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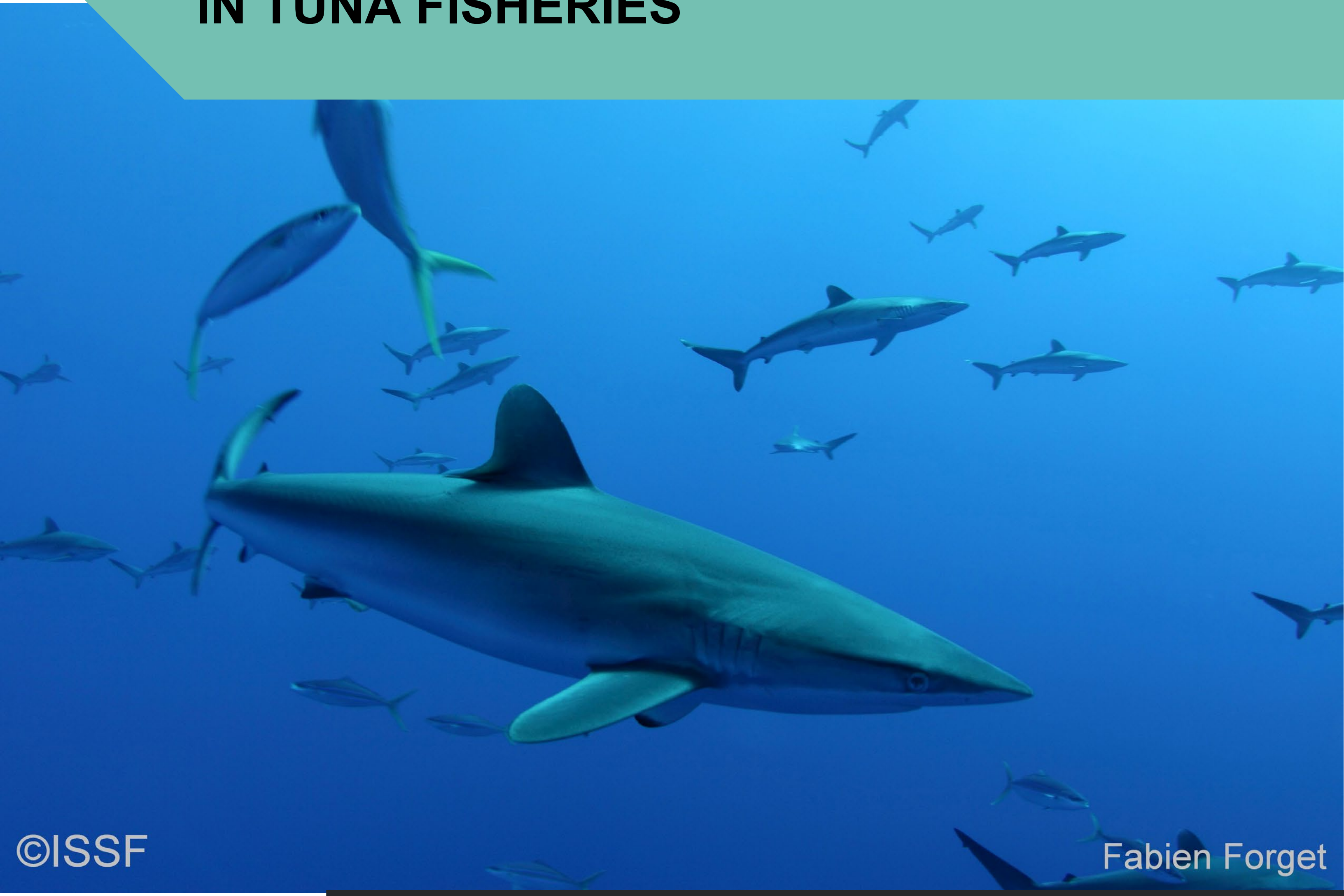
INPUTS FOR COMPREHENSIVE BYCATCH MANAGEMENT STRATEGY EVALUATION IN TUNA FISHERIES



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Abstract

There has been growing concern over the sustainability of marine megafauna exposed to bycatch fishing mortality. This study assembled databases of mitigation methods for at-risk species exposed to pelagic longline, tuna purse seine and drift gillnet fisheries. The databases enable the discovery of bycatch mitigation methods and enable accounting for multispecies effects of alternative bycatch mitigation strategies across exposed populations and stocks of at-risk species. The study defines key inputs for comprehensive, multispecies bycatch management strategy evaluation of: the size of the effect of an intervention on catch and fishing mortality rates; multispecies conflicts and mutual benefits; strength of evidence, including in practice; commercial viability costs; compliance likelihood; and rates of components of fishing mortality. The robust evaluation of alternative bycatch management strategies against this suite of criteria enables simulating the outcomes of alternative strategies to determine which best meets objectives. The report includes a draft Decision or Resolution on holistic bycatch MSE to aid regional fisheries management organizations in identifying candidate elements for potential inclusion in measures.

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Executive Summary

There has been growing concern over the sustainability of marine megafauna exposed to bycatch fishing mortality. To enable the discovery of bycatch mitigation methods for tuna fisheries and to identify any multispecies conflicts, this study assembled databases of cross-gear and gear-specific catch mitigation methods for exposed at-risk species. Methods were identified to mitigate the catch and fishing mortality rates of at-risk species that are applicable across marine capture fishing gear types and that are applicable specifically to pelagic longline, tuna purse seine, and drift gillnet fisheries. To identify any multispecies conflicts, each bycatch mitigation method record identifies the direction of effect, if any, on catch and fishing mortality rates by at-risk species group. The information in the assembled databases supports evidence-informed integrated bycatch management that accounts for the multispecies effects of alternative bycatch mitigation strategies.

The report also defines key inputs for comprehensive, multispecies bycatch management strategy evaluation (MSE). This includes accounting for:

(1) **Effect size**: The size of the effect of an intervention on catch and fishing mortality rates enables determining the relative contribution of alternative bycatch management measures towards meeting objectives.
(2) **Multispecies conflicts and mutual benefits**: Some methods mitigate the catch or fishing mortality rate of one at-risk bycatch species but exacerbate adverse impacts on another. Other methods can benefit multiple exposed populations and stocks of at-risk bycatch species. Identifying conflicts as well as mutual benefits from alternative bycatch management methods supports carefully considered, intentional tradeoffs.
(3) **Strength of evidence**: The relative degree of risk of error and bias of efficacy of alternative bycatch management measures provides information on the relative strength of evidence. For example, single studies have higher risks of error and bias and are more context-specific than meta-analytic syntheses, where evidence from meta-analytic synthesis studies is generalizable and relevant over diverse settings and ideally should inform the development of regional-level bycatch policy.
(4) **Evidence of efficacy in practice**: Particularly for bycatch mitigation methods that rely on crew behavior, the efficacies of some bycatch mitigation measures might be less effective during real-world, commercial fishing operations, as determined through analyses of observer and electronic monitoring data, than under controlled conditions of experiments. It is therefore important to validate through observational and “pragmatic” studies that the efficacy of an intervention when used under controlled conditions is of similar effectiveness when employed in real-world conditions.
(5) **Commercial viability costs**: Bycatch mitigation methods can create economic viability, practicality and crew safety costs.
(6) **Compliance likelihood**: Compliance likelihood with alternative weighting designs can be influenced by whether fishers would be expected to voluntarily employ the design based on the costs to commercial viability and how different the design is from conventional practices. If voluntary compliance is not likely, then compliance is influenced by the robustness of the fishery’s management framework. Fisheries with deficits in monitoring, control, surveillance or enforcement systems, or where outcomes of enforcement actions are inadequate incentives for compliance, have a high risk of noncompliance.
(7) **Rates of components of fishing mortality**: The efficacies of alternative bycatch management methods vary depending on the species-specific rates of components of fishing mortality. For example, retention bans and limits, bans on shark finning, and international trade bans might not be effective for species with high at-vessel and post-release mortality rates unless the

measures cause a reduction in shark targeting practices. Methods that reduce catch rates contribute to reduced total fishing mortality regardless of the rates of components of fishing mortality.

The robust evaluation of alternative bycatch management strategies against this suite of criteria enables fisheries stakeholders to simulate which alternative strategy best meets objectives. The report includes a case study of application of a decision support tool for integrated bycatch MSE. The report also includes a draft Decision or Resolution on holistic bycatch MSE to aid regional fisheries management organizations to identify candidate elements for potential inclusion in measures.

1. Introduction

Fisheries can have profound impacts on co-occurring, incidentally caught bycatch[1] species, particularly those with low intrinsic population growth rates, late maturity and other life history traits that make them especially vulnerable to anthropogenic mortality (Musick 1999; Chaloupka 2002; Forrest and Walters 2009; Pardo et al. 2016; Dulvy et al. 2021). There has been growing concern over the sustainability of bycatch mortality of marine megafauna given their vulnerability to exploitation, ecosystem-level cascading effects through food web links for some apex predators in some systems (Estes et al. 2011; McCauley et al. 2015; Young et al. 2016; Pacoureau et al. 2021), and reduced population fitness from fisheries-induced evolution (Stevens et al. 2000; Heino et al. 2015). There has also been increasing attention to risks that bycatch poses to food, nutrition, and livelihood security (Belton and Thilsted 2014; Bene et al. 2015; FAO 2020).

Fisheries bycatch is currently largely managed in a piecemeal manner and not through the holistic, multispecies evaluation of alternative bycatch management strategies to identify the strategy that best meets objectives. Management strategy evaluation (MSE) has conventionally been applied to evaluate the likely performance and tradeoffs of alternative fisheries management strategies against objectives for individual stocks of principal market species, and more recently for multispecies, ecosystem-level, and bycatch evaluations (Punt et al., 2016; Kaplan et al., 2021). Some bycatch MSE approaches have used expert opinion (Arlidge et al., 2020; Booth et al., 2020) and others have employed quantitative, model-based approaches (Tuck, 2011; Harley et al., 2015; Harley and Pilling, 2016; Smith et al., 2021). The narrow scope of bycatch MSE assessments (e.g., to simulate the effects of alternative combinations of bycatch mitigation interventions on catch and mortality risk of selected epipelagic sharks; Harley et al., 2015; Harley and Pilling, 2016) theoretically, given the availability of robust data inputs, could be expanded to simulate effects across exposed at-risk bycatch species and for a broader range of objectives (multispecies conflicts, costs to commercial viability, compliance likelihood; see Section 5.1).

Global guidance on bycatch management, including from the Food and Agriculture Organization of the United Nations, is single-taxa specific and has not accounted for cross-taxa objectives (seabirds, FAO 1999a; sharks, FAO 1999b; sea turtles, FAO 2010; marine mammals, FAO, 2021). Regional fisheries management organizations (RFMOs) also employ taxa-specific bycatch conservation and management measures, e.g., a standalone measure to manage fisheries bycatch of sea turtles, a separate measure for seabirds, etc., that are not based on multispecies bycatch MSE (Gilman et al. 2014b; ISSF 2017a).

