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RESEARCH PAPER

# Mitigating bycatch in tuna fisheries

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**Abstract** Monitoring and managing fisheries bycatch is increasingly recognized as a critical component of robust fisheries management frameworks. This review, addressing this subject, begins by defining bycatch and analyzing the reasons it happens, from accidental to intentional discarding. It identifies the most common species composing bycatch of the main tuna fisheries using purse seine and longline gear. Considerations of options available to estimate bycatch, their potential biases and uncertainties, and ways to address these issues are discussed. The formulas used to estimate bycatch also point to the options to reduce them, lowering bycatch per unit of effort or lowering effort itself. It shows that a mean can be reduced by reducing all its component figures, or by eliminating the high values at the extreme of the distribution (i.e., where a small proportion of events causes a large proportion of the problem), a common issue in bycatch. A generic strategy is described that can be applied to all gears and fisheries, and it is then described for the fisheries of interest, showing examples of its application. These cover many mitigation actions based on gear and operational changes. Management options aiming at reducing bycatch are also mentioned. A detailed description of the ways the strategy has been implemented for purse seiners and longliners is provided. Finally, market strategies, education and awareness of stakeholders, mainly fishers, and some potential future developments are briefly described.

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## Introduction

Over the past decades, the bycatch issue has gone from invisible or neglected, to a major force shaping fisheries management. The tuna fisheries are no exception. The tuna-dolphin problem in the eastern Pacific was probably the first major bycatch issue to generate intense public attention (Perrin 1969, 2009). In this region, the association of yellowfin tuna (*Thunnus albacares*) with dolphins (mainly spotted dolphins, *Stenella attenuata*, and spinner dolphins *S.*

*longirostris*) resulted in high mortalities of some dolphin species following their capture in tuna purse seine nets. The public reaction to this was a major factor in the development of fishery management measures (Hall et al. 2003). More recently, the drive to ecosystem-based fisheries management (Link 2010; Hilborn 2011; Essington and Punt 2011) has made it more imperative to understand bycatch in fisheries as a factor contributing to the destabilization of oceanic communities.

We will use a set of definitions of bycatch that are based on the fishers' decisions to retain or discard. This is important because communication with fishers is critical for managing bycatch issues. When the capture of non-target species is a welcome event (i.e., it increases the overall value of the catch), discussion of mitigation measures become meaningless. With the definition used in this chapter (originally defined in Hall 1996 and described below), bycatch is clearly a negative component of the fishing operations that does not benefit anyone. This also reflects the public's negative perception of bycatch.

## Definitions

The following definitions are adapted from Hall (1996):

CAPTURE is everything that is caught by the gear. There are three possible fates for captured organisms:

- *Release* Captured organisms are released alive and apparently unharmed such that they are expected to survive the interaction.
- *Bycatch* Captured organisms are discarded dead or so severely injured that it is clear that they will die post-release.
- *Catch* Captured organisms that are retained for utilization. Utilization includes the fraction that is landed and sold, used as bait, consumed by crew, etc.

A more complete classification of the components of captured organisms is available, but for this review the focus is on bycatch. There may, however, be delayed post-release mortalities of released captured organisms, and other indirect impacts of the fishing operations that result in mortality (Gilman et al. 2013). These should be accounted for by fishery management systems. These definitions are dynamic, and market or regulatory changes may switch species or individuals from one category to the other. We avoid the use of the word or the concept of target species which may be obvious in some fisheries, but unclear in others.

## Types of bycatch situations

"K-bycatch" are species with late and infrequent reproduction, small litter size, slow growth, etc. In these cases, there may be resource conservation issues if rates of fishery mortality are not sustainable, and the mitigation actions aimed at decoupling the target-bycatch systems are insufficient. Fishing effort, when it is managed, is managed to maximize the yield from the target stocks. The joint capture of species with different population parameters may result in unsustainable harvest of those with lower growth and reproductive rates. For example, the fishery-induced mortality of marine mammals, sea turtles, seabirds (such as albatrosses and petrels), sharks, etc., in tuna fisheries has resulted in conservation problems. This occurs because the bycatch are species with lower productivities than target species.

"Size bycatch" refers to juveniles or undersized individuals of the target species that are discarded, and may negatively impact the productivity of the fishery. Size bycatch results from a failure of the size selectivity of the gear, and it is strongly affected by market prices.

"Regulatory bycatch" are discards imposed by regulations mandating the non-retention of some species, size, sex, etc. For example, the retention of some shark species has been banned in some tuna fisheries.

"Global impact bycatch" refers to removal of important fractions of the community and that may be from high trophic levels ans which alters ecosystem structure. The purse seine fisheries capturing tunas that associate with FADs may be included in this category. Although many of the species removed have high productivity and the losses likely sustainable, it is currently not possible to assess the global impact of these removals on the pelagic communities (Hall and Roman 2013). They may affect the community in a selective way, (e.g., removing only species that associate with FADs or with dolphins), thus altering ecosystem structure.

National and international programs or laws have set as a goal the development of highly selective fisheries to reduce waste and to minimize conservation problems (e.g., FAO 2010). When the species affected are in danger of extinction' improved selectivity will contribute to the maintenance of ecosystem biodiversity. But the objectives of bycatch management are not so obvious when the impact on bycatch populations is sustainable) (Fauconnet and Rochet 2016). Sometimes, ethical or cultural factors may come to the forefront (Hall and Donovan 2001), adding a level of complexity to the analysis of trade-offs.

Bycatch, as we define it, is waste and as such is not desirable to any of the stakeholders (Hall 1996). There are several initiatives in different regions and fisheries to eliminate discarding by mandating the retention of everything captured (Wåge 2007; MRAG 2007; Catchpole and Gray 2010; Johnsen and Eliasen 2011; Rochet et al. 2014; Borges 2015; Kopp et al. 2016). Unfortunately, there is little scientific evidence that this is beneficial to the ecosystem if products without value are landed and discarded on land (Diamond and Beukers-Stewart 2011). Rather, the objective of this policy is to encourage the fishers to avoid unwanted captures, or to a broadened utilization of them (Catchpole et al. 2005; Gezelius 2008; Johnsen and Eliasen 2011; Batsleer et al. 2016). As the megafauna is not included in the full retention, the main targets of the policy are fishes and invertebrates, therefore the policy may improve selectivity or reduce effort, if vessel capacity is taken up by these other species (Condie et al. 2014). Both of these consequences may have positive ecosystem effects under some scenarios.

## Other ecological impacts of the fisheries

Although we focus on bycatch mitigation, there are other ecosystem-level impacts of tuna fisheries that we will touch on briefly and simply as a reminder that the picture is not complete (Fonteneau et al. 2013; Hall and Roman 2013; Gilman et al. 2013; Lescrauwaet et al. 2013).

- Benthic communities may be adversely impacted by bycatch thrown overboard (in many cases in very deep water).
- Individuals may be injured by the fishing operation, without being seen.
- Individuals caught in the net or on hooks can be preyed upon (Huang and Liu 2010; Hamer et al. 2012).
- "Ghost fishing" (Matsuoka et al. 2005) refers to capture by lost gear. Purse seine gear is not frequently lost, although the FADs used by this fishery to aggregate tunas are. And FADS can entangle turtles, sharks, etc. (Filmalter et al. 2013). Longline gear is lost much more frequently because of encounters with large animals or other vessels that cut the lines.
- Fisheries discards may be used by other species in the ecosystem, producing an energetic subsidy that may disrupt the competitive equilibria among species (Ramsay et al. 1997; Bicknell et al. 2013; Heath et al. 2014; Patrick et al. 2015).

Effective ecosystem-based fisheries management will require that we consider these impacts (Gilman et al. 2013, 2016; Lescrauwaet et al. 2013), but should not be limited to the management of bycatch or other sources of fisheries mortality. It should identify characteristics of ecosystems (e.g., the size spectrum) that may drive them into alternative and undesirable states (Cury and Christensen 2005; Link 2005; Rochet and Rice 2005; Atkins et al. 2015; Trenkel et al. 2015; Jørgensen et al. 2016.

## Why bycatch occurs

Purse seines: The dimensions of purse seines are quite large (max diameter around 600 m) and encircle a large volume of water. Mixed with the schools of marketable tunas there often are:

- tunas of unmarketable size,
- individuals or schools of other species that were associated with the tuna school,
- individuals or groups that just happened to be in the area encircled or that recently swam into it,
- prey species that were being attacked by the tuna,
- tuna predators.

Of these, some individuals may escape harmed or unharmed, and leave no evidence of their presence. Others may be released alive through the actions of the fishers (e.g., dolphins, whale sharks, whales, sea turtles). There is a general consensus that most of these survive, but there are few studies estimating their survival rates, or the other impacts of temporary capture (Hutchinson et al. 2015; Eddy et al. 2016). Some unmarketable individuals are discarded dead because they succumb to the stressful conditions in the net, physical injuries caused when the net volume is reduced (the sacking-up operation), or other causes. Some otherwise marketable individuals may have to be discarded because the duration of the set may have resulted in spoilage, making them unfit for utilization (Gilman et al. 2013). A particular type of impact in the tuna purse seine fisheries is the entanglement of individuals in the webbing that fishers hang below their FADs, which can be particularly significant for sharks (Filmalter et al. 2013).

