviate from best practice gear technology approaches to mitigate problematic bycatch and all but one lacks quantifiable performance standards. Consensus-based requirements and opt-out provisions in decision-making processes pose constraints to the adoption of best practice bycatch mitigation measures. There is inadequate regional onboard observer coverage, and insufficient and inconsistent data collection protocols for discards. Constraints to access and pool observer datasets precludes needed large temporal and spatial scale analyses. Inadequate resources for surveillance and enforcement lead to low compliance by RFMO member states and IUU fishing.

5.1. Tuna RFMO bycatch conservation and management measures

Table 2 summarizes and critiques conservation and management measures adopted by the five tuna-RFMOs to mitigate problematic bycatch in purse seine and pelagic longline fisheries. Critiques consider whether the measures require best practice gear technology methods.

Four of the tuna-RFMOs have binding measures on longline-seabird bycatch; an IATTC does not despite evidence of a problem [62,183–187]. The five seabird measures are in need of improvement, including in the areas where they are required, allowing relatively ineffective measures as options, not requiring best practice designs for gear technology approaches, and providing exclusions for smaller vessels despite an evidence of problematic bycatch by vessels in this size class.

Three of the tuna-RFMOs have adopted binding measures to address turtle bycatch: IOTC, IATTC, and WCPFC measures require gear technology methods to mitigate turtle bycatch in purse seine fisheries, while only WCPFC has a measure requiring gear technology methods to mitigate the capture of sea turtles in longline fisheries for swordfish. These measures are also in need of improvement, including in areas where they are applicable, not requiring best practice gear technology approaches, insufficient detail to ensure effective implementation of best practices, and an exclusion of longline vessel classes for which problematic sea turtle interactions are documented to occur.

IOTC, IATTC, ICCAT, and WCPFC have adopted measures restricting shark finning practices and prohibiting the retention of thresher shark species. None of the tuna-RFMOs' shark measures require the employment of gear technology best practices to minimize shark catch levels in longline or purse seine fisheries. However, a WCPFC sea turtle measure allows swordfish longline vessels to potentially select the use of whole fish bait, documented to lower shark CPUE relative to using squid for bait [12,67–69,117,130,132]. Measures prohibiting retention of certain at-risk shark species may reduce fishing mortality of these species. Measures restricting shark finning practices in longline fisheries have limited potential to control shark fishing mortality, except for fisheries with extensive resources for surveillance and enforcement, and where there are limited markets for shark meat [12,132]. With an expanding exploitation of sharks for fins and meat [12], improved data collection, stock assessments for all affected shark species, monitoring, and precautionary shark management measures, through gear technology measures, but also input/output controls, are needed in order to ensure sustainable levels of shark fishing mortality in pelagic longline and purse seine tuna fisheries.

IATTC has been extremely effective at reducing direct mortality of dolphins in purse seine sets on dolphins, a problem that does not occur in other regions. Regional assessments have not been conducted to determine if tuna RFMO measures are warranted to mitigate cetacean interactions in longline fisheries [11,75,92,93]; increased observer coverage rates increased, improved data collection protocols, and analyses are required to address this deficit.

All of the tuna-RFMOs, excluding CCSBT, have adopted legally binding measures to mitigate the bycatch of juvenile/small tunas and unmarketable species and sizes of other fish species. Time/area restrictions, including IATTC and WCPFC time/area closures for purse seine sets on FADs, may reduce catches of juvenile and small tunas, and other unmarketable species and/or sizes of fish. Measures for required catch retention, and ICCAT's limitations on retention of small swordfish, bluefin, and marlin, might provide an economic incentive to avoid making sets when high levels of small target species would be caught, avoiding areas known to have high densities of small and juvenile fish of these species, and to develop and use effective gear technology mitigation methods. None of the tuna-RFMOs require gear technology measures to mitigate longline bycatch of small swordfish.

Of the tuna RFMO bycatch measures, only those of the IATTC-administered Agreement on the International Dolphin Conservation Program (AIDCP) include quantifiable performance standards (Table 2) [51,153]. For example, none of the tuna RFMO's seabird measures specify standards for the outcomes of required gear technology measures through the designation of threshold seabird catch rates or levels, or standards for indirect performance such as minimum sink rates for terminal tackle. Or, for example, measures designed to create an incentive to reduce juvenile/small bigeye tuna catch in purse seine sets on FADs and other aggregating objects lack specific standards for performance, for example, by establishing a maximum threshold for the bigeye proportion of a vessel's catch and/or landings, which might be an effective incentive for vessels to avoid bigeye. In the absence of such measurable, quantifiable standards for the performance of RFMO bycatch mitigation measures, comparison of bycatch rates before vs. after mitigation measures, accounting for the influence of other factors with possibly significant effects on bycatch rates, provides a measure of efficacy [113,117]. However, data deficiencies due to inadequate monitoring are often an obstacle to implementing this approach at regional scales.

5.2. Fisheries monitoring, access and pooling observer datasets, and bycatch assessments of data-limited fisheries

Regional onboard observer coverage is generally insufficient in global tuna fisheries [222]. Observer data are key to identifying and understanding trends in bycatch rates and levels, and in assessing performance of mitigation measures in a commercial setting, where, for example, methods for an employment of prescribed bycatch reduction methods likely differ from experimental conditions [10,113,223]. Adequate data collection protocols and observer coverage rates are needed to allow for robust statistical analyses of bycatch interactions, including

Table 2
Conservation and management measures to mitigate bycatch adopted by the tuna Regional Fisheries Management Organizations.