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[1] Because of the broad diversity in global fisheries — including in their markets, management frameworks, and fisher practices — the definition of bycatch varies by individual fishery and over time. There is tremendous variability in bycatch definitions, including those adopted by different nations, in fishery-specific management plans and regulations, and in publications. For example, disparate bycatch definitions applied to tuna fisheries have included: species other than tunas (small-scale tuna fisheries, Gillett 2011); dead discards (purse seine fisheries, Hall and Roman 2013); and captured species other than tuna and tuna-like species and billfishes (longline fisheries, Clarke et al. 2014; tuna fisheries, IOTC, 2024). As a result, the Food and Agriculture Organization of the United Nations (FAO) has deemed it impossible to adopt a standard international definition of bycatch (FAO 2011).

Fragmented, piecemeal bycatch management systems can cause unintended multispecies conflicts (Gilman et al. 2019). Some methods that mitigate the catch or mortality of one vulnerable bycatch species can exacerbate risks to others. This includes, for example, acoustic pingers (pingers reduce the bycatch of small cetaceans and seabirds but increase the bycatch of bottlenose dolphins and some pinnipeds); alternative hook shapes used in longline fisheries (circle hooks used in place of J-shaped hooks of the same size reduce marine turtle at-vessel mortality rates and leatherback turtle catch rates, and reduce at-vessel mortality rates of sharks, but increase shark catch rates); tuna purse seine set type (e.g., in some regions, drifting FAD sets have higher shark but lower Mobulid ray catch per set compared to free school sets); and spatial management such as no-take marine protected areas (e.g., fishing effort displaced from a closed area can reduce catch of sharks but increase catch of seabirds) (Dagorn et al., 2013; Hall and Roman, 2013; Clarke et al. 2014; Gilman et al. 2019, 2022).

When bycatch is managed in a piecemeal, species-by-species fashion, cross-taxa conflicts that are unplanned, with unintended consequences, can result. Instead, conducting holistic, multispecies MSE — to identify conflicts as well as mutual benefits among bycatch species groups from implementing alternative bycatch management strategies — supports carefully considered, intentional tradeoffs when cross-taxa conflicts cannot be avoided. Through multispecies MSE, the bycatch management measures adopted by decision-makers would cause known and acceptable cross-taxa tradeoffs that best meet objectives (Gilman et al., 2019). Multispecies MSE predicts how well an individual alternative bycatch management strategy is likely to meet specific, measurable objectives on: desired catch and fishing mortality rates and levels of at-risk bycatch; acceptable multispecies tradeoffs; and acceptable costs to economic viability, practicality, and crew safety. Then, the MSE process can compare alternative strategies' simulated outcomes so that managers can select the framework that best meets objectives.

There are, however, numerous bycatch mitigation methods that do not create conflicts and in some cases result in shared benefits to multiple at-risk bycatch groups. For example, using non-entangling and biodegradable designs of fish aggregating devices (FADs) in tuna purse seine fisheries reduces the entanglement of sharks, marine turtles, and other groups without exacerbating the bycatch of other at-risk species (ISSF, 2019). Various seabird bycatch mitigation methods that prevent seabird access to pelagic longline baited hooks during setting, such as side-setting and bird-scaring *tori* lines, do not cause multispecies conflicts (Clarke et al. 2014). Employing an integrated approach to evaluate alternative bycatch management strategies allows management authorities to identify mitigation methods that cause multispecies conflicts so that any unavoidable conflicts are intentional, planned and acceptable tradeoffs.

To support the discovery of candidate bycatch management methods and the implementation of multispecies bycatch MSE, this study assembled databases of cross-gear and gear-specific bycatch mitigation methods for at-risk species exposed to fisheries bycatch (Appendices 1-4). Methods were identified to mitigate the catch and fishing mortality rates of at-risk species groups that are applicable across marine capture fishing gear types and that are applicable specifically to pelagic longline, tuna purse seine, and drift gillnet gear types. Drift gillnets (driftnet), typically used in multispecies fisheries, have relatively high catch rates of at-risk species (Ardill et al., 2012; Gillett. 2011; Northridge et al., 2017; Gray and Kennelly, 2018; Roda et al., 2019). Purse seine and pelagic longline, the main gear types used to catch global tuna and tuna-like species (Scombroidei) and billfishes (Xiphioidei), can also have substantial bycatch of at-risk species (Gilman, 2011; Gray and Kennelly, 2018; FAO, 2023; Hare et al., 2023; ISSF, 2023). To identify any multispecies conflicts, the direction of effect, if any, caused by a bycatch mitigation method on catch and fishing mortality rates is identified by individual at-risk bycatch species groups. The report includes a draft RFMO Decision or Resolution on holistic bycatch management (Appendix 5) to aid RFMOs with identifying elements for their potential inclusion in their draft measures. The report defines key inputs for holistic bycatch MSE. The information in the assembled databases supports evidence-informed integrated bycatch management that accounts for the multispecies effects of alternative bycatch mitigation strategies.

2. Methods to Mitigate the Bycatch of At-risk Species in Tuna Fisheries

Tables 1-4 (contained in Appendices 1-4) describe methods to mitigate the catch and fishing mortality rates of at-risk species groups that are susceptible to bycatch in pelagic longline, tuna purse seine, and drift gillnet fisheries. **Table 1** contains methods that are applicable across marine capture fishery gear types. **Tables 2-4** describe bycatch mitigation methods specific to pelagic longline, tuna purse seine, and drift gillnet gear types, respectively. The review for drift gillnet fisheries focused on evidence from the Indian Ocean where gillnet fisheries supply about a third of tuna landings (Anderson et al., 2020). The drift gillnet review also included evidence from outside this region, recognizing that the responses to bycatch mitigation methods are likely applicable across regions. Most of the bycatch mitigation methods included in the tables are commercially available and are in use in some fisheries. However, the tables also include some methods that currently have limited or no industry uptake, including those that are in the concept or initial R&D stage and are not currently commercially available. Bycatch mitigation methods that pose a risk of injuring vulnerable bycatch species (e.g., fish and vegetable oil slicks, lasers, and acoustic harassment devices, WPRFMC 2019) were included with notes about this risk.

To identify any multispecies conflicts, for each bycatch mitigation method, the direction of effect, if any, of the method on catch and fishing mortality rates is identified by individual at-risk species groups. Catch rate refers to the number or weight of captures per unit of effort. Fishing mortality rate is used in this report to refer to the proportion of the catch that dies due to the fishery interaction.

In **Tables 1-4**, the bycatch mitigation methods are categorized within tiers of a sequential mitigation hierarchy (Milner-Gulland et al., 2018; Booth et al. 2020; Gilman et al., 2023a). Measures that *avoid* the risk of capture of bycatch species are considered before those that *minimize* catch risk. These are then followed by *remediation* interventions that reduce one or more component of fishing mortality and sublethal impacts. Finally, *offsets* of residual impacts that were not possible to avoid, minimize, and remediate are considered as a last resort.

Measures to avoid unwanted bycatch completely prevent one or more extrinsic factor that influences capture risk, referred to as susceptibility or catchability attributes. These attributes include areal (i.e., geospatial) overlap exposure, encounterability (i.e., vertical overlap) exposure, and selectivity (Stobutzki et al. 2002; Hobday et al. 2011). For example, spatiotemporal fisheries management, including static and permanent no-take marine protected areas to temporally- and spatially-dynamic closures, may avoid bycatch risk of a threatened species by eliminating areal or temporal overlap between fishing vessels and a species' distribution (Gilman et al., 2022).

Bycatch minimization methods reduce one or more capture susceptibility attribute. Bycatch minimization methods can be broadly categorized as: (1) input controls on effort, (2) output controls on catch levels or rates that indirectly also reduce fishing effort, and (3) measures that involve changes in fishing methods and gear designs that reduce areal overlap exposure, reduce vertical encounterability exposure, or increase selectivity to reduce bycatch rates (Pascoe et al., 2010; Hall et al. 2017; Poisson et al., 2022). Limited entry and buyback programs that reduce fishing capacity are examples of bycatch minimization approaches. Spatiotemporal fisheries management that reduces areal or temporal overlap between a fishery and a bycatch species is an additional example. Changes in gear designs and fishing methods have been categorized according to their mechanism for reducing bycatch catchability (Broadhurst 2000; Werner et al. 2006; Willems et al. 2016; Darquea et al. 2020):

- reducing areal overlap
- reducing depth overlap
- reducing temporal overlap
- increasing selectivity due to morphological characteristics or the design of a gear component
- increasing escapement;
- reducing gear detection
- increasing gear detection
- shielding the gear to limit access
- repelling predators
- reducing the attractiveness of the gear

The next step in the bycatch mitigation hierarchy is to reduce the probability of fishing mortality. The components of total fishing mortality are (ICES 2005; Gilman et al. 2013):

- pre-catch losses, where an organism that escapes prior to capture dies due to the fishing operation
- retained catch
- dead discards, where this non-retained catch may have been dead when the crew retrieved it upon the haulback of the gear, or retrieved alive but died by time the crew discarded it
- ghost-fishing mortality by gear that was abandoned, lost, or discarded
- post-release mortality of catch that is retrieved and then released alive but later dies due to stress and injury sustained from the fishing interaction
- collateral (also referred to as unaccounted or cryptic) mortalities indirectly caused by various effects of fishing

For the first five components of fishing mortality, there are methods available to reduce the probability of mortality (e.g., Hall et al. 2017). Indirect, collateral sources of fishing mortality, however, are more challenging to document as well as to mitigate (ICES 2005; Uhlmann and Broadhurst 2015).

The final, fourth tier of the bycatch mitigation hierarchy is to offset residual bycatch mortalities. To meet a “bycatch-neutral”, no-net-loss objective, residual adverse impacts that were not avoided and minimized could be offset by obtaining an equivalent gain — or a more-than-equivalent net gain could be obtained to meet a bycatch positive objective (Booth et al. 2021; Gilman et al., 2023a).

3. Main At-risk Species Exposed to Tuna Fisheries and Sources of Uncertainty in Bycatch Estimates

A targeted literature review was conducted to compile relevant publications, which were then synthesized to estimate capture rates and magnitudes of at-risk bycatch species in global pelagic longline, global tuna purse seine, and Indian Ocean drift gillnet fisheries. Future research could employ a substantially more robust, quantitative meta-analytic synthesis approach to provide optimal strength of evidence for estimated species- and gear-specific catch rates and magnitudes, such as methods employed by the Food and Agriculture Organization of the United Nations to estimate global fisheries discards (Roda et al., 2019).

There are few global estimates of species- and gear-specific rates and magnitudes of bycatch of at-risk species, and no estimates of temporal trends in bycatch. Even low levels of anthropogenic mortality of certain age classes and sex can threaten some populations of at-risk species exposed to fisheries bycatch (e.g., ca. 35 mortalities in gillnets in New Zealand threatens the viability of a yellow-eyed penguin population with 1700 pairs, Crawford et al., 2017). The weight of global discards, which includes non-retained at-risk bycatch, was first estimated by the Food and Agriculture Organization of the United Nations (FAO) to be 27 MMT for the period 1992-2005, which was subsequently revised down to 20 MMT (Alverson *et al.,* 1994; FAO, 1997a). A second assessment estimated global discards of 7.3 MMT for the period 1992 to 2005 (Kelleher, 2005) and the most recent third estimate was 9.1 MMT for the period 2010-2014 (95% CI: 6.7–16.1, 10.8% of the estimated mean weight of global catch) (Roda *et al.,* 2019). This latest FAO discard estimate was around half of the initial estimate. The temporal pattern and estimate from FAO's most recent assessment are both consistent with the findings of Zeller et al. (2018).