Longlines: Pelagic longlines depend upon feeding behavior; fish must detect, locate, and prey upon baited hooks. The majority of the longline captures happen on the baited hooks. Sharks and marine mammals, however, depredate pelagic longline catches and thus become hooked or entangled (Yamaguchi 1989a, b). In other cases, an individual may be snagged by a hook during the hauling of the line, or it may simply run into the hook. Individuals may also get entangled in the gear. Pelagic longlines can be thought of as baited transects that may cover 100 km of the sea surface and may fish up to 4000 hooks (Ward and Hindmarsh 2007). These transects are set along thermal fronts or in other regions where the oceanographic structure concentrate the prey of tunas, swordfishes and others large pelagic fish (Yamaguchi 1989a, b). Currents, however, can pull the gear across the boundary (i.e., from its intended location relative to oceanographic features into adjacent habitats) and capture unwanted species (Carruthers and Neis 2011). Fishing depth and duration also affect the species composition of the catch. Whereas, the size and shape of the hook, together with the type of bait affect the hooking rates. Larger sizes of hooks may keep small individuals or species from become hooked when attaching the bait, so good choices of hook sizes may reduce unwanted captures. Some of the individuals that become hooked may nonetheless escape (e.g., shark bite-offs); but the post-release survival of these individuals is unknown. Subsequent survival is likely to vary with the species, sizes, condition, etc. of the individual escaping, as well as with the impact of the capture operation (e.g. duration on gear, location of hook, etc. Other captures may be released alive as a consequence of fishers' handling and release practices. Researchers are only beginning to document effects of the capture process (including post-release survival) on released individuals (Swimmer et al. 2014; Afonso and Hazin 2014; Dapp et al. 2015).

## Species composing the bycatch

Total bycatch in purse seines amounts to less than 2–5% of the total capture by weight (Hall and Roman 2013), and varies depending on prices and availability of fish. For example, species such as black skipjack tuna, *Euthynnus lineatus*; bullet tuna, *Auxis rochei*; frigate tuna, *A. thazard*; kawakawa, *E. affinis*; and several others are retained and utilized in some areas and are purely bycatch in other regions (Torres-Irineo et al. 2014). Unmarketable tunas comprise over 85–90% of the bycatch. Bycatch also include marlins and other billfishes, some sharks (mainly *Carcharhinus falciformis*), rainbow runner (*Elagatis bipinnulata*), yellowtail amberjack (*Seriola spp.*). Recently mahi–mahi (*Coryphaena hippurus*) and wahoo (*Acanthocybium solandri*) are making up an increasing proportion of bycatch.

The species composition of bycatch in longlines is not easy to estimate given the paucity of observer data, but includes:

- Blue (*Prionace glauca),* shortfin mako (*Isurus oxyrinchus),* silky (*Carcharhinus falciformis),* oceanic whitetip (*C. longimanus*), dusky (*C. obscurus*); crocodile (*Pseudocarcharias kamoharai),* porbeagle (*Lamna nasus*), bigeye (*Alopias superciliosus*), thresher (*Alopias* spp.), and hammerhead sharks (*Sphyrna* spp.),
- Mobulid rays (*Manta* spp. and *Mobula* spp.),
- Olive ridley (*Lepidochelys olivacea)*, green/black (*Chelonia mydas)*, loggerhead (*Caretta caretta)*, hawksbill (*Eretmochelys imbricate)*, and leatherback (*Dermochelys coriacea*) sea turtles,
- Seabirds including albatrosses, petrels and shearwaters (mainly in temperate or cold regions) (Anderson et al. 2011),
- Lancetfish (*Alepisaurus* sp.) and snake mackerel (*Gempylus serpens*) (Watson and Kerstetter 2006),
- Pilot whales (*Globicephala* sp.), false killer whales (*Pseudorca crassidens*), Risso's dolphins (*Grampus griseus*). Marine mammals generally become entangled in the gear or become hooked when attempting to feed upon the baited hooks or to depredate longline catch (Yamaguchi 1989a, b; Watson and Kerstetter 2006).

## Estimation of Bycatch

Only at sea monitoring can reveal the extent of bycatch. Observer programs are costly and complicated to implement, but they are the currently preferred tool. Electronic monitoring alternatives are in development, and in the future they will be implemented as a cost-effective way to monitor the captures. A major issue that needs to be kept in mind while dealing with the estimation of bycatch is that not all individuals have the same value to the population point (e.g., a reproductive female sea turtle is more valuable than a juvenile; or a reproductive female arriving at the nesting beach is more valuable than one just starting a migration from thousands of miles away). The impact of removal of these on population dynamics is very different, so the estimation of mortality rates and the mitigation strategies should take this into account (Hall 2015).

### Purse seines

Because the dolphin mortality issue brought considerable pressure on the industry, and resulted in the adoption of individual vessel quotas that require extensive monitoring, the Inter-American Tropical Tuna Commission (IATTC) has had 100% observer coverage on purse seiners operating in the eastern Pacific since 1993. The Western and Central Pacific Fisheries Commission also, more recently, mandated 100% purse seine observer coverage. The other oceans have observer coverage of only 5–10%. Low levels of coverage can result in:

- statistical biases;
- very imprecise estimates, and
- observer effects, as the vessel crews adjust their behavior when an observer is present (Cochran 2007; Hall and Boyer 1986; Amandè et al. 2010).

Electronic monitoring has the potential to complement observer programs. Tests of equipment are under way (International Seafood Sustainability Foundation 2012a). Several studies suggest that coverage of the order of 20–25% provides reasonable estimates for many species (e.g., Amandè et al. 2010, 2012). But even with high coverage, mortality of individuals that are not retained in the net and brought on board are not recorded (Gilman et al. 2013).

When ratio estimates have been used there is a need to estimate bycatch for the unobserved fraction of the fleet. These are based on bycatch per ton, or direct estimates based on bycatch per set (Hall and Boyer 1986; Lawson 2006; Amandè et al. 2010). The data are sometimes stratified by flag (i.e., county of ship's registry), if the vessels from different flags use different areas or techniques. In most cases they are stratified by type of set, since sets on dolphins, unassociated tuna schools, or floating objects are considerably different in their capture of both tunas and bycatch (Amandè et al. 2010). Other characteristics that may be used to standardize effort include: net depth, detection equipment, time of day, and the use of mitigation equipment or maneuvers.

### Longlines

We can identify at least three types of longline sets: bottom, shallow, and deep. In general bottom longlines are not used to capture tunas, but the other two types are. Usually deeper sets (of the order of 100–400 m) target bigeye or albacore tunas, however, there are also shallow night sets that target bigeye and yellowfin tunas. Most longline fisheries, whether industrial or artisanal, generally have very limited or no observer coverage (e.g., Debski et al. 2016). The durations of the trips are frequently long (months at a time), and the living conditions demanding. This, plus costs and logistical issues, make observer programs very complicated to implent. The sampling units used in these fisheries when there are observers are usually sets (when most lines in the fleet have similar characteristics) or the number of hooks fished (when vessels of many sizes participate in the same fisheries) (Lawson 2006). When catch rates are very different in different time periods (e.g., day vs. night), it is also necessary to stratify by that factor. The same concept applies to different fishing depths (Bigelow et al. 2006), bait types, etc. Knowledge of the gear used (hook type, size, and offset, bait, etc.) is critical to standardize the catch rates. A set of best practices for data collection in these fisheries is available (Dietrich et al. 2007).

### Statistical formula and components

The formula used to estimate bycatch is:

$$\begin{aligned}\text{Bycatch} &= (\text{Bycatch per unit of effort}) \times (\text{effort}) \\ &= \text{BPUE} \times \text{f}.\end{aligned} \quad (1)$$

BPUE has been expressed as:

- number of individuals or biomass per ton of fish captured or retained, or
- number of individuals or biomass per set (purse seine fisheries) or per 1000 hooks (longline fisheries).

The measure of effort used is not always equivalent to the traditional definition of effort, since in it can be "operational effort" or quantity of fishing operations. Units such as "search time" are not meaningful in this context. More important, the formula used to estimate bycatch shows clearly the options available to reduce it. Effort can be reduced by limiting the number of fishing operations (e.g., umber of sets in a year), or BPUE can be reduced.

There are multiple options to achieve the latter:

- BPUE may be trimmed by eliminating the highest values. In areas or periods with very high densities of the bycatch species, the BPUE in those areas is usually also high. Moving fishing effort away by implementing time-area closures is preferable as the most gains are obtained at the lowest cost to the fishers.
- Some fishing operations are riskier than others with respect to bycatch (e.g., night purse seine sets cause much higher dolphin mortality than day sets; shallow longline sets cause higher sea turtle and shark catch rates relative to deeper sets). Regulations or other incentives aimed at operational changes may therefore be directed at eliminating these.
- Technological changes in fishing gear may be incorporated that reduce the average BPUE.
- Handling changes can be introduced through fishers education and training programs specifically designed to increase releases and survival of unwanted or regulated species.
- Regulatory changes, such as a mandate to release bycatch alive, can also reduce BPUE.