Measure	Legally binding?	Critique
Seabirds		
CCSBT: in 1997, required bird-scaring (tori) lines south of 30°S [171]; adopted guidelines in 1999 [172]. A 2008 recommendation states that, when fishing in the IOTC and WCPFC areas, CCSBT members and cooperating non-members will comply with IOTC and WCPFC measures on protecting ecologically related species [173].	Y	The 30°S. northern boundary may be problematic: Australia determined seabird bycatch measures are necessary North to 25°S. [174]. ICCAT and IOTC require seabird measures North to 20°S [175] and 25°S [176], respectively. The CCSBT measure lacks performance standards. An estimated 80%, 12%, and 8% of southern bluefin tuna catch comes from the IOTC, WCPFC, and ICCAT areas, respectively [177]. However, CCSBT [173] does not require compliance with ICCAT bycatch measures. As a result, CCSBT vessels fishing in the ICCAT area, if from a nation that is not a member of an ICCAT, are required only to employ a tori line, found to be insufficient as a stand-alone measure at grounds with deep-diving seabirds [178].
IOTC: a 2010 resolution, superseding previous measures, requires, when south of 25°S, use of at least two seabird mitigation methods selected from two lists of nine alternatives [176].	Y	There can be substantial differences in the efficacy of the nine alternative seabird bycatch mitigation measures [10,62,112,113]. For example, a vessel that selects to use weighted branchlines and offal discharge control would very likely have a substantially higher seabird catch rate than a vessel that employs night setting and tori lines. The 'offal discharge management' measure, which prohibits offal discharge during setting and discourages discharge during hauling, is inconsistent with WCPFC [179]. There have been mixed findings of the effect on seabird catch rates from intentional 'strategic' offal discards [62,180,181]; refraining from discharge may be more effective over the long-term. The measure lacks performance standards.
IATTC: in 2005, recommended: (i) implementation of the FAO International Plan of Action—seabirds; (ii) collection of an information on seabird interactions, including bycatch in fisheries; and (iii) Working Group on Stock Assessment to assess the impact of seabird bycatch in eastern Pacific tuna fisheries [182].	N	There is a need for a legally binding measure requiring best practices to mitigate seabird interactions in pelagic longline fisheries. An IATTC [183] reviewed seabird interactions in Eastern Pacific fisheries, concluding that longline fisheries operating in the IATTC Convention Area may adversely affect some seabird species. There is an evidence of relatively high rates of seabird bycatch in several Eastern Pacific longline fisheries [62,184–187].
ICCAT: in 2007, required pelagic longline vessels to carry and use tori lines when fishing south of 20°S [175]. Longline vessels targeting swordfish using monofilament longline gear that set their gear between nautical dusk and dawn, and using a minimum swivel weight of 60 g within 3 m of the hook, may be an exempt [175].	Y	Seabird bycatch avoidance measures are not required for longline vessels operating in the North Atlantic, where seabird bycatch has been documented [62,168,188–190]. The measure lacks performance standards, including a minimum sink rate for terminal tackle for swordfish vessels claiming the tori line exemption.
WCPFC: in 2007, required longline vessels operating in areas south of 30°S and north of 23°N to employ two seabird avoidance methods selected from two lists of a total of eight alternatives. Exempts vessels <24 m in areas north of 23°N [179].	Y	As with the IOTC seabird measure, there can be substantial differences in the efficacy of some of the eight seabird bycatch mitigation measures included in the list of alternative measures [10,62,112,113]. Exemption for smaller vessels is problematic: high seabird bycatch rates have been documented by vessels, in this size class, in this area [59–61,111–113]. As with the CCSBT seabird measure, the selection of 30°S as the southern hemisphere northern limit may be problematic [173,175,176]. While seabird bycatch is documented to be an extremely rare event in the tropical Pacific [57,191], the selection of 23°N as the northern hemisphere southern limit is problematic: high seabird catch rates have been documented south of this boundary [113,187]. The 'management of offal discharge' measure is inconsistent with an IOTC: the IOTC measure prohibits offal discharge during setting and discourages discharge during hauling [176]; the WCPFC measure allows a vessel to either refrain from all discharges or strategically discharge from the opposite side of the vessel from setting and hauling [179]. Refraining from discharge is possibly more effective over the long-term [62]. The measure lacks performance standards.
Sea turtles		
CCSBT: no specific measure on managing sea turtle bycatch. 2008 Recommendation requires compliance with IOTC and WCPFC measures on protecting ecologically related species when fishing in the IOTC and WCPFC areas [173].	N	A small proportion of southern bluefin tuna longline effort occurs in the ICCAT area [177]. However, CCSBT [173] does not require employment of an ICCAT sea turtle measures.