The summaries of gear-specific at-risk bycatch below exclude teleost species. The understanding of the conservation status of teleost bycatch is extremely limited due to extremely poor data quality and few assessments. For example, very few of the >650 species of non-target teleost species that are captured in pelagic longline fisheries have been assessed at the global species-level, and substantially fewer at the stock and population level (Clarke et al., 2014).

Pelagic longline fisheries can have substantial bycatch of sharks, rays, marine turtles, seabirds, and marine mammals (Gilman, 2011; Gray and Kennelly, 2018; FAO, 2023; Hare et al., 2023; ISSF, 2023):

- **Seabirds**: Most problematic at higher latitudes, longline bycatch is the main at-sea threat to most populations of albatrosses and petrels (Dias et al., 2019). Anderson et al. (2011) estimated that between 160,000 and potentially over 320,000 seabirds are killed each year in global longline fisheries (both pelagic and demersal), of which at least 50,000 are in pelagic longline fisheries. Albatross and petrel species make up the majority of seabird bycatch in the southern hemisphere and north Pacific pelagic longline fisheries. Shearwaters (Procellariidae spp.), gulls (Larus spp.), the northern gannet (*Morus bassanus*), storm petrels (Hydrobatidae spp.), and Mediterranean shag (*Phalacrocorax aristotelis*) make up the majority of seabird bycatch in the north Atlantic and Mediterranean (Valeiras and Caminas, 2003; Anderson et al., 2011; Karris et al., 2013; Clarke et al., 2014; Li et al., 2016).

- **Marine turtles**: Pelagic longline bycatch of marine turtles is problematic mainly in the tropics and subtropics, with anywhere between tens of thousands to hundreds of thousands estimated to be caught annually worldwide (Lewison et al., 2004; Lewison and Crowder, 2007; Gilman, 2011; Wallace et al., 2013). Wallace et al. (2010) identified records of over 56,000 captures of marine turtle in global longline fisheries, representing a lower bound estimate, with most records coming from the Mediterranean Sea and the western Atlantic Ocean. Of the seven extant species of marine turtles, all are captured in pelagic longline fisheries. Six turtle species are categorized as threatened with extinction, and at least five are experiencing decreasing trends in absolute abundance (FAO, 2010).

- **Sharks and rays:** Composing as much as half of the total catch in some pelagic longline fisheries, pelagic sharks can be target, incidental, or discarded bycatch (Gilman et al., 2008a; Clarke et al., 2014). Clarke et al. (2014) identified 79 species of elasmobranchs that have been documented to be captured in pelagic longline fisheries, of which 29 species were categorized as threatened with extinction (according to the 2012 IUCN Red List). Blue shark (*Prionace glauca*) and pelagic stingray (*Pteroplatytrygon violacea*) are the predominant shark and ray species, respectively, captured in global pelagic longline fisheries (Gilman, 2011).

- **Marine mammals**: Cetaceans (baleen and toothed whales; dolphins and porpoises) and pinnipeds can be captured (Clarke et al., 2014). Isolated (e.g., island-associated) odontocete populations may be most at risk (Gilman, 2011). Several species of odontocetes depredate catch and bait in pelagic longline fisheries, which can result in their bycatch by becoming hooked or entangled in line, such as the false killer whale (*Pseudorca crassidens*), short-finned pilot whale (*Globicephala macrorhynchus*), and killer whale (*Orcinus orca*) (Hamer et al., 2012; Werner et al., 2015).

The bycatch of at-risk species in **tuna purse seine fisheries** is summarized below (Dagorn et al., 2013; Hall & Roman, 2013; Hare et al., 2023; ISSF, 2023b):

- **Sharks**: Shark captures occur through encircling in the purse seine as well as entanglement in the netting of FAD appendages (Filmalter et al., 2013), however the latter threat is expected to be declining as purse seine fleets transition to using non-entangling drifting FAD designs. Silky shark (*Carcharhinus falciformis*) typically composes over 75% of the shark catch. The oceanic white tip (*C. longimanus*) is the next most frequently captured shark species, followed by hammerheads (Sphyrnidae) of which mainly the scalloped hammerhead (*Sphyrna lewini*) is captured, thresher sharks (*Alopias* spp.), and numerous other shark species that have relatively low catch rates (Dagorn et al., 2013; Hall and Roman, 2013; Poisson et al., 2014a; Filmalter et al., 2021; Gilman et al., 2024). Whale sharks (*Rhincodon typus*) can be captured when sets are intentionally or otherwise inadvertently made on live or dead whale sharks (Romanov, 2002; Dagorn et al., 2013; Hall and Roman, 2013; Gilman et al., 2024).

- **Rays**: Primarily manta and devil rays (*Mobula* spp.) are captured, including the giant manta (*Mobula birostris*), giant devil ray (*M. mobular*), Chilean (sicklefin) devil ray (*M. tarapacana*), and spinetail mobula (*M. japonica*) (Amande et al., 2010, 2012; Hall and Roman, 2013; Croll et al., 2016; Lezama-Ochoa et al. 2017). Croll et al. (2016) estimated that 13,000 mobulids are annually captured in global tuna purse seine fisheries. The pelagic stingray (*Pteroplatytrygon violacea*) is the only species of stingray captured in purse seine fisheries, but with a low catch rate compared to the Mobulid species (Hall and Roman, 2013; Gilman et al., 2024). Mobulids may be captured during relatively infrequent intentional sets on large rays or can be inadvertently caught.

- **Marine mammals**: Cetaceans may be captured during intentional sets on live or dead whales and dolphins or may be inadvertently captured (Romanov, 2002; Gilman, 2011; Hall and Roman, 2013; Escalle et al., 2015). Encircled cetaceans have a high survival rate of over 90% (Escalle et al., 2015). Sets made on tuna schools associated with dolphins occur primarily in the eastern Pacific Ocean (sets on pods of spotted dolphins *Stenella attenuata* and spinner dolphins *S. longirostris*) but have also been observed in other regions (Hall and Roman, 2013; Gilman et al., 2024). Escalle et al. (2015) identified the three broad cetacean species groups that are susceptible to tuna purse seine capture: (1) baleen whales (Bryde's whale *Balenoptera edeni*, fin whale *B. physalus*, sei whale *B. borealis*, and humpback whale *Megaptera novaeangliae*), (2) delphinids (*Stenella* spp., common dolphin *Delphinus delphis*, common bottlenose dolphin *Tursiops truncatus*, rough-toothed dolphin *Steno bredanensis,* short-finned pilot whale *Globicephala macrorhynchus*, false killer whale *Pseudorca crassidens*, melon-headed whale *Peponocephala electra*, and killer whale *Orcinus orca*), and (3) sperm whales (*Physeter macrocephalus*). In a western Pacific Ocean tuna purse seine fishery, the most frequently captured odontocetes were false killer whales (39%, *Pseudorca crassidens*), bottlenose dolphins (13%, *Tursiops* spp.), common dolphins (7%, *Delphinus delphis*), Indo-Pacific dolphins (6%, *T. aduncus*), Risso's dolphins (6%, *Grampus griseus*), rough-toothed dolphins (6%, *Steno bredanensis*) and spinner dolphins (6%, *Stenella longirostris*) (Gilman et al., 2024). In the western and central Pacific, Molony (2005) reported that most marine mammal captures occurred in sets on floating objects, and estimated that fewer than 3,500 marine mammals are captured annually with a less than 10% at-vessel mortality rate.

- **Marine turtles**: Marine turtle captures are extremely rare events, with captures occurring through encirclement in a purse seine as well as through entanglement in the netting of the appendages and rafts of FADs (Gilman, 2011). However, mentioned above, we can be cautiously optimistic that the latter threat is decreasing as purse seine fleets transition to using non-entangling drifting FAD designs. The olive ridley is the most frequently captured turtle species (Hall and Roman, 2013). Hardshelled turtle species, including the olive ridley, green, hawksbill, Kemps ridley, and loggerhead, are captured primarily in associated sets, while the leatherback is primarily captured in school sets (Hall and Roman, 2013). Globally, hundreds of turtles might be captured annually in tuna purse seine fisheries, with ca. 90% retrieved alive and perhaps tens of turtles that are dead or moribund upon capture (Molony, 2005; Hall and Roman, 2013).

Seabird bycatch is very rare in tuna purse seine fisheries. For example, Peatman et al. (2019) estimated that western Pacific Ocean tropical tuna purse seine fisheries annually have about 20 seabird interactions that result in ca. 1 seabird mortality, based on observations of 189 seabird interactions with the gear in 330,787 sets.

Catch composition varies by region as well as by purse seine set type (Molony, 2005; Dagorn et al. 2013; Hall and Roman 2013; Peatman et al. 2017; Pons et al., 2023). For example, in European Union purse seine fishing in the Atlantic Ocean, marine turtle catch rates (number per set) were similar in drifting FAD and free school sets, while in the Indian Ocean the turtle catch rate was higher in FAD sets (Bourjea et al., 2014). Relative to free-swimming tuna schools chasing prey, sets on relatively slower-moving drifting FADs and logs catch a larger number and weight of nontarget species per set and per unit weight of target tunas (Hall and Roman 2013; Lezama-Ochoa et al. 2017; Pons et al., 2023). Shark catch rates, in number or weight of captures per set, are higher in drifting FAD and log sets than in free school sets (Amande et al. 2008, 2010; Clarke et al., 2011; Lopetegui-Eguren et al., 2022). However, when applying a catch rate of the weight of caught sharks per weight of principal market tunas, shark catch rates in school and associated sets are the same order of magnitude (ISSF, 2017b). Set type is also an informative predictor of catch rates of principal market tuna species as well as other at-risk species, such as higher Mobulid ray and leatherback turtle catch rates in free school sets compared to associated sets (Dagorn et al. 2013; Hall and Roman 2013). Set type is also an informative predictor of the body size of the catch, where drifting FAD and other associated sets catch smaller fish, including juvenile yellowfin and bigeye tunas, relative to free school sets (Dagorn et al., 2013; Fonteneau et al. 2013; Hoyle et al., 2014; Restrepo et al. 2017).

Gillnets are relatively size-selective for finfish, but can have poor species selectivity, depending on the species composition at individual fishing grounds (Valdemarsen and Suuronen, 2003; Suuronen et al., 2012). Driftnet fisheries, including in the Indian Ocean, which are typically used in multispecies fisheries with retained commercial catch of several teleost and elasmobranch species, can have relatively high catch rates of several at-risk species groups (Ardill et al., 2012; Gillett. 2011; Northridge et al., 2017; Gray and Kennelly, 2018; Jabado et al., 2018; Roda et al., 2019).