Of course it is better not to capture what is not wanted, as this obviously eliminates the risk of mortality. And the earlier in the process that an individual is released, the better its chances of survival. Bycatch reduction should therefore be seen as a temporal sequence of opportunities to eliminate the unwanted individuals. This also allows for gradual gains, by attacking the problem in a sequential manner or looking for reductions in every step of the process, rather than putting the emphasis in a single action.

A very important consideration in mitigation measures is that actions are "problem-specific". For instance, the backdown procedure used by purse seiners affects only the dolphin captures, without changing the fishing operation or gear selectivity in other ways. The tori lines used to mitigate seabird bycatch are also of this type.

There are, however, other measures to mitigate bycatch that are not specific. These may have a positive effect on bycatch, but may also potentially affect, in a positive or negative way, other components of the ecosystem. Examples of this are: changing hook type or size, changing mesh sizes, hanging the gear deeper or shallower, switching fishing operations from day to night, or even large closed areas. It is necessary to examine in a holistic way the effects of changes proposed when the measures are not "problem-specific" (Gilman et al. 2014, 2016a). The dolphin-safe policy is a good example of an approach based on an incomplete assessment of the consequences, where changes in fishing practices to achieve reductions in dolphin mortality resulted in increased fishing mortality of other less charismatic, but ecologically important, species groups (Hall 1998).

## Mitigation Approaches for Purse Seines

We emphasize technical and operational solutions, and only mention a few management solutions when they complement the other options. Of course, management measures include all the regulations and the mechanisms to implement and enforce the other solutions. A review of recommendations from regional tuna management organizations, and a discussion of the compliance achieved can be found in Gilman (2011), and Bourjea et al. (2014). A compendium of recent research covering a variety of bycatch issues, and organized by the International Seafood Sustainability Foundation is also available (Restrepo et al. 2016).

### Technical and operational

The opportunities for mitigation can be thought of as "lines of defense" in a temporal sequence that follow the stages of the fishing operations (Hall 1996). The best way to avoid a bycatch is never to capture it. If that fails, the next step is release from the net or from the hooks, and so on. Obviously opportunities are different in different fisheries and for different species. A review of some of the options for purse seiners follows; the list is not exhaustive but is illustrative of the approaches available.

Avoiding capture

Some large species such as whales or whale sharks (*Rynchodon typus*) may have tuna associated with them, and the fishers encircle the whole association. The data available on the impact of the operation on the survival of the species released is encouraging (Escalle et al. 2016), but still, organizations (e.g., International Seafood Sustainability Foundation) recommend that vessels avoid this situation, thus avoiding the capture entirely. Other industry organizations have recommended the use of a set of Best Practices to improve the survival of the individuals released (e.g., Asociacion Nacional de Armadores de Barcos Atuneros Congeladores—ANABAC and Organizacion de Productores Asocia- dos Grandes Atuneros Congeladores—OPAGAC 2012). In many cases the individuals captured are only seen after the set is made. A research program is under way to reduce shark bycatch by developing techniques to release them from the net (Dagorn et al. 2010; Restrepo et al. 2016), since a low proportion of the sharks going through the seining—brailing process survive (Filmalter et al. 2012; Poisson et al. 2013; Hutchinson et al. 2015). Acoustic means have been proposed to assess the abundance of small bigeye tunas, to avoid sets with high densities when it is not desirable to capture them, as well as to avoid fishing in areas determined, from information from echo sounder buoys, to have relatively high proportions of undesirable sizes or species (e.g., juvenile bigeye tuna). More research is needed. The use of multiple frequencies is quite promising (Moreno and Boyra 2015).

Tuna fishers hang old netting under the FADs to enhance their attractiveness. Sharks and sea turtles have been observed entangled in this webbing, and sea turtles also can get captured on the surface floating structure of FADs. As many thousands of FADs are deployed annually, the use of non- and less-entangling designs and use of biodegradable materials have been proposed and are being tested to eliminate this source of mortality (Franco et al. 2009).

Spatial approaches, identifying areas with high bycatch or with high bycatch/catch ratios are also viable options. Areas with high densities of silky sharks have been observed in some oceans (Amandè et al. 2008; Watson et al. 2009). High-use inter-nesting habitats for sea turtles have been identified by tracking the nesting females (Shillinger et al. 2010), and they could likewise provide the basis for spatial–temporal closures.

Releasing from the net

Perhaps the most successful example is the backdown procedure, a maneuver that allows the escape of dolphins in purse seine sets made on yellowfin tuna associated with dolphins (Hall et al. 2003). Whales, whale sharks, and sea turtles are also released from the net, using procedures such as cutting the net to produce an opening of the right size, or sinking the corkline using long poles or weights, however research conducted to date by ISSF has not found these methods to be successful (Restrepo et al. 2016). Specific instructions and best practices are detailed in documents produced by the industry or foundations and are available on the web: http://www.ldrac.eu/upload/archivo-LDRAC-position-on-FADS-management-50659b3c41433.pdf and http://iss-foundation.org/knowledge-tools/guides-best-practices-2/.

Sea turtles become entangled in the purse seine net fall on the deck or railing of the boat during the maneuver to lift the net towards the power block; they thus suffer life-threatening injuries. To avoid this source of mortality, a speedboat or the crew on the deck stop hauling of the net, and the turtle is released. In the eastern Pacific Ocean, mortality has been from a peak of close to 150 sea turtles per year to under 20 per year (Hall and Roman 2013).

Experiments are under way to develop methods to release smaller-size tunas and other species using a modification of a section of the net (sorting grid). This follows devices tested in Norwegian fisheries by Beltestad and Misund (1996), and Misund and Beltestad (2000), but adapting the grid such that it can be rolled back through the power block. The effectiveness for tuna purse seines also remains to be demonstrated.

Releasing from the deck

Only a few hardy species or individuals survive the pursing process (i.e., the sacking up of the net and the brailing operations), and arrive alive on deck from where they can be released. This procedure for releasing bycatch is also limited to sets with smaller catches of tunas, otherwise bycatch species are crushed and/or suffocate in the net and during brailing operations. The deck operations may be modified to accelerate release of individuals (e.g., with dedicated ramps or conveyor belts) to enhance chances of survival. Shade or water spraying could also be used to improve the conditions when individuals have to spend time on deck. There are, however, very limited data on survival of individuals removed from the net and subsequently released from the deck, and this is an area of research that must become a priority if this system is to be considered effective.

A novel idea proposed by a veteran tuna skipper, Capt. Dick Stephenson, is the use of specialized fish pumps with large diameter hoses to bring the fishes to the deck alive, where species can be sorted, and what is not wanted released. Fish pumps are common in other purse seine fisheries, but not in tuna fisheries. Impeller or suction pumps could be used, taking advantage of the developments of these systems brought about by the needs of salmon aquaculture that require the transport of live individuals. The hose with the intake of the pump could be placed: (a) deep in the net to extract individuals dying earlier in the set, if the species/sizes sinking first are the desirable portion of the capture; or (b) shallow or in mid-water to capture individuals circulating in the net alive, and to bring them on board to a sorting area. In both cases, the sacking up of the net (when most of the injuries and mortality probably occur) would be eliminated. Larger species can be kept away from the pump's intake with a system of bars on the opening to the pump. After the desired individuals or species are on board, the larger individuals remaining in the net (which could include sharks, rays, and even larger bigeye tuna) could then be released.

### Utilization

Retention and utilization of mahi–mahi and wahoo has increased in the purse seine fleet from about 20% of the individuals captured to 80% in the past five to eight years (Hall and Roman 2013). Utilization, however, does not increase fishing mortality of these species, as individuals are dead when discarded. Utilization serves two positive purposes:

- it reduces effort on the tunas, which could be beneficial in some cases by filling wells with other species that would have been discarded dead at sea; and
- it diversifies the fishery it distributes the impacts over more species, and thus reduce overall ecosystem impacts (Garcia et al. 2011).

The decision to retain these other species may be dictated by economic conditions, or by regulations. The increase in mahi–mahi and wahoo retention is an example of a market-based change. An example of regulatory-based change are the measures to retain all tunas captured that are already in place in some tuna Regional Fisheries Management Organizations (RFMOs) (e.g. IOTC Res.10–13 2011, IATTC Res. C-06-03 2006), and initiatives to increase the full retention to all species have been proposed in some industry-driven programs (e.g. http://iss-foundation.org/), and are being studied (e.g., Chan et al. 2012 http://ebfmtuna-2012.sciencesconf.org/7429d). The utilization of these species, however, requires operational or technological changes:

- in some cases, a modification of the operation during the sets (e.g., divers entering the seine to harpoon the most valuable specimens for flash-freezing and sashimi utilization), or
- modification of storage wells, replacing the brine used for tunas by other systems, or
- modification of fish handling if regular brine is used.