Table 2 (*continued*)

Measure	Legally binding?	Critique
IOTC: a 2009 resolution requires members to report data on sea turtle interactions and for vessels to follow sea turtles handling and release guidelines and posses and use specified turtle release equipment [192]. Purse seine vessels are required to: (i) avoid encircling sea turtles; (ii) when a turtle is encircled or entangled, take measures to safely release the turtle, including stopping the net roll as soon as the turtle comes out of water, disentangling the turtle before resuming net roll, and to the extent practicable, resuscitating the turtle before returning it to the water; and (iii) release all turtles observed entangled in FADs or other gear. Longline vessels are encouraged to use whole fish bait.	Y	There is a need for a legally binding measure to require the employment of best practices to mitigate sea turtle interactions in pelagic longline fisheries. The current measure requires the possession and use of turtle handling and release equipment, but does not require measures to avoid and minimize turtle captures. Restricting setting on FADs and other tuna aggregating devices; stipulating minimum time periods for monitoring FADs; and recovering FADs when not in use are additional best practice methods to reduce sea turtle bycatch in purse seine fisheries [21]. Measure does not specify what actions vessels must take to avoid encircling turtles. The measure lacks performance standards.
IATTC: a 2004 resolution established a three-year program to: (i) collect and analyze information on sea turtle–fishery interactions in the eastern Pacific Ocean; (ii) review the efficacy and effects on target species catch rates of sea turtle avoidance methods; (iii) educate the industry sector; and (iv) establish a voluntary fund to augment the capacity for sea turtle conservation by coastal developing countries [77]. The program was extended in 2007. Program activities, implemented in collaboration with numerous organizations, have included: (i) the exchange of circle hooks for J hooks, tuna hooks and narrower circle hooks; (ii) distribution of dehookers; (iii) placement of onboard observers to monitor hook trials; and (iv) training in data collection and database management for participants in the hook trials [183]. A 2007 resolution calls for purse seine vessels to: (i) avoid encirclement of sea turtles to the extent practicable; (ii) monitor FADs for entangled turtles; (iii) release turtles observed entangled in FADs; and (iv) conduct research and development of new designs of FADs to reduce turtle entanglement [193]. A previous measure required rescuing turtles sighted in nets before they become entangled, and when turtles are entangled in the net, to stop net roll as soon as the turtle comes out of the water, and not start again until the turtle has been released [194]. The 2007 resolution further calls on longline vessels to: (i) carry and use turtle releasing equipment; and (ii) conduct trials of combinations of circle hooks and bait, depth and other turtle bycatch mitigation measures [193].	Y	There is a need for a legally binding measure requiring best practices to mitigate sea turtle interactions in pelagic longline fisheries. The current measure requires the possession and use of turtle handling and release equipment, but does not require actions to avoid and minimize turtle captures. Restricting setting on FADs and other tuna aggregating devices; stipulating minimum time periods for monitoring FADs; and recovering FADs when not in use are additional best practice methods to reduce sea turtle bycatch in purse seine fisheries, which are not included in the measure [21]. Measure does not specify what actions vessels must take to avoid encircling turtles. The measure lacks performance standards for sea turtle interactions in longline or purse seine fisheries.
ICCAT: a 2003 resolution encourages the: (i) collection and provision of data on sea turtle–fishery interactions and other threats to sea turtles; (ii) live release of caught sea turtles; and (iii) sharing of information on technical measures to reduce turtle catch levels and handling and release practices. The resolution also calls for (iv) the development of data collection and reporting methods for the incidental bycatch of sea turtles in fisheries for tuna and tuna-like species [195]. A 2005 resolution encourages circle hook research and exchange of ideas on improving the handling and release of caught sea turtles [196].	N	There is a need for a legally binding measure to require the employment of best practices to mitigate sea turtle interactions in pelagic longline and purse seine fisheries.
WCPFC: a 2008 measure requires purse seine vessels to: (i) avoid encircling sea turtles; (ii) safely release turtles that are encircled or entangled in FADs or other gear, including, when turtles are entangled in the net, stopping net roll and disentangling the turtle; and (iii) carry and use dip nets to handle turtles [197]. The measure requires shallow-setting, swordfish-targeting longline vessels to employ one or more of the following: (i) use only large circle hooks, defined as, "…generally circular or oval in shape and originally designed and manufactured so that the point is turned perpendicularly back to the shank", that have an offset $\leq 10^{\circ}$; (ii) use only whole finfish for bait; and (iii) use any other measure approved by the Commission to be capable of reducing turtle interaction rates. Members are to establish their own definitions of what constitutes a 'large' hook, and what constitutes a 'shallow-set, swordfish targeting' fishery. Swordfish fisheries	Y	Additional restrictions on setting on FADs and other aggregating devices; stipulating minimum time periods for monitoring FADs; and recovering FADs when not in use are additional best practice methods to reduce sea turtle bycatch in purse seine fisheries [21]. Measure does not specify what actions vessels must take to avoid encircling turtles. The single factor effect of using either a large circle hook with the specified threshold offset, or whole fish bait, on turtle catch rates is less certain than is the use of the combination of the two measures [21,22,67,115–117,119]. The efficacy of the longline measure is compromised by not defining what constitutes a "large" hook, such as a minimum width for the narrowest point of the hook. There is no empirical basis for requiring circle hooks to have an offset $\leq 10^{\circ}$ [122]. While there is an evidence of order of magnitude higher sea turtle catch rates in shallow-setting, swordfish-targeting longline fleets relative to deeper-setting tuna-targeting fleets, there is a large and growing