Between 2000 and 2020, the five countries with the largest weight of landed catch from Indian Ocean drift gillnet fisheries were Iran, India, Indonesia, Pakistan, and Sri Lanka, which combined accounted for about 85% of the total gillnet retained catch in the region since 2000 (IOTC, 2023; Elliott et al., 2024).

- **Seabirds**: Numerous species of mainly diving but also non-diving seabirds are susceptible to capture in gillnets (Zydelis et al., 2013; Crawford et al., 2017; Hanamseth et al., 2017; Northridge et al., 2017). An estimated 400,000 shearwaters, penguins, guillemots, and ducks are annually discarded dead in global anchored and drift coastal gillnet fisheries (Zydelis et al., 2013). Recent assessments of the catch composition of the Indian and Iranian gillnet fisheries did not identify seabird bycatch, but these studies were based on port sampling of landed catch and logbook programs (Dehghani, 2023; Koya et al., 2023), which do not provide robust information on discarded catch, including seabird bycatch (FAO 2002; Walsh et al, 2002; Mangi et al. 2016; Emery et al. 2019).

- **Marine turtles**: Substantial turtle bycatch levels have been observed in several small-scale, artisanal gillnet fisheries (Lee Lum, 2006; Alfaro-Shigueto et al., 2011; Casale, 2011), including in the Indian Ocean (Temple et al., 2018; Gautama et al., 2022; Roberson et al., 2022; Koya et al., 2023). Nel et al. (2013) estimated that 29,500 turtles are annually captured in Indian Ocean driftnet fisheries.

- **Marine mammals**: Cetaceans, pinnipeds, and sirenians (dugongs and manatees) are captured (mainly incidental but targeted in some fisheries) in gillnet fisheries and can have high at-vessel mortality rates (Read et al., 2006; Reeves et al., 2013; Gray and Kennelly 2018; Temple et al., 2018; Elliott et al., 2024). Reeves et al. (2013) estimated that several hundred thousand marine mammals are captured annually in global gillnet (both anchored and drift) fisheries. A semi-quantitative ecological risk assessment employing a productivity-susceptibility analysis (PSA) found that Indian Ocean driftnet fisheries pose a high risk to cetaceans, with the highest risk for small and medium-sized oceanic delphinids, and a relatively low risk to baleen whales (Kiszka et al., 2023). Another PSA found that the sei whale *Balaenoptera borealis* and Indo-Pacific humpbacked dolphin *Sousa chinensis* were the cetacean species at highest risk in Indian Ocean driftnet fisheries (Roberson et al., 2022). Anderson et al. (2020) estimated that Indian Ocean driftnet fisheries annually capture and land 80,000 cetaceans. The Pakistan driftnet fishery captures about 8,000 cetaceans annually, and the main captured species is the spinner dolphin (Kiszka et al., 2021). Both coastal and offshore driftnet fisheries in the Indian Ocean capture cetaceans (Anderson et al., 2020; Kiszka et al., 2021; Koya et al., 2023).

- **Sharks**: Driftnet fisheries in the Indian Ocean have documented capture of sharks, including the whale shark, silky shark, grey reef shark, milk shark (*Rhizoprionodon acutus*), mako shark, and hammerhead sharks, where sharks are typically a commercial, retained part of the catch (Temple et al., 2018; Roberson et al., 2022; Dehghani, 2023; Koya et al., 2023). Murua et al. (2013) estimated 97,000 t of elasmobranchs are captured annually in Indian Ocean gillnet fisheries. A PSA found that the shark species with the highest vulnerability to Indian Ocean gillnet fisheries are the coastal crocodile shark, smooth hammerhead shark, pelagic thresher shark, silky shark, and scalloped hammerhead shark (Murua et al., 2018). A more recent PSA found that the great white shark *Carcharodon carcharias* was the shark species of highest risk from Indian Ocean driftnet fisheries (Roberson et al., 2022).

- **Rays**: Tuna gillnet fisheries in the Indian Ocean have documented capture of rays, including mobulids, where rays are typically a commercial, retained part of the catch (White et al., 2006; Fernando and Stevens, 2011; Fernando, 2018; Temple et al., 2018; Martin, 2020; Fernando and Stewart, 2021; Hilbourne and Stevens, 2023; Koya et al., 2023). A PSA found that the giant oceanic manta ray *Mobula birostris* was the ray species at highest risk in Indian Ocean driftnet fisheries (Roberson et al., 2022). Martin (2020) analyzed data from the IOTC Regional Observer Scheme regional database for the Pakistani driftnet fishery, finding that the fishery retained 42% of the number of mobulid catch. Over 56,000 mobulids were estimated to be captured in 2011 and retained for gill rakers (gill plates) in Sri Lanka’s driftnet fisheries targeting skipjack and yellowfin tunas and billfishes (Fernando and Stevens, 2011). In Indonesia’s driftnet skipjack fisheries, based on a survey at four landing seaports between 2001 and 2005, the annual mobulid catch was estimated to be over 4,000, retained for their gill rakers, skin, and meat (White et al., 2006). The spinetail mobula (*Mobula japanica*) composed about half of the ray catch in this fishery (White et al., 2006).

There are extremely low bycatch levels in **pole-and-line fisheries**. The limited bycatch that does occur primarily consists of dolphinfish (*Coryphaena hippurus*), rainbow runner (*Elagatis bupinnulata*), juvenile kawakawa tuna (*Euthynnus affinis*), and frigate mackerel (*Auxis rochei*). There is also some bycatch of at-risk species of seabirds, sharks such as the epipelagic silky and oceanic whitetip sharks, and cetaceans (Gilman, 2011; Miller et al., 2017; Cruz et al., 2018). Due to the use of barbless hooks and flick-off practices, and a relatively short duration for handling and release, discards are believed to have high post release survival rates (FAO, 1997b; Miller et al., 2017). However, concerns with pole-and-line fisheries have been raised over:

- the bycatch of reef fish and juvenile classes of target species in baitfish fisheries that supply live bait to pole-and-line fisheries (Gillett, 2010)
- broad, ecosystem-level effects from the fishing mortality of baitfish species
- overexploitation of target baitfish species (Gillett, 2010)
- impacts on food security of coastal communities resulting from baitfish removals (Gillett, 2010)
- adverse ecological effects of anchored and drifting FADs that are used by many pole-and-line fisheries (Miller et al., 2017; Adam et al., 2019; ISSF and IPNLF, 2019; Proctor et al., 2019; Gilman et al., 2022b)
- fishing on schools associated with live megafauna such as whale sharks (Fontes et al., 2020)

Other hook-and-line gear types used to target tuna and tuna-like species and billfishes, such as **troll and handline**, have been documented to have bycatch of at-risk species such as albatrosses and petrels in Brazilian tuna troll and handline fisheries (Bugoni et al., 2008).

There is substantial uncertainty in estimates of the rates and magnitudes of bycatch fishing mortality of at-risk species, with several main sources of this uncertainty. Most fisheries lack or have extremely low independent observer or electronic monitoring coverage rates. Observer coverage rates remain at very low levels in most marine capture fisheries. For instance, 47 of 68 fisheries that catch marine resources managed by regional fisheries management organizations have no observer coverage (Gilman et al. 2014). Fisheries EM coverage has expanded in recent years: There have been about 100 EM pilots in both industrial and artisanal, small-scale fisheries since the first was conducted in British Columbia, Canada in 1999, and there are about a dozen fully implemented EM programs with *ca.* 1000 fishing vessels (Michelin et al., 2018; Van Helmond et al., 2020). This represents tremendous progress in technology development and uptake but EM is still in an incipient stage with very limited coverage of the *ca.* 4.6 million vessels of global fisheries (FAO, 2020).

There are three main sources of statistical sampling bias faced by observer programs (Babcock et al. 2003; Benoit and Allard 2009):

- **Observer effect**: Fishers may alter fishing practices and gear when an observer (or EM) is present.
- **Observer displacement effect**: Observers may not be placed on certain vessels for various reasons (undesirable conditions, too small, unsafe, mismatch in languages, and logistically challenging for placement and retrieval).
- **Coercion and corruption**: Observers can be bribed or intimidated by fishers. This risk increases the more significant the consequences of the reporting.

EM can provide more certain monitoring data compared to conventional human observer programs because EM systems have the capacity to overcome these main sources of statistical sampling bias. Having vessels permanently outfitted with EM systems overcomes an observer effect, where either all or a random sample of EM imagery can be analyzed. Because vessel specification requirements for EM systems are much lower than for a human observer, EM avoids an observer displacement effect so that sampling is random and balanced proportionately across fleet strata. EM analysts do not have direct contact with vessel skippers and crew, and therefore the risk of EM analyst coercion and corruption is lower than with human observers placed on fishing vessels.

Furthermore, observers can be deceived by crew, such as when crew conceal the capture of bycatch species subject to quotas. This is still a risk with EM systems, but unlike observers, who can monitor only a single area of the vessel at a time, EM analysts can view multiple fields of view simultaneously, and EM systems can monitor continuously.

EM systems can also be used in a cost-effective audit model, where all vessels have EM systems, and random samples of imagery and sensor data are reviewed to assess the precision of logbook data. To incentivize improved logbook data quality, penalties (e.g., full review of EM imagery, assign an observer, or issue a fine) can be assigned when a vessel is found to systematically record logbook data with low precision with EM data (Stanley et al. 2011; Emery et al. 2019).

Inadequate sampling designs can also cause inadequate monitoring rate sampling by fleet segment or stratum. To avoid statistical sampling bias, the necessary observer or EM coverage rate, as well as data fields and data collection methods, for a particular fishery depend on: (1) the objectives of analysis, including required levels of accuracy and precision of catch rates, and (2) aspects of each individual fishery, such as how many vessel classes exist, how many ports are used, the spatial and temporal distribution of effort, the frequency of occurrence of catch interactions for each species of interest, the amount of fishing effort, and the spatial and temporal distribution of catch (Hall 1999; FAO 2002; Babcock et al. 2003; Wakefield et al. 2018). In general, variability in precision and biases in bycatch estimates decrease rapidly as the observer coverage rate increases to about 20%, assuming that the sample is balanced and there are no observer effects, and then decrease slowly towards 0 with 100% coverage (Hall 1999; Lennert-Cody 2001; Lawson 2006). At lower coverage rates, catch estimates will likely have large uncertainties for species with low capture rates (Amande et al. 2012) and can result in high uncertainty even for species that are more commonly caught if a small sample size is observed per stratum (e.g., by port, vessel category, and season) (Bravington et al. 2003). When low coverage rates result in small sample sizes, it is very likely that rare species that are exposed to capture will not be identified. Species richness and other species-level biodiversity indices are extremely sensitive to sample size and species abundance distribution (evenness). The less even the relative abundance of species in a community is, the larger the proportion of relatively rarer species within that system that will be detected with more sampling effort (Heck et al. 1975; Lawton et al. 1998).