### Management

Many of these technical and operational changes may turn into regulations to ensure their implementation. The more common measure has been the use of quotas, establishing a maximum allowed annual bycatch in numbers or biomass. The problem with quotas is that they generate the equivalent to a "race for the fish"; vessels run to fill their wells trying to maximize catches before the bycatch quota is reached. A better alternative is the use of individual vessel quotas, where the total allowable bycatch quota is divided among all vessels participating in the fishery in an even way (all the same bycatch, as in the AIDCP 2009) or following some algorithm that considers the type of vessel, historical catches, fishing area, etc. This system depends on an extensive monitoring of the catches. Spatial–temporal closures have been used to reduce the capture of juvenile bigeye tuna (which are generally retained, and therefore not a bycatch as defined), such as the IATTC Resolution C-09-01. Other spatial options are being proposed, or become obvious from the spatial distribution of some species of interest that include areas of dense aggregation of reproductive individuals, juveniles, etc (e.g. Amandè et al. 2011). These options are also being considered to reduce bycatch of sharks, seabirds, and sea turtles (Watson and Kerstetter 2006; Shillinger et al. 2010; Inter-American Convention for the Protection and Conservation of Sea Turtles, CIT-CC8-2011-Tec.1). An important consideration when analyzing closures is that the effort displaced from the closed areas will simply be deployed in other areas, thus possibly increasing other adverse impacts of the fishery.

## Mitigation Approaches for Longlines

Watson and Kerstetter (2006) provided a history of the evolution of longline gear and early attempts to increase its selectivity. A combination of bycatch mitigation approaches is warranted because multiple species are caught; and because targeted species, gear types, setting methods, markets, monitoring levels, regulations, and enforcement differ among pelagic longline fisheries. Bycatch utilization is also an option, but depends upon landing regulations and markets. Opportunities for bycatch mitigation occur throughout the capture process, and procedures can center on either keeping the gear away from the unwanted species or keeping the unwanted species away from the gear. Bycatch avoidance approaches based on the former exploit differences in the distribution of species and individuals that are to be retained, and those that will be discarded. Bycatch avoidance approaches based on the latter exploit differences in feeding behavior or (more recently) differences in their sensory abilities. Once bycatch species become hooked, there are a suite of approaches for releasing sharks, sea turtles, etc. from longlines alive and in good condition. Modified gear, modified setting and hauling practices, the use of de-hooking tools, and careful handling practices can minimize capture stresses and injuries. Mitigation approaches for releasing incidental captures from the deck are limited in pelagic longline fisheries, however, and would only have conservation benefits if the harm from additional handling stress outweighs the increase in post-release survival.

Measures to reduce the capture of seabirds and sea turtles in pelagic longline fisheries have been studied for several years because of increasing concern about the impact of longline fisheries on these species. At the 23rd meeting of the Committee on Fisheries of the United Nations Food and Agriculture Organization (FAO COFI) in February 1999, the International Plan of Action to reduce incidental catch of seabirds in longline fisheries (IPOA-Seabirds) was adopted. IPOA-Seabirds requires relevant countries to promote mitigation measures, awareness-raising, and data collection through developing their own national plans of action (e.g., Huang 2011). FAO held expert and technical consultations on sea turtles and fisheries in 2004 and developed the “Guidelines to Reduce Sea Turtle Mortality in Fishing Operations” in 2005. Mitigation measures have also been developed to reduce incidental captures of seabirds and sea turtles through research conducted in various fishing grounds (FAO 2005; Watson et al. 2005; Largacha et al. 2005; Hall et al. 2006; Gilman et al. 2006a, b, c; Kiyota and Yokota 2010; ACAP 2011; Lokkeborg 2011; BirdLife International 2012). More recently, several pelagic sharks were also added to the list of conservation concerns. The impacts on sharks come from directed fisheries, and from bycatch in other fisheries, including tuna longline fisheries. Only the latter case will be considered here. In a similar situation, mobulid rays (*Manta* spp. and *Mobula* spp.) are beginning to receive attention because of concerns about, or a lack of information on, their conservation status.

### Technical and operational approaches

#### *High-seas longlines and seabirds*

Changes in fishing gear or methods can be used to mitigate seabird bycatch and combinations of different methods may be appropriate in the context of individual fisheries (Brothers et al. 1999; FAO 1999a; Gilman et al. 2003, 2005, 2007a, 2008b; Robertson et al. 2010; Anderson et al. 2011; Melvin et al. 2014). Seabirds are attracted both to the baits and the catches. Unless the birds are hooked during gear haulback, their survival is unlikely as they will be dragged down with the gear as it is deployed and drown. As a result, the efforts to mitigate this bycatch are focused on avoiding their capture during setting.

*Avoiding capture* Albatrosses and large petrels are surface scavengers. They are susceptible to longline interactions primarily in a limited zone near the sea surface behind the stern of vessels, generally while the lines are being set. Devices and methods that prevent seabirds from feeding in this "bird zone" are intended to reduce the incidental hooking and entanglement, and currently include:

- Avoid peak areas or periods. There are temporal and spatial ways to avoid captures. In general terms, avoiding areas of high spatial or temporal seabird abundance should contribute to lowering the capture rates (Huang and Yeh 2011).
- Set lines at night. As most albatrosses feed visually during daytime, night setting can reduce the occurrence of incidental catch, although it is also necessary to keep deck light to a minimum. There are, however some problems such as heavy work schedule, increased risk of injury to the crew during line setting, and reduced effectiveness at the time of full moon.
- Reduce visibility of the bait. Blue-dyed bait is has been because it was presumed that this would make it difficult for seabirds to find the baits from the air. It was confirmed from at-sea surveys that this method restrains feeding activities of seabirds and lowers the incidental catch rates to one tenth or less of the control figures. It was also found that the blue-dyed bait does not much affect the catch rate of targeted fish species. Reduction of dyeing costs, or alleviation of labor in the dyeing process, are however, necessary for widespread adoption of this technique.
- Scare birds away from the lines. Tori lines are deployed from posts on the stern of the vessel and are outfitted with materials that wave in the wind. Tori lines move a sweeping motion behind the vessel that scares the birds from the area where the baited hooks are entering the water. Tori lines are cost-effective, but efforts are needed to adjust the configuration and use of these devices so that they will exert maximum deterrence (Melvin et al. 2009a, b, 2010). In general, there are three types of Tori lines. The first is the standard type having long streamers, which is used by distant-water tuna fishing vessels globally. The second is the light streamer type having numbers of short streamers used by near-shore fishing vessels. The third is a hybrid type adopting the two types of streamers. Avoidance effects change depending on the species composition of seabirds, the number of birds associating with the fishing vessel at the time of line setting, and the type of Tori line used (Yokota et al. 2011a, b).
- Sink the baited hooks faster. Weighted branch lines improve the sinking rate of baited hooks, makes them less accessible to albatrosses and some petrels (Melvin et al. 2009a, b), and reinforce the effectiveness of the other techniques. But due consideration needs to be given to reduce operational burdens and risks to fishers. Weighted branch lines increase the danger of crew injury when the hook pulls out during haul back and the weight flies back toward the crew. Recently, the issue of safety has been addressed by attaching two weights or safe lead systems.
- Protect baited hooks through side-setting. Side-setting refers to deploying lines from the side of the vessel rather than the stern (Gilman et al. 2007a, b, 2016b). This method allows the baited hooks to sink faster relative to baited hooks that are set from the stern which are effected by the propeller current. Furthermore, the bait sinks while it is close to the vessel hull making it more difficult for seabirds to detect or access the bait. The effectiveness of this method has been confirmed (Yokota et al. 2011a; Gilman et al. 2007a, 2016b), and it has been used by some Hawaii-based longline fishing vessels. It requires initial changes in the deck layout and crew work patterns, but may increase practicality (Gilman et al. 2007a, b).
- Under-water line setting. This method deploys baited hooks beneath the water surface and is in use in bottom longline fishing. The practical application to the pelagic longline targeting tuna is, however, difficult due to complex gear configuration (Brothers et al. 2000; Gilman et al. 2003, 2007a, b; Lokkeborg 2003, 2011).
- Control waste disposal. This is designed to reduce seabirds' attraction to the fishing vessel by not disposing what can become seabirds' food (e.g., fish offal, collected fishing baits, leftover human food). The fewer the number of birds attracted to the vessel, the fewer the interactions when the lines are being set or retrieved.

Various other measures have been tested but were not found to be effective. For example, a water-jet device firing water over the area where the lines being deployed is less effective in the presence of strong winds, and to have insufficient range especially in fisheries that overlap with seabirds with deep diving capabilities. Explosive noise, magnetic action, light and electricity have been tried, but lose their effectiveness with repeated use as seabirds become habituated.

Sea bird capture rates differ drastically by area (Huang and Yeh 2011), and depend on the species composition and number of seabirds, fishing gear and fishing methods, the sea conditions, etc. It is therefore necessary to adjust countermeasures by area. It is also important to encourage innovation among fishers to invent and test effective methods that fit their operating style and area, as in the cases where fishers developed Tori lines and the double weighted branch lines. In parts of the Southern Hemisphere additional seabird captures occurs when diving petrels (e.g., white-chinned petrel) and flesh-footed shearwaters retrieve sinking baits at depth and return them to the surface, this making them accessible to albatrosses and other large seabird species. In the areas where deep diving species of seabirds occur in large numbers, bird interactions can be reduced by using a combination of Tori lines, weighted branch lines, and nighttime setting. In the North Pacific, on the other hand, where deep diving seabirds are rare in the longline fishing areas, it is possible to reduce adequately incidental catch using only a single methods (e.g., night setting or Tori lines).