determined by the Scientific Committee to have minimal observed turtle interaction rates over a three-year period, and $\geq$ 10% observer coverage during the three-year period, are exempt from the measure, where 'minimal' rates are to be determined by the Scientific Committee. All longline vessels are required to carry specified turtle handling and release equipment [197].		body of evidence of problematic levels of sea turtle mortality in longline tuna fisheries [21,23,116,119]. The measure lacks performance standards.
Sharks		
CCSBT: no specific measure on shark bycatch. 2008 recommendation requires compliance with IOTC and WCPFC measures on protecting ecologically related species when fishing in the IOTC and WCPFC areas [173].	N	Measures restricting shark finning practices have limited potential to control shark fishing mortality levels, except in fisheries with limited markets for shark meat and strong resources for surveillance and enforcement [12]. None of the shark measures require employment of longline or purse seine gear technology best practices for shark bycatch mitigation. ICCAT has pursued improved collection of species-level shark catch data since 1995, but lack of compliance has impeded effective shark stock assessments [201]. Similarly, IOTC passed a resolution in 2005 calling for shark catch data reporting, and passed a second resolution in 2008 when compliance with the 2005 shark data reporting resolution was poor [198,199]. Measures prohibiting retention of certain at-risk shark species may contribute to reduced fishing mortality of these species. A small proportion of southern bluefin tuna longline effort occurs in the ICCAT area [177]. However, CCSBT [173] does not call for CCSBT members to employ ICCAT measures related to the protection of ecologically related species, including sharks.
IOTC: a 2005 resolution requires: (i) annual reporting of data on shark catches; (ii) keep all parts of retained sharks, excluding head, guts, and skins, to the point of first landing; (iii) have onboard fins that total $\leq$ 5% of the weight of sharks onboard, up to the first point of landing, or otherwise ensure compliance with the 5% rule through certification, observer monitoring or other method [198]. An IOTC [199] prohibits the retention, transshipment or landing of all species of thresher sharks, intended to address concerns over the status of the bigeye thresher shark (*Aliopias superciliosus*), but applicable to all thresher species due to the difficulty in differentiating between bigeye and other thresher species.	Y	
IATTC: a 2005 measure requires members' vessels to: (i) keep all parts of retained sharks, excluding head, guts, and skins, to the point of first landing; (ii) have onboard fins that total $\leq$ 5% of the weight of sharks onboard, up to the first point of landing, or otherwise ensure compliance with the 5% rule through certification, observer monitoring or other method [200]. An IATTC has passed resolutions annually since 1999 to evaluate and reduce elasmobranch bycatch [200].	Y	
ICCAT: a 2004 measure requires vessels to: (i) keep all parts of retained sharks, excluding head, guts, and skins, to the point of first landing; (ii) have onboard fins that total $\leq$ 5% of the weight of sharks onboard, up to the first point of landing, or otherwise ensure compliance with the 5% rule through certification, observer monitoring or other method [202]. Recommendations adopted in 2006 and 2007 reminded contracting parties of requirements for the provision of shark catch data [203,204]. In 2009, an ICCAT prohibited the retention, transshipment or landing of bigeye thresher sharks, excluding a small-scale Mexican coastal fishery [205].	Y	
WCPFC: a 2009 measure requires members to either: (i) have onboard fins totaling $\leq$ 5% of the weight of sharks; (ii) land sharks with fins attached to the carcass; or (iii) land fins with the corresponding carcass [206]. The measure calls for the reporting of annual shark catches at the species-level for identified species of concern [206].	Y	
Marine mammals		
IATTC: in purse seine fisheries, vessels operating in the Eastern Pacific Ocean of nations that are contracting parties to an AIDCP receive annual, individual vessel dolphin mortality limits, there is an annual cap of 5000 total dolphin mortalities in the fishery, as well as annual mortality caps for individual dolphin stocks, established at 0.1% of each stock's minimum estimated abundance [51,153,207]. When making dolphin-associated sets, participating vessels allocated individual dolphin mortality limits are also required to have an onboard observer (for vessels with a carrying capacity exceeding 363 metric ton), use a Medina dolphin safety panel, complete backdown no later than 30 min after sunset (prohibition on night setting), conduct backdown after dolphins are captured, deploy at least one rescuer during backdown, and carry specified dolphin safety/rescue equipment, and other measures [153,207].	Y	To determine if mitigation measures are needed in longline fisheries, monitoring is required to determine cetacean interaction levels and identify affected populations [11]. Dolphin mortality was reduced from 133,000 in 1986 to 886 in 2007 in Eastern Pacific purse seine sets on dolphins [208]. Possible indirect adverse effects on dolphin populations require further investigation [79,97,98]. Measure includes specific, quantifiable performance standards.
CCSBT: no specific measure on marine mammal bycatch. 2008 Recommendation requires compliance with IOTC and WCPFC measures on protecting ecologically related species when fishing in the IOTC and WCPFC areas [173]. Neither of these two RFMOs have relevant measures in place.	N	There is a need to assess if problematic cetacean interactions are occurring in pelagic longline fisheries to determine if mitigation measures are needed. Measures prohibiting purse seine sets on whale-associated tuna schools would avoid injury and mortality of whales.
IOTC: no measures on marine mammal bycatch.	N	
ICCAT: no measures on marine mammal bycatch.	N	
WCPFC: no measures on marine mammal bycatch.	N	

Table 2 (*continued*)