Deficits in observer data collection protocols can also cause substantial underestimates of magnitudes of at-risk bycatch (Precoda and Orphanides, 2024). For example, fisheries observers with a main responsibility of estimating retained target catch might not observe catch, including at-risk bycatch species, that crew remove from the gear in the water or that drop out of the gear during the haulback (Hamer et al., 2013; Precoda and Orphanides, 2024). For example, Precoda and Orphanides (2024) estimated that observers in a US northwestern Atlantic gillnet fishery underestimated marine mammal bycatch by as much as 25% when tasked primarily with documenting fish catch compared to when their primary task was to observe marine mammal bycatch. Similarly, deficits with EM systems can prevent EM analysts from accurately estimating discarded catch, such as when cameras are not positioned to cover all areas where crew discard catch, or due to inadequate deck lighting (Gilman et al., 2020a). In tuna purse seine fisheries, selectivity bias can result from grab sampling to estimate the catch of target tuna species (Lawson 2013; Hoyle et al., 2014). Methods employed by observers to estimate the catch of non-target species can also introduce substantial uncertainty. For example, observer sampling protocols to estimate bycatch by counting non-target catch from one brail or counting discards for a sample of catch sorting time and extrapolating linearly to the total number of brails and to total sorting time in a set, respectively, can introduce error (Briand et al., 2018). Observers of the SPC/FFA Regional Observer Programme use visual inspections to estimate the number and weight of bycatch species, as time permits, while sampling the target tuna catch on the upper deck (Itano et al., 2019; Forget et al., 2021). The small sample of non-target catch may be unrepresentative of the underlying catch from the total set, and monitoring only from the upper work deck will result in undercoverage bias because small species and small individuals within species of non-target catch may be detected primarily on the lower well deck (Forget et al., 2021). Observers may have a more difficult time quantifying bycatch on vessels that do not use a hopper to sort catch after brailing onto the deck before the catch goes down a chute to a lower deck for sorting and storage in wells (Poisson et al., 2014a; Hutchinson et al., 2015). The SPC/FFA Regional Observer Programme tasks observers with recording the weight or number of each captured non-target species, as well as the number or weight of species of special interest that are observed inside or touching the net that are not subsequently landed on deck (SPC & FFA, 2018). Observers are directed to only record the number of captures when it is possible for them to obtain an accurate count, and observers are to record an estimated weight only when a large volume of a species was captured (SPC & FFA, 2018). As conducted previously to estimate the precision between estimates of target catch through grab and spill sampling (Lawson, 2013), research to identify bias in non-target species-specific observer catch estimates is a priority to produce accurate estimates of catch rates and fleetwide extrapolations, especially in purse seine fisheries with low observer coverage rates (Amande et al., 2012). Developments in fisheries EM systems used in purse seine fisheries might improve the accuracy of bycatch estimates (Briand et al., 2018; Forget et al., 2021).

There are also collateral, cryptic sources of bycatch fishing mortality that are not readily detected by observer and EM programs (Gilman et al., 2013). For example, catch may be removed from gear prior to the haulback due to mechanical action, depredation, and decomposition, and estimates of ghost fishing mortalities are highly uncertain (Macfadyen et al., 2009; Precoda and Orphanides, 2024).

4. Case Study Application of a Decision Support Tool for Integrated Bycatch Management Strategy Evaluation

Gilman et al. (2022) developed a decision support tool to assist stakeholders to define and evaluate alternative strategies for the integrated management of fisheries bycatch. As one component of a fishery improvement project (FIP) (Cannon et al., 2018; CASS, 2022), stakeholders of an albacore tuna longline fishery applied an adapted version of the support tool to develop a bycatch management plan (Thai Union et al., 2022).

This process was implemented for a fishery comprised of 10 distant-water pelagic longline vessels that fish across the Pacific Ocean primarily at higher latitudes to target albacore tuna. The vessels are flagged to Vanuatu and are owned by Tunago Fishery Co., a Taiwanese company. The vessels range in length between 46.5 and 53.5 m, have 30 crew, and transship catch on the high seas (i.e., areas beyond national jurisdiction). The vessels land catch mainly in Suva, Fiji.

The steps to develop the integrated bycatch management strategy are summarized in **Figure 1**.

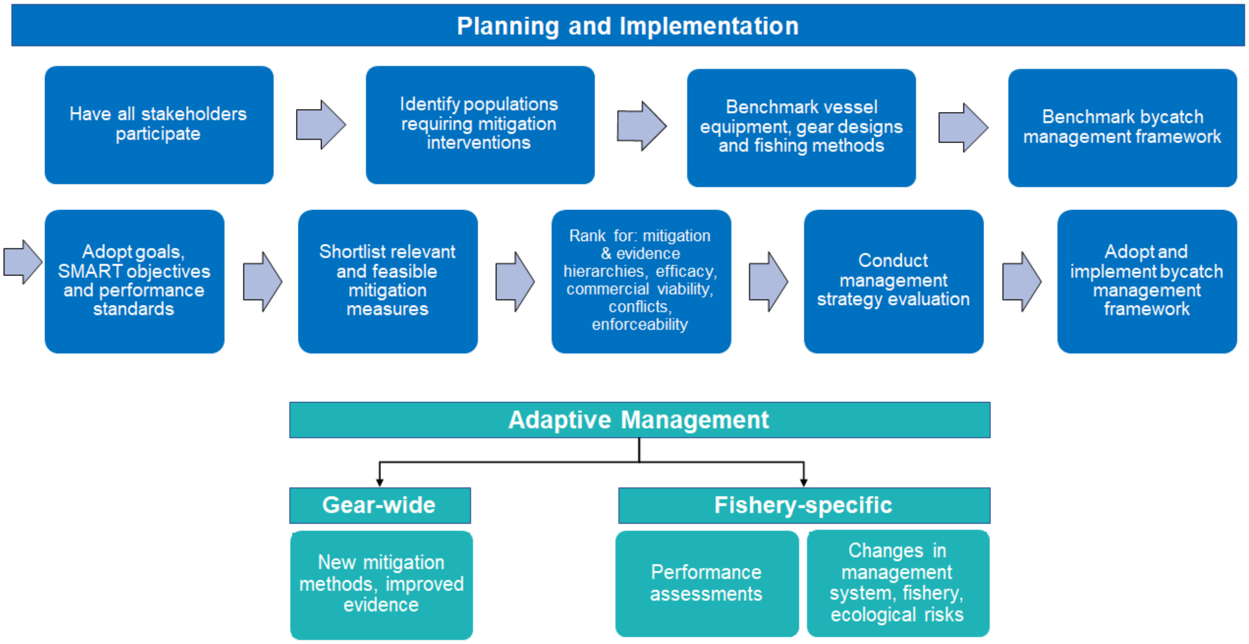

Figure 1. Process to develop the Tunago-Thai Union bycatch management framework (adapted from Gilman et al., 2022).

The first step of the process was a stakeholder assessment. The FIP members identified, and ensured there was direct involvement of, relevant participants in developing and implementing a bycatch management plan. This component also identified incentives for bycatch improvements by each stakeholder.

Next, participants benchmarked contemporary ecological risks of populations and stocks susceptible to capture in the fishery, and identified species requiring mitigation interventions. The participants defined the scope of the bycatch management strategy based on explicit or otherwise implicit thresholds for acceptable impacts and species-specific fate of the catch.

The third activity was to identify contemporary vessel equipment, fishing methods and gear designs that significantly explain catch and survival rates of vulnerable bycatch. Participants also identified information gaps on gear designs that would be addressed through activities included in the workplan. For example, information on branchline weighting designs was not initially known, which was addressed through a dockside inventory audit.

The participants also benchmarked the contemporary fisheries management framework, including monitoring, control, surveillance, enforcement, and outcomes of enforcement actions, and reviewed the legal and regulatory framework. Findings from available performance assessments of the bycatch management framework and of individual bycatch mitigation measures were also compiled and synthesized.

With this enabling information, the participants were then able to define and adopt overarching goals, objectives, and performance standards to achieve the goals for the bycatch management framework that balanced stakeholders' competing priorities, and that were specific, measurable, achievable, relevant, and time-oriented. The objectives covered: (1) Catch and fishing mortality levels or rates of vulnerable bycatch species; (2) level of residual bycatch removals, or otherwise offsets to achieve no net loss or a net gain; (3) acceptable multispecies conflicts; (4) acceptable commercial viability costs; and (5) improvements in other management components (legal, regulatory, monitoring, surveillance, enforcement).

With the goals and objectives defined, participants then adopted a shortlist of candidate bycatch management methods of relevance to the fishery and that they determined could be feasibly implemented.

The participants ranked these shortlisted bycatch management measures. Weights were assigned to each alternative method according to: (1) tiers in mitigation and evidence hierarchies; (2) how they meet objectives for mitigation of catch and mortality rates of at-risk bycatch species; (3) whether they meet objectives on acceptable multispecies conflicts; (4) whether they meet acceptable effects on commercial viability (practicality, safety, economic viability); and (5) likelihood of compliance given the capacity of the fisheries management system to conduct compliance monitoring and the effect of crew behavior on performance of the method.

Participants then implemented a qualitative MSE process to compare how alternative bycatch management frameworks would meet their objectives. This process enabled the stakeholders to identify bycatch management frameworks that are likely to achieve their objectives on desired improvements in catch and mortality rates of at-risk bycatch species, and on acceptable multispecies conflicts and commercial viability costs, and compare the tradeoffs among objectives that each alternative framework was simulated to produce.

Following these bycatch planning steps, the FIP participants then adopted a bycatch management strategy that met objectives for: (1) mitigating the catch and mortality of at-risk bycatch species; (2) acceptable costs resulting from multispecies conflicts; (3) acceptable costs to commercial viability components of economic viability, practicality and crew safety; and (4) improvements with the fisheries management system's monitoring, control, surveillance and enforcement components to enable achieving the bycatch objectives. The one-year bycatch management workplan was developed to implement the management strategy.

The bycatch management strategy includes regularly scheduled performance assessments that are intended to inform adapting the management strategy and workplan as needed.

5. Next Steps for Comprehensive, Multispecies Bycatch Management

5.1. Priority Inputs for Multispecies Bycatch Management Strategy Evaluation

Bycatch MSE can account for the key criteria defined in this section. These inputs are important for the robust evaluation of alternative strategies for managing bycatch in a regional or national fishery. Holistic bycatch MSE can predict how well an individual alternative bycatch management strategy is likely to meet specific and measurable objectives on: desired catch and fishing mortality rates and levels across the multiple populations and stocks of exposed at-risk bycatch species, acceptable multispecies tradeoffs, and acceptable costs to economic viability, practicality and crew safety. Then, the MSE process can compare alternative strategies' simulated outcomes so that managers can select the framework that best meets objectives.

5.1.1. MULTISPECIES CONFLICTS

As is evident from the databases of bycatch mitigation methods presented in Appendices 1-4, multispecies conflicts from bycatch mitigation methods are prevalent. Management authorities may be faced with situations where available bycatch management options reduce the catch rate or fishing mortality rate of one at-risk species but exacerbate the risks of another. Holistic, multispecies bycatch MSE accounts for these multispecies conflicts so that tradeoffs are intentional and acceptable. For example, switching from using a J-shaped hook to a wider circle hook in a pelagic longline fishery could cause a large reduction in fishing mortality of a critically endangered marine turtle population with an acceptable relatively small increase in fishing mortality of a stock of a pelagic shark species with a conservation status that is relatively less critical — e.g., that is experiencing overfishing but is not overfished.