*High seas longlines and sea turtles*

In some (primarily shallow-set) longline fisheries, a large proportion of hooked sea turtles are alive when the gear is retrieved (Parga 2012), but post-release survival rates can be low. Experimental fishing operations using research and commercial vessels, and experiments involving captive animals, have been conducted to develop mitigation techniques to reduce incidental mortality of sea turtles in longline fishing operations (e.g., Watson et al. 2001; Largacha et al. 2005; Piovano et al 2009; Sales et al. 2010).

*Avoiding capture* Sea turtles spend most of their time within the uniform temperature surface layer. Deep-setting longlines have very low hooking rates of sea turtles, but the shallower hooks near the floats may capture sea turtles. To reduce this problem, techniques been developed that only deploy baited hooks at depths that sea turtles do not reach (Polovina et al. 2003; Shiode et al. 2005; Beverly et al. 2009) and eliminating the shallowest two hooks is required in the American Samoa longline deep-set fishery; although the efficacy of the latter prescribed gear design has yet to be assessed (NMFS 2011). Sea turtles also, in general, have a preference for warm water. Restricting fishing to water temperatures below 20 °C has been shown to reduce significantly loggerhead turtle interactions in the western North Atlantic (Watson et al. 2005). Additional investigation of oceanographic characteristics on the vertical movements of sea turtle and targeted fish species would help to reduce further the incidental catch of sea turtles (Shillinger et al. 2011).

Using circle hooks in place of similar-sized J-shaped hooks are the best documented technical solution for reducing the incidence of capture of leatherback sea turtles and the severity of capture injuries of hard-shelled species of sea turtles (Parga 2012; Gilman and Huang 2017). Circle hooks have the terminal portion (i.e., point end) curved such that that barb is perpendicular to the shank (Serafy et al. 2012) and are designed to lodge in the corner of the jaw in fishes (Molina and Cooke 2012). Because of this design, circle hooks tend to lodge in the mouth instead of the esophagus of hard-shelled species of sea turtles, causing fewer deep-hooking injuries (Parga et al. 2015). Unlike hard-shelled sea turtles, leatherback turtles tend to get caught by becoming foul-hooked on the body and then become entangled in line. Circle hooks may therefore reduce the capture of leatherback the due primarily to their shape (Watson et al. 2005; Gilman 2011). Circle hook use is promoted primarily to reduce the severity of hooking injuries in hard-shelled sea turtles that feed on the baited hooks (Valente et al. 2007). Circle hooks have been documented to reduce the deep-hooking of sea turtles that ingest hooks compared to those that ingest a J-shaped hook (Read 2007; Sales et al. 2010; Andraka et al. 2013). Circle hooks may therefore also improve the survival of released sea turtles, although our understanding of the seriousness of the injuries resulting from swallowed, versus mouth-hooked, is far from complete (Parga 2012). Use of wider hooks has been shown to reduce the catch rate of hard-shelled sea turtles (reviewed by Gilman and Huang 2017). The ideal size and shape of circle hooks are being studied through captive experiments and thorough experimental fishing operations. A recent symposium on the use of circle hooks as a mitigation system provides information on experiments carried out in many different fisheries and regions (Serafy et al. 2012). And the effect of circle hooks on catches of tunas, billfishes and sharks are also being investigated (Gilman et al. 2012).

Using fish bait has been shown to lower catch rate of sea turtles compared to squid bait by up to 75%. Kiyota et al. (2005) conducted observed captive sea turtles feeding on baited-hooks and found individuals were likely to swallow the whole squid bait which had flexible and tough muscle texture. In contrast, sea turtles bit off pieces of fish baits, then ingested the pieces. Swimmer et al. (2006) and Yokota et al. (2009) tested the use of blue-dyed bait in the laboratory and at sea. While the tank experiments were encouraging, the field studies were not successful. A review of sensory studies (Southwood et al. 2008) identified some additonal potentially interesting approaches, but the efficacy in longline fisheries of most of these approaches remain untested.

*Releasing sea turtles from longline gear* Although shallow-set longlines have a higher risk of catching sea turtles, many of the sea turtles are alive when the gear is retrieved and individuals can reach the water surface to breathe, and practical tools and methods to rescue and release live-captured sea turtles have been developed. Longline vessels are now encouraged to carry large hoop nets which help to haul live sea turtles onboard, and de-hooking devices for safely removing hooks. Long-term captive experiments on the survival rates of deeply-hooked sea turtles were encouraging as almost all hooked sea turtles survived and could eliminate or neutralize the effect of the fishing hooks (Parga 2012). These results indicate that proper handling can improve post-release survival rates of hooked sea turtles, even if the hooks are not removed. Studies on post-hooking survival of sea turtles are clearly important, and studies relating the location of the hooks to rates of survival have been published in recent years (Swimmer et al. 2006; Stokes et al. 2011, 2012; Parga 2012; https://sites.google.com/site/turtlepostreleasemortality/).

### *Small scale, shallow set artisanal longline fisheries and sea turtles*

Small-scale longline vessels (6–30 m in length) target pelagic fishes operate world-wide, but here we focus on the eastern Pacific Ocean (EPO) fisheries off Latin America (from Peru to Mexico) because of their very high rates of interactions with sea turtles. The fisheries operate nearly year round. In Ecuador and Peru they target mahi–mahi during the austral summer; and tunas, billfishes, and sharks in the austral winter. In contrast, vessels operating from Central American adjust target species according to availability. Vessels operate independently, with the exception of the Ecuadorian fleet where larger vessels ("motherships", 10–20 m in length) tow a number of smaller boats (< 8 m in length called "Fibras", derived from the Spanish name for fiberglass) to the fishing grounds up to hundreds of miles offshore. On the fishing grounds, the motherships provide supplies, accommodations for the crews, and storage facilities for the catch.

The EPO fisheries employ either standard monofilament longline gear, or basket gear with a braided polypropylene or polyethylene mainline. The latter is the most common longline gear in Ecuador and Peru. Important for sea turtle survival when caught, braided polypropylene or polyethylene mainline float, as opposed to monofilament main lines which sink. The EPO longline fisheries employ a variety of sizes of J-style and circle hooks (Mituhasi and Hall 2011), as well as a variety of fresh and frozen baits. The former is Humboldt squid (*Dosidicus gigas*) that are caught on the fishing grounds the night before the longline set, and the latter purchased squid, frigate mackerel and sardine. The EPO longline fisheries interact with all five species of sea turtles. Olive ridley and green sea turtles are the most common, but less frequently encountered leatherback and loggerhead turtles are of most concern because of their depleted populations (Hall et al. 2012). An important aspect of the small-scale pelagic longline of the EPO is that the gear is generally set at very shallow depths, especially the braided longline gear targeting mahi mahi. As a result, the vertical movements of turtles overlap the vertical distribution of the hooks resulting in high rates of turtle encounters (typically 1–2 turtles per 1000 J hooks, Andraka et al. 2013) compared to deep-set longlines deployed from distant water fleets targeting tunas (0.03 turtles per 1000 hooks, Donoso and Dutton 2010). Fewer hooked or entangled turtles are dead at haulback since shallow-set gear allows animals to reach the surface to breath. Mitigation measures in the EPO longline fisheries should therefore focus both on reducing hooking/entanglement rates and improving the post-release survival. To accomplish the former, avoiding areas close to nesting beaches during the nesting season (Shillinger et al. 2011) is an obvious solution. Likewise, employing knowledge of fishers and compilation of observer data could help to define the routes and timing of turtle migrations. For example, in southern Mexico fishers are aware of belt-like areas with high densities of turtles which they refer to as "turtle lanes" or "turtle streets".

A hook exchange program implemented across the entire EPO longline fisheries verified the effectiveness of circle hooks in reducing interaction rates and the mortality of sea turtles, while maintaining catch rates of target species of fishes (Largacha et al. 2005; Hall et al. 2008). The only exception has been the Ecuadorian and Peruvian fisheries targeting mahi–mahi where small J-hooks had higher catch rates of smaller individuals of market species than the wider circle hooks. Circle hooks, however, reduce deep hooking (for both turtles and fishes, Parga 2012) allowing fishers to remove hooks from turtles more easily than if they are swallowed. Further adoption of circle hooks in the EPO longline fisheries will, however, require the availability of circle hooks in local markets at competitive prices (Yokota et al. 2012). This will, in turn, require reduction or elimination of tariffs (almost all hooks used in the EPO longline fisheries are imported). The Ecuador and Nicaragua governments have already taken these measures. The use of fish bait could also reduce the incidence of hooking. Fishers from Central America already use fish bait, however, and this change would represent significant additional costs to Ecuadorian and Peruvian fleets.

Sea turtle entanglement is much more common in EPO longline fisheries using the thinner and flexible floating braided mainlines, compared to monofilament mainlines, presumably because turtles encounter the former more frequently while swimming on or just under the surface. Replacing the braided by monofilament mainlines is expensive and it would force vessels to use hydraulic hauling systems, which would be impossible to implement in many instances because of space limitations aboard fishing vessels., redesigned float lines (i.e., the line connecting the float to the mainline) employing monofilament line tested in Ecuadorian mahi–mahi fishery in 2007, however, yielded close to a 90% reduction in turtle entanglements. Such simple and economical solutions may well be applicable to other shallow-set fisheries.