Measure	Legally binding?	Critique
Juvenile and small tunas/unmarketable species and/or sizes of fish		
CCSBT: no measure on bycatch of juvenile and small tunas and unmarketable species and/or sizes of other fish species. 2008 Recommendation requires compliance with IOTC and WCPFC measures on protecting ecologically related species when fishing in the IOTC and WCPFC areas [173].	N	While pelagic longlining is the main method for catching southern bluefin tuna, the Australian component of the southern bluefin tuna fishery employs purse seine vessels to supply tuna ranches. The Australian purse seine southern bluefin tuna fishery does not employ FADs [209], suggesting that a CCSBT measure is not likely needed to address purse seine bycatch of juvenile/small tunas (also noting that the catch of small tunas in this fishery would not constitute bycatch as the catch is destined for ranching grow out). Best practice measures to mitigate longline bycatch of small swordfish should be considered. A small proportion of southern bluefin tuna longline effort occurs in the ICCAT area [177]; however, CCSBT [173] does not call for members to employ ICCAT measures related to the protection of ecologically related species.
IOTC: temporal one-month per year closure to longline and purse seine vessels of an area off Somalia is in effect from 2011 to 2012 [210]. Encourages retention and landing of all purse seine-caught bigeye, skipjack, and yellowfin, and incidental species [211].	Y	Time/area measure may ease pressure on juvenile and small tunas. Restricting purse seine sets on FADs would further reduce catches of juvenile/small bigeye and yellowfin tunas and unmarketable species and sizes of fish. Best practice measures to mitigate longline bycatch of small swordfish should be considered.
IATTC: called for the establishment of a maximum number of purse seine sets on floating objects [212]. Requires retention and landing of all purse seine-caught bigeye, skipjack, and yellowfin [213]. Measures call for continued research on sorting grids, technology to identify species and size composition in schools prior to setting, and real time fleet communication of the locations of juvenile tuna hotspots [194,213]. Temporal closure, of 59, 62, and 73 days duration for 2009–2011, respectively, for large purse seiners, and one-month per year time/area closure to all purse seine tuna vessels in an area off the Galapagos Islands, where relatively high levels of bigeye tuna bycatch occurs [213].	Y	Tuna catch retention measure might provide an economic incentive to refrains from setting when high levels of small target species are present, and for the development and use of techniques to reduce the catch of small tunas, however, performance standards are lacking [213]. Time/area restriction may ease pressure on juvenile/small tunas. Restrictions of purse seine sets on FADs, called for in an IATTC [212], but never directly instituted (the time/area closures are an alternate mechanism to control catch levels), would further reduce catches of juvenile/small bigeye and yellowfin tunas and unmarketable species and sizes of fish. Best practice measures to mitigate longline bycatch of small swordfish should be considered.
ICCAT: measures establish limits on swordfish and bluefin tuna minimum weight and length, percentage of small swordfish and bluefin in landings, and percent of bluefin retained in non-bluefin fisheries [214,215,216]. Measure limits blue and white marlin landings by longline and purse seine vessels [217]. Has time/area closures in the eastern Atlantic and Mediterranean for purse seine, longline, bait boat, troll, trawl and recreational and sport fishing vessels for bluefin tuna [214,218], an annual two-month closed period on the retention of swordfish in the Mediterranean [219], and a prohibition of fishing in western Atlantic bluefin spawning areas [216].	Y	Time/area closures may ease pressure on swordfish and juvenile/small bigeye and yellowfin tunas. The bluefin and swordfish minimum size limits and limits on marlin landings might create incentives to avoid fishing in areas where these are abundant, and might reduce fishing mortality if discards survive. Restricting purse seine sets on FADs would reduce catches of juvenile and small tunas and unmarketable species and sizes of fish. Additional measures to mitigate longline bycatch of small swordfish should be considered, including prescribed employment of circle hooks, deeper setting, and restricting setting at seamounts.
WCPFC: in 2009, adopted a three-month closure on purse seine sets on FADs and other floating objects, and catch retention of all bigeye, skipjack and yellowfin tuna by purse seine vessels, in the area bounded by 20°N and 20°S [220,221]. 2009 measure prohibits purse seine sets on data buoys on the high seas, in part, to reduce mortality of juvenile tunas [163].	Y	2009 measure clarifying the FAD closure and catch retention requirements [221] promises to effectively eliminate purse seine sets on FADs and other floating objects in the designated area and period, and nearly eliminate tuna discards in the designated area. The FAD seasonal restriction will reduce catch of juvenile and small tunas and unmarketable species and/or sizes of fish. The measure does not stipulate performance standards for purse seine catch rates/levels of juvenile and small tunas/unmarketable species and/or sizes of fish. Best practice measures to mitigate longline bycatch of small swordfish should be considered.

documentation of bycatch rates, fleet-wide extrapolations, and an identification of when and where interactions occur. The objectives of analyses (i.e., required levels of accuracy and precision), the rate of bycatch interactions, amount of fishing effort, and distribution of catch and bycatch determine the requisite onboard observer coverage rate [224,225].

Observer coverage is close to 100% for IATTC and WCPFC member states' large purse seiners, but is extremely low in all other pelagic longline and purse seine tuna fisheries across the five tuna-RFMOs [75,222,226]. Mandatory since 1999, IATTC manages a regional AIDCP observer program, including a national program component, with 100% coverage of large purse seine vessels with a carrying capacity exceeding 363 metric ton [153,222,227]. An IATTC is the only one of the five tuna-RFMOs with a regional observer program that is fully managed by the Secretariat, where at least 50% of observers on each Party's vessels must be IATTC observers [207,222]. An ICCAT is now developing a regional program with 100% coverage of purse seine vessels targeting eastern Atlantic bluefin [214]. The other RFMO observer programs consist of national or sub-regional programs that report to the RFMO; there have also been short-term regional observer programs with an uneven spatial and temporal coverage [75,222]. There is no requirement for observer coverage in IATTC member's longline fisheries or small purse seine vessels [222].

Starting on 1 January 2010, WCPFC coverage of purse seine vessels is intended to be 100% within the area bounded by 20°N and 20°S, and has adopted a target of 5% coverage by 30 June 2012 of all trips by longline and other vessels [220,222,228]. Current WCPFC coverage of longline effort is $<1\%$ [75]. National and subregional programs will supply observers for the WCPFC regional program, where the Secretariat will assist with coordination and ensure that observers are certified to Commission standards [222].