5.1.2. STRENGTH OF EVIDENCE, INCLUDING EVIDENCE OF EFFICACY IN PRACTICE

Policy decisions should be guided by the relative degree of risk of error and bias and strength of evidence of the efficacy of alternative management interventions. Independent synthesis of all accumulated information is a fundamental principle for developing transparent, evidence-informed regional conservation policy. Evidence from meta-analytic studies ideally should inform the development of global- and regional-level bycatch management strategies.

Meta-analytic syntheses produce the most robust and generalizable findings that are optimal for guiding regional bycatch management. Otherwise, given too few studies to support robust meta-syntheses, decisions should rely on qualitative syntheses of accumulated studies. There is a risk that results from a single study are context-specific — and hence lack external validity and broad applicability. Results may be affected by the specific conditions of an individual study, such as the study area, study period, species involved and environmental conditions, preventing the results from that single study from being applicable under different conditions. This may explain cases where individual studies have conflicting findings. Furthermore, a single study may have low power and fail to find a meaningful result due to providing a non-representative sample. Bycatch mitigation methods with findings only available from studies with relatively weak forms of evidence, or lacking any evidence, should only be considered as a precautionary approach when more certain alternatives are unavailable. Strictly applying a hierarchical approach on study evidence to make policy decisions, however, risks ignoring potentially important findings derived from studies using methods that are ranked low on an evidence hierarchy. Instead, in making bycatch management policies, authorities should account for all accumulated evidence and the implications of different approaches for testing different hypotheses.

Estimates of the efficacy of some bycatch mitigation methods derived from analyses of monitoring data provide a more realistic prediction of the effect of the method when used during real-world, commercial fishing operations than estimates from experiments, despite the latter having a relatively lower risk of bias. Thus, robust fisheries monitoring systems that supply independent information on key data fields are a prerequisite for holistic bycatch management. The efficacy of some bycatch mitigation measures is strongly affected by crew behavior. This can cause substantial differences in the efficacy of these bycatch mitigation methods between estimates from experiments, where researchers implemented the mitigation measure, versus from analyses of observer or electronic monitoring data, where fishers implemented the bycatch mitigation method during commercial operations. Therefore, for bycatch mitigation methods whose efficacy is affected by crew behavior, analyses of observer and electronic monitoring data may provide a more certain estimate of responses during commercial fishing operations than experiments, where experiments that optimally apply a treatment provide useful information on the upper bound of effectiveness. For example, crew may not be as attentive to maintaining a bird-scaring tori line over the area where bait hooks are accessible to seabirds and to casting baited hooks under the tori line streamers to the same degree that researchers are when conducting an experiment. Crew also might not deploy a tori line at all if there are deficits in one or more management framework component of monitoring, control, surveillance, enforcement, and outcomes of enforcement actions (discussed below). It is therefore important to validate that the efficacy of an intervention when used under controlled conditions is of similar effectiveness when employed in real-world conditions through “pragmatic” studies that rely on robust independent monitoring. To account for this real-world efficacy, considering whether the efficacy of a specific method is affected by crew behavior is important, which is discussed below in the criterion on *Likelihood of Compliance*.

5.1.3. EFFECT SIZE AND TIER OF A SEQUENTIAL MITIGATION HIERARCHY

Bycatch management strategies can be assessed based on the predicted size of their effect on catch and fishing mortality rates of at-risk bycatch species, and hence how they contribute to meeting bycatch management objectives. This enables determining the relative value of alternative bycatch management approaches towards meeting outcome objectives.

To be achievable, objectives and milestones must account for the capabilities of the fisheries management system, including data quality. A data-limited fishery — such as with minimal observer coverage — might initially be restricted to adopting primarily **process** objectives, such as to have all vessels in a longline fishery use only forage fish species for bait by a specified date, and not **outcome**-based objectives, such as to reduce oceanic whitetip shark bycatch mortalities so that the stock is safely above a biological limit reference point.

The tier in which a bycatch mitigation method is categorized indicates the method's relative effect on the catch and fishing mortality rate of at-risk species. In a sequential mitigation hierarchy, bycatch mitigation methods that **avoid** capture are considered before those that **minimize** catch. These are followed by **remediation** interventions that reduce fishing mortality and sublethal impacts. Finally, **offsets** of residual impacts are a last resort. While a sequential mitigation hierarchy framework has been included in environmental impact assessment policies for wetlands and terrestrial natural resources since the 1960s, it is surprisingly still absent from the fisheries sector.

5.1.4. COSTS TO COMMERCIAL VIABILITY

Alternative bycatch management measures can be assessed according to their costs to the following:

Economic viability: For example, does a bycatch mitigation method reduce catch rates of commercial species, have a high initial outlay or ongoing cost, or reduce fishing effort which in turn reduces catch levels of marketable species?

Practicality: For example, is substantial crew time required to implement a bycatch mitigation method, reducing their time available for sleeping and eating? Or is the method unpleasant to implement, such as dyeing bait blue to reduce seabird interactions? Whether a fishery has small-scale vessels, or is industrial with large vessels, will affect assessments of practicality for some mitigation methods. For example, satellite and radio buoys, used to track the location of drifting longline gear, help avoid gear loss — reducing the risk of ghost fishing and other adverse effects of derelict gear. This equipment commonly used in larger-scale fisheries but might be impractical for use by small vessels with limited deck space for storage (and might also be cost-prohibitive for use by artisanal fleets).

Safety: Does implementation of the mitigation method increase the risk to crew safety, such as attaching longline branchline weights closer to hooks to reduce seabird catch rates, which can increase the risk of crew injury from weight flybacks when catch throws the hook?

5.1.5. COMPLIANCE LIKELIHOOD

Alternative bycatch management approaches can be assessed based on the enabling conditions of the fisheries management framework that are needed to deter noncompliance.

An initial consideration is whether fishers would be expected to voluntarily employ the method — including whether it causes high or low costs to commercial viability (discussed above), and whether the method constitutes a major change from conventional practices.

Another key consideration is whether efficacy relies on crew behavior, as discussed above.

And a third consideration is whether the method is suitable given the capacity of the management system to conduct robust compliance monitoring, and that has adequate consequences (penalties and/or rewards) to incentivize compliance. This accounts for what approaches effectively enable compliance monitoring, the state of the fisheries' surveillance program, the robustness of the enforcement framework and outcomes of enforcement actions in response to an identified infraction.

These main considerations for compliance likelihood of alternative bycatch management approaches are summarized as follows:

- Is voluntary compliance expected?
    - Costs to components of commercial viability
    - Degree of change from conventional practices
- Does the method's efficacy rely on crew behavior?
- Are the fishery's MCS and enforcement frameworks adequate?
    - What methods enable robust compliance monitoring (dockside vessel inspection audits, port sampling of landed catch, satellite-based vessel monitoring systems, at-sea human observers / fisheries electronic monitoring, etc.) — and does the fishery have the needed monitoring and surveillance systems?
    - Does the fishery have robust legal and regulatory frameworks, and are outcomes of enforcement actions adequate incentives for compliance?

For fisheries with limited monitoring and surveillance, and/or weak enforcement frameworks, bycatch mitigation methods whose performance is strongly affected by crew behavior and which are not convenient for crew to employ, may be unsuitable.

Methods whose efficacy does not rely on crew behavior during fishing, such as methods for which compliance can be determined through dockside inspections or satellite-based vessel monitoring systems, have high promise for compliance.

And methods that are affected by crew behavior but can be confirmed without observers and fisheries electronic monitoring systems — such as static area-based management tools, and input controls such as on the number and time-of-day of fishing operations, which can be monitored with a satellite-based vessel monitoring system — may also have high promise for compliance.

5.1.6. COMMERCIAL AVAILABILITY

Assessing the commercial availability of a bycatch mitigation gear technology method — whether equipment and materials required for a bycatch measure are readily available — can inform the relative suitability of a method for fishery uptake.

5.1.7. RATES OF INDIVIDUAL COMPONENTS OF FISHING MORTALITY

Different bycatch management interventions will be effective depending on at-vessel mortality rates (the proportion that are dead at haulback before being handled by crew), fate (whether the catch is retained or discarded), and post-release mortality rate (the proportion of live released catch that survive). There can be large variability in rates of these three fishing mortality rate components by species, and sex and size within species. For example, about 95% of pelagic stingrays are alive when retrieved while only about a quarter of salmon sharks are alive at retrieval by global pelagic longline vessels.

Methods that decrease at-vessel mortality rates, such as operational factors of longline hook and bait type, passive gear soak duration, passive gear fishing depth, and longline branchline length, will not be effective for species that are largely retained.

Retention bans, bans on shark finning, and CITES international trade bans might not be effective for species with high at-vessel mortality rates unless the bans cause a reduction in shark targeting practices.

Handling and release methods can be effective for non-retained species that have both low at-vessel and post-release mortality rates. But handling and release methods have a relatively lower conservation benefit for species with high post-release mortality rates.

Methods that reduce catch rates, such as input controls, bycatch quotas, and gear technology methods, contribute to reducing total fishing mortality of at-risk species regardless of whether they have high or low at-vessel or post-release mortality rates.

5.2. Next Steps for Robust Comprehensive, Multispecies Bycatch Management

Systematic literature review protocol: This study assembled the databases of bycatch mitigation methods through a targeted literature review. The databases should periodically be updated through implementation of a systematic literature review. Systematic reviews employ an impartial, transparent and thus replicable approach, and reduce the risk of biased selection of publications and risks of introducing prevailing paradigm, familiarity, citation and publication biases.

Expanded database fields: The current assembled databases of bycatch mitigation methods could be expanded to include fields for all of the key input for robust, holistic bycatch MSE identified in the previous section.

Expanded database records for prescribed combinations of methods: The databases of bycatch mitigation methods could be expanded to include combinations of methods that are required by RFMO binding measures or are recommended by an advisory intergovernmental organization. Combinations of methods may maximize mitigation efficacy and enable meeting objectives. Furthermore, there are synergistic, interacting effects of some mitigation methods. For instance, the time-of-day of fishing operations and fishing depth determine encounterability vertical exposure and catch risk for pelagic predators whose vertical distributions vary temporally due to diel vertical migration cycles, time of day of foraging, and temporal variability in diving behavior. Interacting effects of hook type, bait type, and leader material are an additional example: Hook shape, hook size, and bait type can affect anatomical hooking position and therefore affect the ability of some species to escape when monofilament leaders are used, but not when more durable wire and multifilament leader materials are used.

Webtool to Support Integrated Bycatch Management Strategy Evaluation: Establish a webtool, or integrate new content and functionalities into an existing web platform (such as WCPFC's

Bycatch Management Information System or New England Aquarium's Bycatch.org), to enable fisheries management authorities and other stakeholders to discover bycatch mitigation methods relevant to specific gear types, and that include data fields for each method to identify key criteria for bycatch MSE, defined in the previous section.