Because the majority of turtles hooked or entangled in EPO longline fisheries are alive at haulback (Parga 2012), proper handling procedures are important to maximize post-release survival. Tools such as de-hookers, mouth openers, and dip-nets made available to fishers at low cost, and workshops to train fishers in appropriate handling techniques and procedures to release turtles in good condition, are clearly important. The best practices for handling turtles are situational however (e.g., when it is better to remove the hook vs. when it is better to leave it in place), and will require extensive training which can be done through audio visual materials. Videos developed in conjunction with Ecuadorian fishers (aboard their vessels), veterinarians, and sea turtle biologists are available at the website: (http://www.iattc.org/Downloads.htm).

In summary, for reducing sea turtle interaction with shallow-set longlines in the EPO we recommend mitigation techniques:

- be tested with fishers to demonstrate how new technologies work and the resulting differences in catch rates of target and non-target species,
- employ materials locally available that do not add unreasonable operating costs,
- not require major changes in operating procedures,
- involve fishers who are good at effective gear modifications and development of practical technologies, and
- involve an understanding of specific fisheries and be appropriately fisheries-specific.

### *High-seas longlines and sharks*

*Avoiding capture* Mitigation approaches that utilize differences in species distributions include seasonal or regional closed areas. But at a much finer scale, mitigation methods may include operational decisions such as how and when gear is set, fished, and hauled. The efficacy of these approaches depends upon consistent and dependable differences in the distributions of targeted and unwanted catch. Within a fishing season or region, different fishing depths (as well as methods of setting and hauling) can be used to avoid unwanted species by decreasing the availability of baited hooks (Shiode et al. 2005; Beverly et al. 2009). To be most effective, avoidance methods should focus on the species, times, and areas with the highest catch rates. For example, blue sharks can account for up to 90% of the shark catch in many pelagic longline fisheries (e.g., Francis et al. 2001; Gilman et al. 2008a, b; Carruthers et al. 2009). In the Canadian longline fishery, 10% of the sets account for almost half of the observed blue shark catch (Carruthers 2011) because catch rates appear to be influenced by environmental factors operating over short time and space scales; catch rates can range from 10 to > 150 blue sharks per 1000 hooks within 10 days and a 100 km fishing area (Carruthers et al. 2011). Although factors driving these apparent aggregations are unknown, longline captains report that high blue shark catches occur when gear is pulled across thermal fronts or during storms (Carruthers and Neis 2011). For blue sharks, the appropriate mitigation scale may therefore be within a longline set or between sequential sets over a few days. But clearly the appropriate time and space scales will depend upon their predictability.

Because longline catch results when animals interact with the baited hooks, differences in feeding times might be used to reduce the catch of unwanted species without decreasing targeted catch. Although such differences have been documented (e.g., Ward et al. 2004), they have not been widely investigated as a method for reducing shark-longline interactions. Mitigation measures that utilize differences in feeding behavior and prey preference have thus far largely focused on hook appendages and different bait types. Development of artificial baits was active area of research for many years for economic and logistic reasons, but not has not been extensively explored to increase gear selectivity. More recently, use of repellent devices, such as electropositive metals (Kaimmer and Stoner 2008; Brill et al. 2009) or magnets near the hooks have shown some promise. However, field trials of these deterrents have had mixed results (reviewed in O'Connell et al. 2014; Molina and Cooke 2012) because the effect of magnetic and weak electric fields is limited to short distances, has not been successful for all species studied, and may depend on an individual's habituation to the stimuli or immediate competition from conspecifics.

*Increasing post-release survival rates* There are various approaches during capture, dehooking, and release to increase rates of post-release survival. Fishers targeting sharks, or concerned with heavy hook losses, use braided stainless terminal section of the gangions because sharks can bite through monofilament nylon leader material (Ward et al. 2008). Eliminating wire leader material decreases the number of sharks brought alongside the vessel, but it is unknown if this increases rates of post-release survival and more experiments are needed.

Circle hooks reduce at-vessel mortality rates of sharks (Godin et al. 2012), and increase the likelihood that sharks survive capture by two to three times, compared to J-hooks (Carruthers et al. 2009). The use of circle hooks, however also produce higher catch rates of some shark species, compared to J-hooks (Watson et al. 2005; Kerstetter and Graves 2006; Ward et al. 2009; Piovano et al. 2010; Sales et al. 2010; Gilman et al. 2012, 2016a). The advantages for shark conservation resulting from the adoption of circle hooks will, therefore, depend on the condition of the stocks and the simultaneous adoption of practices that ensure sharks are released in good condition—such as shorter soak times. Shorter soak times, like circle hooks, increase the likelihood that bycatch are available for live release (Campana et al. 2009; Carruthers et al. 2009; Diaz and Serafy 2005; Ward et al. 2004). Surprisingly, Carruthers et al. (2011) found that shorter soak times did not lower the catches of swordfish.

Campana et al. (2009) reported that one-third of badly injured or gut-hooked blue shark died post-release, whereas all healthy sharks survived. These results clearly imply that common-sense improvement of handling and release practices (e.g., no gaffing, finning, or cutting out hooks) could reduce rates of post-release mortality. The use of dehookers or remote line cutters (to sever leaders close to the hook) likewise could reduce rates of post-release mortality as they reduce or eliminate the trailing branch line (Casale et al. 2008), and they can be used to release unwanted species while the fish remain in the water. Moreover, when trailing branch lines are swallowed, and the line is long enough to be affected by intestinal peristalsis, hemorrhaging, ulceration and death can result (Casale et al. 2008). American and Canadian crews are currently using de-hookers and line cutters to release unwanted sharks, pelagic sting rays, and sea turtles (Carruthers and Neis 2011; Watson et al. 2005). Longline fishers interviewed by Gilman et al. (2008a) did not, however, use commercially available de-hookers and line cutters because of safety concerns. Longline fishers do not, however, routinely release bycatch from the deck due to difficulties in handling large marine predators, and time and safety considerations (e.g., Carruthers and Neis 2011). Tecommending the release of bycatch after it has been brought onboard would therefore be suitable only when benefits from additional gear removal outweigh stresses associated with increased handling and air exposure. For example, recommended protocols for American fishers (e.g., NOAA 2008) are to board turtles for gear removal provided the animal size and sea conditions allow it to be done safely, but do not recommend boarding marine mammals, sharks, and teleost fishes. In other countries boarding may be the norm and research for the development of "Best Practices" to improve survival should be a priority. For example, complete removal of fishing gear from sharks might be recommended if it affects movement or feeding, keeping in mind the safety of the crewmembers.

*Utilization* Bycatch is generally perceived as waste if dead individuals are discarded; utilization would seem preferable. Several tuna RFMOs have, however, adopted bans on retention of some shark species to create an incentive for quick release. Where methods to avoid bycatch or to release individuals in good condition are unlikely or not feasible, utilization of bycatch could be warranted. Moreover, methods to increase utilization could be done ashore through regulations governing how sharks are landed and sold. For example, such enforcement could be used to reduce the practice of "finning" (removing the fins and discarding the shark body) by requiring that the entire carcass be landed (Clarke et al. 2006). Finning has been banned by several international tuna management organizations, although efficacy of such approaches varies widely (Camhi et al. 2009).

## Management

Risk assessments, mitigation measures, and management of bycatch have been the subject of international conferences and this has led to modification of the management plans (e.g., http://iss-foundation.org/rfmo-resolution-database/). Individual nations are following the suggested guidelines (e.g., Brazil, De Oliveira et al. 2012) or developing their own programs.

Because most pelagic species are highly migratory, crossing ocean basins or moving 10′s of degrees of latitude during annual migrations, closed areas cannot be used to protect species throughout their life histories. Archival tagging data have shown, however, a remarkable degree of site fidelity to critical foraging and breeding areas for some species (Game et al. 2009), with tagged fish returning to the same offshore bank the following feeding season and recaptured within 5 km of the original tagging site (Neilson et al. 2009). Predictable feeding areas are associated with topographic features on continental shelves (e.g., Hobday and Campbell 2009), as are well-known predictable spawning areas (e.g., Block et al. 2005). Such feeding or spawning areas, or other so called "bycatch hotspots" (Lewison et al. 2014; Roe et al. 2014; Huang 2015) are in some cases predictable and frequently within national jurisdictions, which address common criticisms of the feasibility of closed areas (e.g., Kaplan et al. 2010). For example, seasonal or regional closures may be appropriate for species such as porbeagle shark (*Lamna nasus*), which follows consistent migration paths along the Northwest Atlantic continental shelf (Campana et al. 2010). Resources for monitoring and enforcement should be available if a closure system is to be utilized (Game et al. 2010) however.