In 2001, CCSBT adopted a target of 10% observer coverage for catch and effort of member's longline fisheries [229] and data standards have been established with the intent of obtaining representative coverage of different vessel types, and temporal and spatial coverage [222,228]. CCSBT Members are responsible for providing observers for their vessels, and the data collected become part of the CCSBT database [222,229]. To date, CCSBT coverage has varied substantially amongst fleets, and the 10% target for far-seas longline fleets has not been achieved, nor has there been international exchange of observers or pooling of observer data from more than one Member [222].

IOTC established a regional observer program in 2009, which will require 5% coverage of sets for vessels >24 m overall length for each gear type while fishing in the IOTC Area [138]. IOTC will further require, by January 2013, 5% coverage for vessels <24 m overall length when fishing at grounds outside their Exclusive Economic Zone [222,230]. The IOTC observer program will be operated by Member states, with no provisions for an international exchange of observers or pooling of datasets [230].

In 2008, ICCAT adopted a resolution calling for the establishment of a regional observer program for eastern Atlantic bluefin tuna fisheries and ranching operating in the eastern Atlantic and Mediterranean Sea, as part of the multiannual bluefin tuna recovery plan, which is not yet operative [214,222]. Full coverage is planned for ICCAT purse seine vessels with length >24 m during a two-month open season period, and for all purse seiners involved in joint fishing operations regardless of the vessel length. The program will be coordinated by the Secretariat, and operated by private fisheries monitoring companies [214,222]. Under the resolution, ICCAT Contracting Parties are to ensure 20% coverage of bluefin-targeting longline vessels and 20% coverage of purse seine vessels between 15 and 24 m in an overall length; ICCAT Members are responsible for providing observers to meet this target, with no requirements for an international exchange of observers or pooling Member datasets [222].

Globally, national observer coverage of tuna fisheries is also poor. Worldwide, 40 nations are engaged in longline fishing of which only 15 have observer programs [226]. A review of the observer data collected by national programs, and held by the Secretariat of the Pacific Community Oceanic Fisheries Programme on behalf of its member countries and territories, showed that coverage of the entire western central Pacific Ocean pelagic longline fisheries has been extremely low ($<0.1\%$) from 1990 to 2004 [75]. Coverage was only slightly higher (0.8% observer coverage from 1995 to 2005) for pelagic longline vessels based in the countries and territories of the tropical and subtropical Pacific Islands [191]. The observer data held by the Secretariat of the Pacific Community are not evenly distributed amongst flag States, areas and seasons, which may limit accurate characterizations of statistically rare events [191].

Due to the ocean basin-scale distributions of marine megafauna, and because megafauna bycatch occurs in multi-national fleets operating in domestic waters and on the high seas, there is a need for observer data collection over large spatial scales and the ability to access and pool the resulting datasets to support large temporal and spatial scale analyses. For example, pooling datasets provide larger sample sizes, which can achieve sufficiently long time series needed to determine if the observed patterns are long-term trends or cyclical, short-term, serially correlated patterns, and provide broader spatial coverage across fishing grounds. Most research-quality fishery-dependent datasets are not in the public domain. Fishery data collected from observer programs are often subject to legal confidentiality measures, and in some cases, for example, are required to be amalgamated or to reduce spatial resolution of geographic references prior to public disclosure (e.g., [231]), which precludes some research applications. To support robust assessments of bycatch of highly migratory species in marine capture fisheries, the following improvements are needed:

- substantial increases in bycatch data collection to provide adequate characterizations across time (seasonal and inter-annually), region, fisheries, and vessels [75,191,232];
- employment of standardized monitoring and data recording methods (e.g., spatial resolution and precision [233], species-level taxonomic nomenclature [234], and units for measuring fishing effort and bycatch rates [10]) to enable meaningful comparisons between and the integration and pooling of datasets;
- open access to regional- and national-level observer program datasets, including those of the five tuna-RFMOs, in order to support broader research and validation, such as through publication of datasets to the Ocean Biogeographic Information System data portal and to data repositories such as the recently established Data Observation Network for Earth. In the case of fishery-dependent datasets, achieving open access will require addressing issues over confidentiality, and other general impediments to providing open access to research data [235–238]; and
- cataloging of rich metadata of fishery-dependent datasets to: (i) enable discovery of relevant data sets; (ii) determine whether pooling individual datasets is merited, and (iii) determine how individual datasets can best be integrated. To provide the requisite information to determine if pooling of various databases is suitable, standards for metadata would benefit by capturing information on sampling effort, data collection methods, and estimates of positional error [239].

The tuna-RFMOs have begun to implement ecological risk assessments to infer priority bycatch issues in data-deficient fisheries [240–245]. Ecological risk assessment of the effects of fishing involves a hierarchical approach with three levels along a continuum from a qualitative first order to quantitative rigorous assessment: Level 1 involves a qualitative assessment based on expert and stakeholder opinion; Level 2 involves a semi-quantitative assessment through a productivity (natural growth rate of a population in the absence of fishing mortality – an indicator of a population's relative resistance to fishing mortality and ability to recover from depletion) – susceptibility (does a population overlap with the fishery temporally and spatially, what proportion of each age class overlaps the fishery, what is the probability that this species interacts with fishing vessels, will be captured, and will suffer injury or mortality in the fishery being assessed) analysis, and Level 3 is a quantitative assessment documenting population-level effects from mortality levels in a fishery in question, with large data requirements [245–247]. For example, level 2 assessments have been conducted for WCPFC for 236 species of target and bycatch species [245], and a Level 2 assessment focused on seabirds, which identified where distributions of seabird species determined to be at risk of capture in pelagic longline fisheries spatially and temporally overlapped with longline fishing effort, and employed selected life history parameters for each included seabird species as indicators of productivity and susceptibility, identifying areas where the highest risk of population-level effects from bycatch in longline fisheries was predicted to occur [241]. Findings could provide the rationale for bycatch mitigation measures, such as time/area restrictions on fishing effort and fishing methods to mitigate bycatch of populations determined to be most vulnerable. ICCAT conducted a similar ecological risk assessment of seabird populations subject to bycatch in pelagic longline fisheries, corresponding to assessment levels 1–3 depending on the species assessed [242,243], and an IOTC conducted a level 2 assessment across species subject to fishing mortality in purse seine and longline fisheries [244].