The proposed webtool could augment the evaluation of individual fisheries against ecological sustainability standards such as of the Marine Stewardship Council and Monterey Bay Aquarium's Seafood Watch program, both of which account for the effects of fisheries on at-risk bycatch.

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Appendix 1. Methods to Mitigate the Catch and Fishing Mortality of At-risk Bycatch Species that are Relevant Across Gear Types and Taxonomic Groups

Table 1 is a database of methods to mitigate the catch and fishing mortality of at-risk bycatch species that are relevant across gear types and taxonomic groups**.** For each method, the species group-specific effects on catch and fishing mortality risk, compliance monitoring requirements, and whether the method is in broad commercial use are identified. For each method, the first row is catch rate response, and the second row is fishing mortality rate response. Catch rate refers to the number or weight of captures per unit of effort. Fishing mortality rate as used here refers to the proportion of catch that die due to the interaction. To clarify, for example, while input controls on effort do not affect catch rates or fishing mortality rates, they could reduce the magnitude of catch and mortalities. A catch rate response, particularly for elasmobranch and teleost species, can have variable economic consequences depending on the fishery, individual vessel within a fishery, season, fishing grounds, etc.

***Table 1.** Database of methods to mitigate the catch and fishing mortality of at-risk bycatch species that are relevant across gear types and taxonomic groups.*

Key
▲ = reduces catch or fishing mortality risk
— = no effect
▼ = increases risk
? = inconclusive/unknown
V = response is variable
O = offset residual bycatch mortalities that could not be avoided, minimized and remediated

Method	Cet-aceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Output controls												
Bycatch thresholds: Individual vessel quotas, risk pool for a group of vessels, or fleetwide cap/total allowable catch)	▲	▲	▲	▲	▲	▲	▲	▲	Avoid	Y	Y	Cochrane, 2002; Pascoe et al., 2010; Gilman et al., 2023b
	—	—	—	—	—	—	—	—	NA			
Retention and international trade bans: Bans on retention by species, sex and size; CITES restrictions and bans on international trade	—	—	—	—	—	—	—	—	NA	Y	N	Cochrane, 2002; Birkeland and Dayton, 2005; Tolotti et al., 2015
	▲	▲	▲	▲	▲	▲	▲	▲	Remediate			
Retention limits: Individual or fleet-based, for marketable species	—	—	—	—	—	—	—	—	NA	Y	N	Cochrane, 2002; Anderson et al., 2019
	—	—	—	—	—	▲	▲	▲	Remediate			
Shark finning ban: Prohibition on retaining fins and discarding the remaining carcass[2]	—	—	—	—	—	V	V	—	Minimize	Y	N	Clarke et al., 2013; Worm et al., 2013; Gilman et al., 2023b
	—	—	—	—	—	V	V	—	Remediate			
Input controls												
Limits on vessels, gear, fishing aids, fishing effort: Limits on number of vessels, vessel size, amount of gear, number of FADs, fishing days, number of fishing operations	—	—	—	—	—	—	—	—	Avoid	Y	N	Cochrane, 2002; Anderson et al., 2019; ISSF, 2023c
	—	—	—	—	—	—	—	—	NA			

Method	Cetaceans	Turtles, hard-shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Limits on duration of fishing operations: Soak duration for passive fishing gear, tow duration for active fishing gear[3]	▲	▲	▲	▲	—	▲	▲	V	Minimize	Y	N	FAO, 2010; Ferreira et al., 2011; Epperly et al., 2012; Northridge et al., 2017
	?	▲	▲	?	V	▲	▲	▲	Remediate			
Handling and release practices	—	—	—	—	—	—	—	—	NA	Y	Y	Poisson et al., 2014a,b; ISSF, 2016, 2023a; Ruiz et al., 2023; Murua et al., 2024
To maximize post-release survival	?	▲	▲	▲	▲	▲	▲	▲	Remediate			
Spatiotemporal management												
Static and dynamic spatial and temporal restrictions	V	V	V	V	V	V	V	V	Avoid	Y	N for static, Y for spatially dynamic	Cochrane, 2002; Anderson et al., 2019; Hilborn et al., 2021; Gilman and Chaloupka, 2024; Monaghan et al., 2024
	—	—	—	—	—	—	—	—	NA			
Real-time fleet communication	▲	▲	▲	▲	▲	▲	▲	▲	Minimize	Y	Y	Gilman et al., 2006; O'Keefe et al., 2014
	—	—	—	—	—	—	—	—	NA			
Real-time **move-on rules**	▲	▲	▲	?	?	?	?	?	Avoid	Y	Y	Fader et al., 2021; Walmsley et al., 2021
	—	—	—	—	—	—	—	—	NA			
ALDFG	—	—	—	—	—	—	—	—	NA	Y	Y	Macfadyen et al., 2009; Gilman et al., 2022b; Escalle et al., 2023; Moreno et al., 2023; Murua et al., 2023c; Zudaire et al., 2023
Mitigate risk of producing and adverse effects of derelict gear[4]	▲	▲	▲	▲	▲	▲	▲	▲	Remediate			
Offsets	O	O	O	O	O	O	O	O	Offset	N	Y	Milner-Gulland et al., 2018; Gilman et al., 2023a
Residual bycatch mortalities that were not avoided, minimized and remediated are offset by obtaining an	O	O	O	O	O	O	O	O	Offset			

Method	Cet-aceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
equivalent or a more-than-equivalent net gain												

[1] Mitigation hierarchy tiers:
Avoid = Eliminate the bycatch risk of one or more species or assemblage completely within the scope of the intervention
Minimize = Reduce the bycatch risk of one or more species or assemblage
Remediate = Avoid or reduce fishing mortality risk
Offset = obtain an equivalent gain to replace any residual bycatch fishing mortality, or obtain a net gain

[2] Variable by fishery and shark species. Finning bans could reduce release and post-release mortality rates of non-retained shark species and particularly benefit species with low at-vessel mortality rates and hence a relatively high capacity to be released alive, but would not affect the fishing mortality of species that are retained and would be of limited benefit to species with high at-vessel mortality rates (Gilman et al., 2023b). Finning bans might indirectly lead to the use of methods that reduce shark catch rates in fisheries where only fins had previously been retained (Clarke et al., 2013; Worm et al., 2013; Gilman et al., 2023b).

[3] For example, longer trawl tow duration is an informative predictor of shark catch rate (Sala, 2018), and for pelagic longline fisheries, a very limited body of research suggests that reducing the duration of daytime gear haulback and possibly total soak duration may reduce loggerhead catchability, reducing the duration that gear soaks at night might reduce leatherback catchability, and reducing total soak time might reduce at-vessel mortality rates of all turtle species (FAO, 2010; Ferreira et al., 2011; Epperly et al., 2012). Limiting gillnet soak duration would also be expected to reduce the pre-catch and at-vessel mortality of catch, including at-risk bycatch species.

[4] For instance, electronic tracking of gear position, no hooks in discarded spent bait, marking gear to increase visibility, using non-entangling FADs, using less durable and biodegradable materials for fishing gear components, disabling or removing derelict gear, and implementing MARPOL garbage management plans.

Appendix 2. Methods to Mitigate the Catch and Fishing Mortality of At-risk Bycatch Species by Pelagic Longline Fisheries

Table 2 is a database of methods to mitigate the catch and fishing mortality of at-risk bycatch species by pelagic longline fisheries. For each method, the species group-specific effects on catch and fishing mortality risk, compliance monitoring requirements, and whether the method is in broad commercial use are identified. Methods are sorted into taxonomic groups for which they are typically prescribed as a bycatch mitigation approach, and then by mitigation hierarchy tier. For each method, the first row is catch rate response, and the second row is fishing mortality rate response. Catch rate refers to the number or weight of captures per unit of effort. Fishing mortality rate is used here to refer to the proportion of the catch that dies due to the fishery interaction. A catch rate response, particularly for elasmobranch and teleost species, can have variable economic consequences depending on the fishery, individual vessel within a fishery, season, fishing grounds, etc. See Beverly et al. (2003) for a description of pelagic longline gear components and vessel equipment.

There were no identified methods primarily designed to mitigate the capture or mortality rate of rays. See measures listed under other taxonomic groups that affect ray bycatch, such as hook shape, hook minimum width, deeper fishing, ban shark lines, and bait type and cross-gear type approaches in **Table 1**.

A mainline line shooter was not included as a bycatch mitigation method for pelagic longline fisheries. This equipment has been considered a method to mitigate seabird bycatch rates and included as an option in tuna RFMO seabird bycatch management measures. However, the sink rate of baited hooks will be unaffected by the sink rate of the mainline until the hook has settled to the full length of the branchline, which in most fisheries is below the depth where seabirds susceptible to pelagic longline capture can dive (for details, see WPRFMC, 2019).

Table 2*. Database of methods to mitigate the catch and fishing mortality of at-risk bycatch species by pelagic longline fisheries.*

Key
▲ = reduces catch or fishing mortality risk
— = no effect
▼ = increases risk
? = inconclusive/unknown
V = response is variable
O = offset residual bycatch mortalities that could not be avoided, minimized and remediated

Method	Cetaceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Seabirds	Sharks, epi-pelagic	Sharks, meso-pelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
CETACEANS												
Weak hook: Hooks with a sufficiently narrow wire gauge so that the hook straightens before other gear components (hook ring, leader, swivels, crimps, line, snap, etc.) fail[2]	?	—	—	—	—	?	?	V	Minimize	Y	Y	Bayse and Kerstetter, 2010; Bigelow et al., 2012; Foster and Bergmann, 2012; McLellan et al., 2015; Gilman et al., 2022
	?	—	—	—	—	?	?	?	Remediate			
Mainline length limit	?	?	?	?	?	?	?	?	Minimize	Y	N	NMFS, 2020
	?	?	?	?	?	?	?	?	Remediate			
Dummy gear sections: Hookless mainline sections and hookless sets	?	?	?	?	?	?	?	?	Minimize	Y	Y	Werner et al., 2006
	—	—	—	—	—	—	—	—	NA			
Set geometry: Multiple short sets; set in a sinusoidal or wavy pattern	?	?	?	?	?	?	?	?	Minimize	Y	Y	Donoghue et al., 2002; Gilman et al., 2006
	—	—	—	—	—	—	—	—	NA			
Encased catch: To physically protect catch from depredation, and visual and acoustic camouflage of target catch such as by using bubble screens or knots	?	?	?	?	?	?	?	?	Minimize	Y	Y	McPherson, 2003; McPherson et al., 2008; McPherson and Nishida, 2010; Hamer et al.,2015; Rabearisoa *et al.*, 2012, 2015
	?	?	?	?	?	?	?	?	NA			
	?	?	?	?	?	?	?	?	Minimize	N	Y	