An alternative approach is to use dynamic, flexible closures, associated with environmental conditions defining habitats (e.g., sea surface temperature), oceanographic features or observed aggregations of bycatch species (e.g., Gilman et al. 2006a; Howell et al. 2008; Hobday et al. 2010, 2011; Žydelis et al. 2011; Maxwell et al. 2015). Flexible closures are a largely underutilized management approach, although it may be restricted to regions with sufficient monitoring and enforcement resources. Bycatch avoidance methods could focus on finer spatial and temporal scales. A particular type of flexible closure is the approach based on sharing of information on locations of high bycatch by fishing fleets to delineate "hotspots" (Gilman et al. 2006a; Little et al. 2015). Spatial dynamic management of bycatch is one of the most promising approaches developed in the past years. Whether they are based on habitat or oceanographic characteristics, or directly gathering information from the fishers at sea, they improve the effectiveness of the management measures. The actions may be taken in real time, and may result in smaller economic impacts on the fleets by being targeted more precisely. There are very few applications used or proposed for tuna fisheries (e.g., Watson et al. 2009; Hobday et al. 2010, 2011). In any case, the promise of the approach is clear, and will become even more useful with the developments in technology to measure ocean and climate variables, fleet locations, etc. (Dunn et al. 2011; Hobday et al. 2013; Lewison et al. 2015; Dunn et al. 2016).

## Market-based Approaches

In some regions, environmental non-governmental organizations (NGOs) and consumers are increasingly demanding that seafood sold by retailers and restaurants be procured from ecologically sustainable sources (Leadbitter et al. 2006; FAO 2008). In response, market-based mechanisms are increasingly being employed not to only identify ecologically sustainable sources of seafood, but to achieve gradual improvements in governance and fishing practices, including reducing bycatch (Gjertsen et al. 2010). Market-based approaches include:

- programs that assess fisheries' ecological sustainability, including seafood eco-label and other certification schemes,
- fishery improvement projects to address gradually deficiencies in fishing practices and governance, and
- ecological sustainability measures in buyers' seafood product procurement specifications (e.g., Johnston et al. 2001; FAO 2008; Gilman 2008; Leadbitter and Ward 2007; IUCN and Western Pacific Fishery Management Council 2008; Parkes et al. 2010).

There has been a recent proliferation of programs assessing the sustainability of individual marine capture fisheries and marine seafood species. Third-party, independent assessment programs, in particular those that employ a peer review process, are perceived by some as necessary for credible and transparent verification of the sustainability of a fishery (Gilman 2008; Leadbitter and Ward 2007; Parkes et al. 2010). Third-party assessment programs for marine capture fisheries include eco-labeling programs, such as the Marine Stewardship Council (global), Friend of the Sea (global), Naturland (Germany), KRAV (Sweden), and Bureau Veritas (France). More recently, on behalf of government agencies and fishing industries of Iceland and Alaska, Global Trust, an ISO 65 accredited (the international standard for independent third-party certification bodies) third-party certification body, developed certification schemes that assess marine capture fisheries against select Articles of the United Nation's Code of Conduct for Responsible Fisheries (Global Trust 2011). Other third-party fishery assessment programs include the Sustainable Fisheries Partnership which developed a fishery assessment program called FishSource. The program launched in 2007 and was modeled after the Marine Stewardship Council fishery assessment method, including assessment of the status of the target stock, ecosystem effects and management quality (Sustainable Sustainable Fisheries Pertnership 2010).

Some authors have argued that the ecological impacts of the Marine Stewardship Council (MSC) have been:

- too concentrated in the best managed fisheries,
- too lenient (Kaiser and Edwards-Jones 2006; Jacquet and Pauly 2007; Ward et al. 2008; Gulbrandsen 2009; Christian et al. 2013).
- favoring "Northern" (i.e., developed nation's fisheries) at the expense fisheries of the developing world (Ponte 2012), usually data- and management deficient.
- operating on ill-defined management units (Moreno et al. 2016)

Other analyses, with a broader coverage of fisheries, differ from that opinion (Hilborn and Cowan 2010, Gutiérrez et al. 2012), although some acknowledge the pitfalls for developing nations (Pérez-Ramírez et al. 2012; Duggan and Kochen 2016). A recent review shows statistically significant improvements in many aspects of the certified fisheries, including enhanced observer and bycatch mitigation programs (Martin et al. 2012).

We argue that the pressure placed on suppliers and the catch sector from major seafood buyers in the US, Europe and other markets to meet their sustainable sourcing requirements, to maintain access to existing markets, obtain access to new ones, and to obtain a price premium, causes the participants in a fishery to review their performance and identify deficiencies. Bycatch issues benefit from this self-criticism. Most of the tuna purse seine fisheries are developing their programs to meet the requirements of the MSC, or to enter the sustainable tuna market in other ways, and this has been the catalyst of many changes, and investments in research by the industry, as the creation of International Seafood Sustainability Foundation shows. These actions extend beyond the issue of bycatch to cover other aspects of fisheries management (control of fishing capacity, reduction of IUU fishing, etc.), and in many cases it has proven more "agile" to produce change than the tuna RFMOs, mired in a complex consensus-based system that frequently fails to produce needed decisions. If a significant portion of the tuna markets participates in these initiatives, then this can create the political will to achieve needed improvements at the tuna RFMOs.

The MSC program is growing and expanding to other regions, and its influence is exerted initially over the export fisheries, where the markets in developed countries drive the change. In any case, the MSC is the largest, and best-structured global organization for the certification of wild capture fisheries and it provides an avenue to push observer programs and bycatch mitigation schemes in many fisheries, including tuna purse seine and longline fisheries, even before they apply for a pre-assessment.

Other third-party assessment programs produce consumer guides, such as those produced by the Blue Ocean Institute (U.S.), Monterey Bay Aquarium (U.S.; Kemmerly and Macfarlane 2009), New Zealand Forest and Bird (New Zealand), Marine Conservation Society (UK), World Wildlife Fund (global), and Greenpeace (global), amongst others, which rank the relative sustainability of individual seafood species, or rank retailers based on the sustainability of their seafood sourcing practices. The regional guides that, in some cases, have replaced the original global ones are more specific in addressing stocks and avoid massive groupings of species in very diverse situations which made the generalizations in the consumer guides easy targets of criticism. These guides can play a major role in consumer education and awareness. In some cases, third-party programs employing inconsistent assessment methods have had conflicting opinions on the sustainability of individual fisheries, creating confusion and diminishing consumer confidence, as well as complicating retailer efforts (Gilman 2008; Leadbitter and Ward 2007; Parkes et al. 2010). First-party assessment programs, where a fishing industry assesses its own sustainability, include the Marine Eco-label Japan, established in 2007 by Japan Tuna; Pescanova, Europe's largest fishing company and processor, created a logo that appears on a small number of packaged seafood; and in Iceland, the fishing industry is currently developing an eco-label (Gilman 2008).

Bycatch issues also play a major role in the ratings for fisheries. The Agreement on the International Dolphin Conservation Program (AIDCP) is a management program administered by the Inter-American Tropical Tuna Commission, one of five tuna RFMOs. The program employs a label (dolphin-safe) and certificate to document compliance by Eastern Pacific Ocean purse seine vessels with prescribed measures to govern dolphin mortality (AIDCP 2005, 2009). The label is applied to tuna caught in sets where no dolphins were injured or killed, and it serves as an incentive to eliminate mortality to add value to the catches. Another version of the dolphin-safe label is administered by a dolphin-protection group, and it applies to all tuna caught in trips when no dolphins are encircled. In the latter case, the objective was to incentivize the fleet away from fishing on dolphins. This objective was not achieved, and the number of sets on dolphins has remained at very high levels, although dolphin mortality has decreased substantially (Hall et al. 2003).

Many fisheries are not yet managed and practiced in ways that would allow them to pass an assessment against the MSC fisheries standard or other sustainability assessment programs. A growing number of North American, European, and Australian retailers and seafood buyers have committed to sustainable sourcing. As they need to source from these fisheries, they have been participating in (and in some cases leading) Fisheries Improvement Projects (FIPs) to help the fisheries meet the requirements for certification (e.g., Sustainable Fisheries Partnership 2012). Through FIPs, companies whose supply chain includes deficient fisheries can catalyze and track gradual improvements in fishing practices and governance. Typically the goal is MSC certification. In this regard, the MSC process could be claimed as being influential on the improvement of fisheries that do not currently meet the MSC standard.

The International Seafood Sustainability Foundation, a global coalition of a large segment of the canned tuna industry and the World Wildlife Fund (WWF), presses for improved management of tuna stocks and bycatch by tuna Regional Fisheries Management Organizations (International Seafood Sustainability Foundation 2012a, b). This Foundation's objective is to align the tuna fisheries so that they meet the requirements for MSC certification, so the process is driven by the MSC eco-label. Among the International Seafood Sustainability Foundation bycatch-related initiatives already in place, promoted, or in research and development are the following (Restrepo et al. 2016):

- better data collection such as progressive increase to 100% observer coverage in all purse seine fleets, support for the development of electronic monitoring systems and FAD logbooks, and harmonization of data across RFMOs,

- mitigation including research on attracting sharks outside the area to be encircled, improving shark survival post-release, reduction of the capture of bigeye tuna through techniques and operational procedures, development and adoption of FADs that do not entangle sea turtles, sharks, etc.,
- management actions including a ban on setting on whale sharks, full retention of all tunas, and full retention of all species (beginning in 2014), and
- improving fishers' awareness and training including skipper seminars (all oceans) and development of a Skippers'Guidebook to Sustainable Fishing Practices (website: http://iss-foundation.org/resources/downloads/?did=392), development and dissemination of best practices to release whales or whale sharks.