Because there is likely to be information gaps for many risk assessment model inputs, and hence high uncertainty in outputs, findings require verification through analyses of available datasets, systematic monitoring and experiments: bycatch rates are affected significantly by various factors of fishing gear and methods [113], knowledge of behavioral characteristics that determine susceptibility to fishing mortality may not be well understood, and there may be uncertainty in estimated species' distributions and life history parameters for some species, including determinations of population-level effects. Furthermore, assessment of population effects may not be a suitable criterion to define fishing mortality levels as being problematic or not for threatened species, where States are obligated, under the Law of the Sea Convention, Fish Stocks Agreement, and Code of Conduct, to reduce risks of adverse effects on threatened species [2–4], without the caveat that fishing mortality is causing population-level effects.

The scope of an RFMO ecological risk assessments need to be expanded from only considering effects of fishing on vulnerable bycatch species to more broadly account for ecosystem-wide effects of bycatch mortality, including consideration of (i) adverse ecological consequences from selective fishing vs. reduced risk from balanced distribution of bycatch fishing mortality across facets of biodiversity [18,28,36–40]; (ii) fishery effects on phylogenetically distinct species [18,37]; and (iii) fishery effects on keystone and foundation species, which have a large role in regulating ecosystem structure and processes [18,28,36–40]. To fully implement ecosystem-based management and a precautionary approach to fisheries management, this will require gradual advances in scientific understanding of effects of bycatch fishing mortality across facets of marine biodiversity, from genetic diversity to ecosystem integrity.

5.3. *IUU fishing, RFMO member compliance and RFMO decision-making*

Illegal, unreported and unregulated (IUU) tuna fishing exacerbates overexploitation and causes economic losses to society, and IUU vessels are unlikely to employ measures to minimize bycatch. An IUU tuna fishing from just the high seas has been estimated to have an annual value of $581 million [248], and ICCAT estimated that >28,000 tons of Mediterranean bluefin was unreported in 2007 [249]; however, the estimated illegal proportion of total tuna landings is believed to be small, ca. 5% [250]. Several regional fishery bodies have taken steps to reduce IUU fishing, including requiring Vessel Monitoring Systems, managing lists of authorized (positive) and illegal vessels, implementing port and at-sea inspection programs, and employing catch and trade documentation programs [251–253]. ICCAT, CCSBT, IOTC, and IATTC have adopted catch documentation schemes for tunas and swordfish, and WCPFC has considered adopting a similar scheme [253]. RFMO catch and trade documentation programs are generally considered to have been unsuccessful in deterring IUU fishing [253–256]. The documentation schemes have weaknesses in their design and implementation resulting from inadequate laws and resources for surveillance, as well as from corruption, including laundering and mislabeling seafood, illegal at-sea transshipment, and non-compliance by some RFMO Members [253–256]. Recommendations to overcome these weaknesses include adopting technological measures (e.g., instituting mandatory electronic catch documentation, to reduce forgery and manipulation) and improved practices for supply chain traceability (e.g., traceability of split catches and shipments) [253–257].

The five tuna-RFMOs employ different decision-making processes to adopt conservation and management measures, where consensus-based requirements and opt-out provisions pose constraints to the adoption of best practice bycatch mitigation measures. CCSBT and IATTC require unanimity by all members for all decisions, such that every individual member has veto power. ICCAT and IOTC do not require consensus for the adoption of measures, and instead provide members with the ability to opt out of adopted measures, so that a party can object to and not be bound by a recommendation that is adopted by the Commission, which can drastically reduce the effectiveness of a regional conservation and management measure. Finally, WCPFC measures are generally made via consensus, whereby a measure can be adopted when there are no formal objections made at the time a decision is made by the Commission, and in cases where consensus is lacking, decisions on questions of substance are taken by a qualified majority (typically by a three-quarters majority) of the members present and voting.

The inability of RFMOs to prevent the overexploitation of tuna stocks and effectively govern bycatch can be attributed to their employment of consensus-based decision-making, combined with conflicting objectives of distant-water fishing nations to maintain their dominance and coastal states to expand their fishing, which has often prevented RFMOs from adopting best practice measures, but also is a result of low compliance by Member states with effective RFMO measures that have been adopted and IUU tuna fishing [35,43,250,258]. To a degree, compromises made in order to adopt bycatch measures have resulted in suboptimal measures, which do not fully employ gear technology best practices. More effective bycatch measures would likely be adopted if decisions were made via a qualified majority [259]. However, there is no indication that the wholesale changes needed to correct these problems of political will and compliance will occur in the near future.

6. Conclusions

There has been mixed progress in addressing unwanted bycatch in longline and purse seine tuna fisheries. It is likely that, given sufficient investment in research and development, commercially viable changes in fishing gear and methods are possible to reduce nearly all bycatch in tuna fisheries to nominal levels. However, even in gear types where substantial progress has been made to identify gear technology solutions, despite the availability of effective bycatch reduction methods that, in some cases, also increase fishing efficiency and provide operational benefits, the majority of fleets are not required to employ these methods. While recognizing that their long-term viability relies on the availability of tuna resources, voluntary action by the tuna fishing industry to reverse and prevent further overexploitation of tuna stocks and to address bycatch issues has been limited. While the tuna-RFMOs have made recent progress in managing bycatch for some species groups, most measures do not employ best practice gear technology methods, several gaps remain, and compliance by many member States is likely low. Governance deficits require attention, including to address inadequate observer coverage, weak or nonexistent national management frameworks, inadequate resources for surveillance and enforcement, lack of performance standards against which to evaluate the efficacy of bycatch measures, and insufficient protocols for evaluating performance of measures to inform an adaptive management.

Several other methods for mitigating bycatch may complement changes in fishing gear and methods. These include input and output controls, fleet communication, industry self-policing, and compensatory mitigation [15,260]. There are also several international time/area restrictions applicable to tuna fisheries, which can contribute to bycatch mitigation. In 2008, the Parties to the Nauru Agreement, a regional agreement establishing terms and conditions for foreign access to the Exclusive Economic Zones of eight Pacific Island Countries, closed to purse seine fishing by vessels licensed by the Parties two areas of international waters that are enclosed by the Parties' domestic waters, and in 2010 further closed international waters between 10°N and 20°S and 170°E and 140°W [261,271]. Four of the tuna-RFMOs have established time/area closures to reduce bycatch of juvenile and small tunas by purse seine vessels and juvenile and small swordfish by longline vessels (Table 2).

Voluntary initiatives by the fishing industry related to reducing unwanted bycatch have been limited, including fleet communication programs, industry self-policing, and cooperative bycatch research [116,139]. While indirectly related to bycatch mitigation, the World Tuna Purse-Seine Organization and the Organization for the Promotion of Responsible Tuna Fishing voluntarily reduced purse seine and longline capacity, respectively. In response to an excess supply of fish to tuna canneries, and concomitant reductions in prices for skipjack from canneries, some owners of tuna purse seiners formed the World Tuna Purse-Seine Organization, which temporarily limited fishing effort by their vessels by reducing the amount of time that their vessels spent fishing [262]. The Organization for the Promotion of Responsible Tuna Fishing reduced the total number of large scale tuna longline vessels by establishing a fund to buy and retire vessels, including vessels using a flag of convenience [49,262]. The fishing industry could improve tuna fisheries sustainability and achieve long-term optimal yields if global longline, purse seine, and pole-and-line fisheries worked collaboratively, instead of competing. Getting the fishing industry more involved in its own governance through rights-based management mechanisms could elicit stronger responsibility and actions by the tuna industry towards achieving long-term sustainability, including the ecological sustainability of bycatch. Rights-based mechanisms allocate rights to a fishery, such as to individual fishers, companies or associations, typically with an aim to avoid exceeding optimal catch levels [259,263], but the concept is also of relevance to meeting bycatch mitigation objectives. For international tuna fisheries, limited entry and individual- and/or fishery-based transferable quotas for target species are relevant rights-based mechanisms to be implemented by the tuna-RFMOs, where substantial resources for monitoring, control surveillance, and enforcement would be required for effective implementation [259,263]. Instituting rights-based mechanisms in tuna fisheries could result in reduced competitiveness of smaller companies with gradual dominance by larger ones, a socioeconomic cost that deserves consideration when comparing costs and benefits across the suite of bycatch mitigation approaches.

Where RFMO and fishing industry initiatives have generally been insufficient, we can be cautiously optimistic that third party eco-labeling for marine capture fisheries, adoption of scientifically rigorous sustainable seafood sourcing policies by retailers, and other market-based mechanisms are becoming an increasingly effective 'voluntary' incentive to improve fishing practices and governance [63,264,265]. However, market penetration of eco-labeled seafood remains nominal: traded Marine Stewardship Council (MSC, the largest global organization for the certification of wild capture fisheries)—labeled seafood has been estimated to represent $<0.01\%$ of global trade of edible wild capture marine seafood by volume and 0.3% by value, with limited distribution, primarily in the U.S. and United Kingdom [264]. MSC recently revised its fisheries assessment methodology to incorporate a risk-based framework, built on ecological risk assessment methods, for an application in assessing data-deficient fisheries [266]. Unfortunately, MSC has yet to demonstrate substantial ecological gains through improvements in marine capture fishery practices [267–270]. Major conservation gains resulting from improvements by deficient fisheries have not occurred through the MSC assessment and certification processes because the fisheries that have undergone assessment and made changes in practices to obtain and maintain the certification have generally been data-rich and relatively well-managed fisheries with limited changes required [270]. Implementation of sustainable seafood sourcing by a rapidly increasing number of retailers suggests that growing demand for certified seafood may result in an increased supply and market penetration. Confusion and diminished confidence created by the recent proliferation of competing and often conflicting certification and eco-labeling programs is one obstacle to the efficacy of the sustainable seafood movement. There is a need for the consolidation of assessment programs, and to harmonize methods for identifying sustainable sources of seafood. Furthermore, gradual improvements in fishing industry practices and governance can be expected in fisheries that are working with retailers and their suppliers to address identified deficiencies, instead of sourcing only from existing good actors.

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