Improvements in fishing practices and management, including addressing bycatch, are also being achieved through retailers' and their buyers' adoption and implementation of best practice environmental measures in seafood product procurement specifications. For example, the Sustainable Fisheries Partnership has produced procurement specifications for canned and fresh/frozen tuna supplied by purse seine and longline fisheries for their corporate partners, which include measures to address problematic bycatch (Sustainable Fisheries Partnership 2011a, b). Likewise, the "Responsible Fisher Schemes" commits participating fishers to adopt best practices dictated by the organizing institution usually including those to mitigate bycatch. Examples include:

- the UK system Seafish: http://rfs.seafish.org/,
- the Australian system: http://www.seafood.net.au/page/?pid=291, and
- the International Seafood Sustainability Foundation ProActive Vessel register http://iss-foundation.org/wp-content/uploads/downloads/2012/10/pvr-doc-3.pdf.

These are a way to reward conscientious fishers, and to separate them from the less careful operators. Even though these programs do not have the reach of the MSC certification (the programs do not address target stock sustainability or governance issues), they show a positive attitude; and when a verification system is available, allow buyers or consumers to make a distinction in their purchases (Gjertsen et al. 2010). They are clearly a step in the right direction, and as such should be encouraged. Sustainability of fisheries will, however, obviously require more than responsible fishers. We agree with Guldbransen (2009) that fisheries certification alone is unlikely to arrest the decline of fish stocks and that more research is needed on the efficacy of private and public efforts to address overfishing and environmental harm resulting from fishing. The diversity of fisheries characteristics precludes a universal solution. Marine protected areas, and more recently catch shares or rights-based management programs, have been presented as such. Many of these approaches have already been implemented in different tuna fisheries, but we contend that none are (or will be) a universal solution. Fisheries certification programs, marine protected areas, and rights-based management are excellent management tools that should be applied when the circumstances favor (or allow) these approaches.

## Education and Awareness

Scientific data from experimental surveys and empirical information from fishers are indispensable for development of bycatch avoidance strategies, as well as technical and operational procedures to reduce bycatch mortality (Shackeroff and Campbell 2007; Hall et al. 2007). It is important to develop fluid and continuous communication with the fishing community with the goals of:

- informing fishers about new methods and inviting them to test these,
- collecting feedback from fishers about their effectiveness and drawbacks, and
- motivating fishers to change their methods and behaviors.

With this feedback, there can be iterative testing of proposed systems or gear modifications until some are found effective in achieving conservation goals, while still maintaining industry profitability (Cook et al. 2007; Jenkins and Garrison 2013). Beginning in 1986, the IATTC pioneered skipper seminars centered on bycatch issues (Hall et al. 2003) which lead to the reduction in dolphin mortality, and interactions among fishers, scientists, and managers that resulted in more intelligent management. Seminars addressing bycatch issues within purse seine fisheries employing FADs, and artisanal longline fleet that interacted with sea turtles, continue to be utilized by the IATTC staff. The model has been adopted by International Seafood Sustainability Foundation, and disseminated to the purse seine fleets operating in other oceans.

Educational activities are important to inform fishers about accurate reporting of incidental mortalities, how to avoid them, and appropriate handling of individuals captured alive. Educational materials have been developed and used for this purpose in some countries and in tuna RFMOs. Researchers involved in mitigation programs and all those organizing fishers' workshops should, however, be specifically trained to carry out these functions because most have had little exposure to the relevant fishing groups (e.g., exporters, boat owners, community leaders, fishers, etc.). If there is failure to produce a constructive relationship, even the best designed programs can fail. Moreover, fishers have a large repository of knowledge, which can be tapped to contribute to development effective and practical bycatch solutions. Several bycatch reduction methods were developed by fishers, including the Tori line and methods to reduce dolphin mortality in the eastern Pacific tuna purse seine fishery (Hall et al. 2000; 2003). As important, participation of fishers can result in a sense of ownership of bycatch reduction methods (Gilman et al. 2007b).

## Concluding General Concepts

There is a suite of criteria that identify optimal methods for mitigating bycatch (Gilman et al. 2003, 2005). In order of priority, methods should:

- avoidance of interactions with unwanted species altogether or at least to minimize their catch,
- minimize injuries sustained during handling and release;
- offset mortality through compensatory mitigation;
- be practical, safe, and economically viable, or better yet provide operational and economic benefits;
- require minimal alteration to traditional gear and practices to increase the likelihood of their acceptance by fishers;
- be commercially available and at a reasonable cost, or at least have a cost commensurate with their effectiveness (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);
- be effective within the limited resources for monitoring, control, and surveillance;
- take into account whether or not crew behavior affects the efficacy (for example, Tori line efficacy can be compromised if the crew does not maintain streamer coverage over the area where baited hooks are being deployed);
- facilitate enforcement (for example, vessel compliance with night setting can be confirmed via vessel monitoring systems and prescribed gear designs can be confirmed via dockside inspections. In contrast, use of Tori lines or blue-dyed and thawed bait to prescription is not easily enforced);
- lend themselves to measurable performance standards without requiring analyses of observer program data (for example, a weighting design that achieves a threshold baited hook sink rate would be preferred.);
- not increase the catch of other unwanted species or sizes, or better yet effectively mitigate problematic bycatch of multiple species.

A further important consideration is the effect of mitigation method across multiple species. For example, the replacement of J and tuna hooks with circle hooks in pelagic longline fisheries to reduce turtle bycatch also reduces seabird bycatch by about 80%. Likewise substituting fish bait for squid to reduce turtle bycatch also significantly reduces shark catch rates by about 30% (ICCAT 2007a, b; Gilman et al. 2008a, 2012). In contrast, setting longlines at night to protect albatrosses and other diurnal foraging seabirds has led to higher bycatch of nocturnal-foraging seabirds (e.g., white-chinned petrels) (Weimerskirch et al. 1999). Prohibiting wire leaders in longline gear to reduce shark catch rates appears to exacerbate seabird bycatch (Branstetter and Musick 1993; Stone and Dixon 2001; Ward et al. 2008). Such potential conflicts have received inadequate consideration because bycath reduction recommendations have tended to have a specific species group focus. For instance, existing International Plans of Action for sharks and seabirds (FAO 1999a, b) do not sufficiently provide holistic assessments (Domingo et al. 2012).

Crew safety issues may also influence the adoption of bycatch mitigation measures. Some fishers are reluctant to attach weights close to hooks on branch lines lacking a wire leader due to safety concerns, thus reducing the sink rate of baited hooks and increasing seabird catch rates. 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, possibly causing serious injury or (in rare cases) killing crew (Gilman et al. 2008a, b). Similarly, some longline fishers are concerned that using long handled line cutters or de-hookers on large sharks would likewise lead to more fly back injuries (Gilman et al. 2008a). To address safety issues of leaded weights Sullivan et al. (2012) developed and tested Safe Leads using both at-sea trials and under different tensions in simulated shark bite-off in the laboratory. And input from fishers from various longline fleets may be the best way to address safety such safety concerns (Hall et al. 2007). Interviewed longline captains were enthusiastic about the de-hooking gear but cautioned that you needed to learn how to use it (Carruthers and Neis 2011).

It is quite clear that when the will to change, created by the right incentives, is present it is possible to find solutions that mitigate the impacts of fishing without affecting food security, employment, or increasing poverty. It is a challenge for the researchers in this field to find those solutions that are practical and economically viable by tapping into the knowledge of the fishers, and building networks of stakeholders that share those common interests.

## The Future

Fisheries have operated in a manner designed to capture and kill a number of individuals, and then decide what to retain. This approach clearly is no longer acceptable. Rather the new ethic should be to either:

- capture as much as practical alive and only kill what you plan to keep, or
- keep and utilize all that has been caught, following a balanced harvest system that distributes the impact along and across the ecosystem.

Bycatch mitigation measures currently favor the former, although the latter may be ultimate solution. Very selective fisheries (i.e., those focusing on one or a few species and only on a limited range of sizes) now appear not to be an optimal harvest stagey if ecosystem structure and function are to be maintained. Recent modeling studies have produced an increasing amount of evidence that fisheries highly selective for species and sizes cause more significantly negative impacts on ecosystem structure and function than do more diversified harvests. Selective fishing (i.e., concentrating fishing mortality on a narrow subset of an ecosystem's components) are now known to cause ecological and evolutionary change, to reduce ecosystem stability, and to alter an ecosystem's function and structure (Zhou et al. 2010; Garcia et al. 2012). In contrast, fisheries whose impacts are distributed across multiple species and sizes (i.e., "Balanced Harvesting") appear to be a more benign way to harvest an ecosystem (Hall 1996; Garcia et al. 2011, 2012; Law et al. 2012). With "Balanced Harvesting" a broader range of species and a broad spectrum of sizes are harvested, and in proportion to their productivity. "Balanced harvesting suggests the need for a paradigm change in fisheries management that may, turn in, drastically alter many of our ideas of bycatch management, and the development of fishing gear and methods.

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