Method	Cet-aceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Minimized soak and haul duration (and see **Table 1** for other input control measures)	?	?	?	?	?	?	?	?	NA			FAO, 2018a; La Manna et al., 2023
Acoustic masking (camouflage): Camouflage the gear and vessel through quieter vessels; masking or disrupting odontocete returning echolocation; bubble screens to reduce the dissemination of vessel sounds; broadcast of sounds to conceal the sounds of the vessel gear, setting and hauling; vessels not remaining near the gear after setting; minimizing shifting in and out of gear	?	—	—	—	—	—	—	—	Minimize	Y	N	ALFA, no date; Gilman et al., 2006; Mooney et al., 2009; Hamer et al., 2012
	—	—	—	—	—	—	—	—	NA			
Active acoustic alerts, deterrents and decoys: Pingers; acoustic harassment devices; decoy vessels; broadcast decoy fishing vessel acoustic cues; broadcast killer whale and other predator sounds	?	—	—	—	—	?	?	—	Minimize	N	Y	McPherson, 2003; Gilman et al., 2006; Nishida and McPherson, 2011; Wild et al., 2017; Lucas and Berggren, 2023
	—	—	—	—	—	—	—	—	NA			
Passive acoustic decoys and deterrents: Incorporate objects into gear that: simulate the acoustic target strength of odontocete-depredated catch, simulate the target strength of species that odontocetes avoid depredating, are perceived as unusual prey, or interfere with echolocation.	?	?	?	?	?	?	?	?	Minimize	N	Y	Deveau and McPherson, 2011; O'Connell et al., 2015; FAO, 2018a
	—	—	—	—	—	—	—	—	NA			
Passive acoustic monitoring: For real-time spatial avoidance – use hydrophones (array, vessel-based) to detect odontocete presence	?	—	—	—	—	—	—	—	Minimize	N	N	McPherson et al., 2004; Thode et al., 2016
	—	—	—	—	—	—	—	—	NA			

Method	Cetaceans	Turtles, hard-shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Chemical repellants: Bait or gear with an added compound that is a taste or olfactory deterrent	?	—	—	?	—	?	?	—	Minimize	N	Y	Gearin et al., 1988; Gilman et al., 2006; Southwood et al., 2007; Swimmer et al., 2007; Hamer et al., 2012; Garagouni et al., 2022
	—	—	—	—	—	—	—	—	NA			
MARINE TURTLES												
Hook shape: Circle hooks in place of J-shaped hooks of the same size (minimum width) and with ≤10 degree offset	▲	—	▲	▲	—	▼	▼	V	Minimize	Y	N	Clarke et al., 2014; Gilman et al., 2016b; Gilman and Huang, 2017; Reinhardt et al., 2018; Swimmer et al., 2017; Santos et al., 2023
	—	▲	▲	—	—	▲	▲	▲	Remediate			
Hook minimum width: Use wider hooks. Hook size affects species and size selectivity within species (for species that tend to be caught by ingesting a baited hook, hooks with a larger minimum width reduce the relative catchability of smaller species and of smaller length classes within a species), and affects anatomical hooking position and resulting pre-catch, at-vessel, post-release and possibly ghost fishing mortality rates. Hook minimum width can be increased by using larger sized hooks as well as by adding an appendage such as a wire or length of plastic to the hook.	—	▲	▲	▲	V[3]	V	V	V	Minimize	Y	N	Sumpton et al., 2011; Clarke et al., 2014; Gilman et al., 2016b, 2018; Gilman and Huang, 2017; Swimmer et al., 2011, 2017; Santos et al., 2023
	▼	▲	▲	—	—	—	—	—	Remediate			

Method	Cetaceans	Turtles, hard-shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Hook shape and width: Wider circle v. narrower J-shaped hook	▲	▲	▲	▲	V[3]	▼	▼	V	Minimize	Y	N	Favaro and Cote, 2015; Gilman et al., 2016b, 2018; Reinhardt et al., 2018; Santos et al., 2023
	▼	▲	▲	—	—	▲	▲	▲	Remediate			
Bait type: Forage fish bait instead of squid bait	?	▲	▲	?	▲[3]	▲	▲	V	Minimize	Y	N	Gilman et al., 2020b; Lucas and Berggren, 2022; Santos et al., 2023
	?	?	?	—	—	▼	▼	?	Remediate			
Deeper fishing: Deeper (all hooks soak >100m) daytime fishing as compared to shallower nighttime fishing (some or all hooks soak < 100m)	▲	▲	▲	▲	▼[4]	▲	▼	V	Minimize	Y	N	Polovina et al., 2003; Ward et al., 2004; Beverly et al., 2009; Musyl et al., 2003, 2011; Monaghan et al., 2024
	?	▼	▼	?	▼	▼	▲	V	NA			
Deeper fishing: Depth of shallowest hook >100 m[5]	▲	▲	▲	▲	—	▲	—	V	Minimize	Y	Y	
	—	—	—	—	—	—	—	—	NA			
Ban lightsticks	▲	▲	▲	—	?	?	▲	V[6]	Minimize	Y	N	Hazin et al., 2002; Murray and Griggs, 2003; Poisson et al., 2010; Afonso et al., 2021; Monaghan et al., 2024
	—	—	—	—	—	—	—	—	NA			
Light emitting device characteristics: Light emitting devices that have wavelengths and a flicker rate that reduce detection by marine turtles	—	—	▲	?	—	?	?	?	Minimize	Y	N	Swimmer and Brill, 2006; Crognale et al., 2008
	—	—	—	—	—	—	—	—	NA			
Branchline and floatline relative lengths: Branchline longer than floatline	—	▲	▲	—	—	—	—	—	Minimize	Y	N	Gilman et al., 2006
	—	—	—	—	—	—	—	—	NA			
Floatline material: Monofilament nylon (polyamide) instead of polypropylene float lines	—	—	—	—	—	—	—	—	NA	Y	N	Hall, 2008
	—	▲	▲	—	?	—	—	—	Remediate			
Bait threading: Single baited instead of threaded bait on hook (and see entry under Seabirds	?	▲	?	?	?	?	?	▲	Minimize	Y	Y	Stokes et al., 2011; Richards et

Method	Cetaceans	Turtles, hard-shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
on anatomical location of hooking bait)	—	—	—	—	—	—	—	—	NA			al., 2012; Gilman et al., 2016b
SEABIRDS												
Branchline weights of a high mass attached close to, adjacent to or incorporated into the hook to reduce seabird catch risk (where the latter 2 designs can reduce catch rates of fishes and possibly other groups). This includes conventional lead-centered swivels crimped in place and sliding weights (e.g., SafeLead, Lumo Lead, GloLead).	?	?	?	?	▲	▲	▲	V	Minimize	Y	N	Robertson et al., 2013; Melvin et al., 2013, 2014; Rollinson et al., 2016; Jimenez et al., 2019; Santos et al., 2019; Gilman et al., 2022c; ACAP, 2023;
	—	—	—	—	—	—	—	—	NA			
Night setting and shallow-set fishing	?	▼	▼	▼	▲[4]	▼	▲	V	Minimize	Y	N	WPRFMC, 2019; Jimenez et al., 2020; ACAP, 2023; Gilman et al., 2023c
	—	▲	▲	—	▲	▲	▲	V	Remediate			
Night setting and deep-set fishing	?	▲	▲	▲	▲[4]	▲	▼	V	Minimize	Y	N	WPRFMC, 2019; Jimenez et al., 2020; ACAP, 2023; Gilman et al., 2023c
	—	▼	▼	—	▼	▼	▼	V	Remediate			
Tori (streamer) line: Single and paired	—	—	—	—	▲	—	—	—	Minimize	Y	Y	Yokota et al., 2011; Melvin et al., 2013; Sato et al., 2016; Jimenez et al., 2020; ACAP, 2023
	—	—	—	—	—	—	—	—	NA			
Hook shielding devices: Such as the HookPod and Smart Tuna Hook	—	?	?	—	▲	—	—	—	Minimize	Y	Y	Baker et al., 2016; Sullivan et al., 2012, 2018; Goad et al., 2019; ACAP, 2023
	—	—	—	—	—	—	—	—	NA			

Method	Cet-aceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Side setting: Side setting entails deploying baited hooks forward and adjacent to the side of the vessel hull instead of setting branchlines from the conventional position at the vessel stern. As with the mechanism for tori streamer lines to reduce seabird capture rates, seabirds may be unable or unwilling to forage for baited hooks near the vessel hull. By the time the vessel stern passes the side-set baited hooks, the hook might have sunk to a depth below which birds can detect or access them. Used in a Hawaii-based fishery and trialed in a Japan fishery, the efficacy of side setting has been assessed only in the north Pacific Ocean (however, the concept was identified by Nigel Brothers from observing Australian vessels that conventionally side set).	—	—	—	—	▲	—	—	—	Minimize	Y	Y	Yokota and Kiyota, 2006; Gilman et al., 2007, 2008b, 2016a
	—	—	—	—	—	—	—	—	NA			
Underwater bait setting devices: Set or release baited hooks at depth (one commercially available design might require longer-duration trials to determine if problems with malfunctions and performance inconsistencies have been adequately resolved)	—	—	—	—	▲	—	—	—	Minimize	N	Y	Brothers et al., 2000; O'Toole and Molloy, 2000; Sakai et al., 2004; Baker and Wise, 2005; Gilman et al., 2003, 2007; Robertson et al., 2015, 2018
	—	—	—	—	—	—	—	—	NA			

Method	Cetaceans	Turtles, hard-shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Blue-dyed bait: Blue-dyed bait might be more difficult for seabirds foraging from above to see due to reduced contrast between the blue-dyed bait and seawater. Alternatively or in addition, the color of the dyed bait might cause an aversion response by seabirds because they might be less likely to recognize it as a prey item. Factors that determine whether dyed bait will have reduced contrast to the sea surface include bait type, the amount of dye absorbed by the bait, sea color, and ambient light levels. Squid soaks up dye better than fish species with scales, and loss of dyed fish scales also reduces efficacy, and therefore the size of the effect of this treatment on seabird catch rates very likely varies by bait type. Completely thawed bait soaks up dye better than frozen and partially thawed bait, and the longer the bait soaks, the more dye it will soak up, until some threshold is reached.	?	—	?	?	▲	—	—	—[7]	Minimize	Y	Y	McNamara et al., 1999; Boggs, 2001; Minami and Kiyota, 2004; Lydon and Starr, 2005; Swimmer et al., 2005; Cockling et al., 2008; Yokota et al., 2009; Ochi et al., 2011; Piovano et al., 2013; Gilman et al., 2007, 2016a, 2021
	—	—	—	—	—	—	—	—	NA			
Ban live bait	?	?	?	?	▲	?	?	?	Minimize	Y	N	Trebilco et al., 2010; Gilman et al., 2020b
	—	—	—	—	—	—	—	—	NA			
Bird curtain: Pole with streamers deployed during the set or during the gear haulback	—	—	—	—	▲	—	—	—	Minimize	Y	Y	Melvin and Walker, 2008; Gilman et al., 2007, 2016a; Gilman and Musyl, 2017; Pierre, 2018
	—	—	—	—	—	—	—	—	NA			
Do not discharge spent bait, offal, and dead discards during setting and hauling	?	?	?	?	▲	?	?	?	Minimize	Y	N	Cherel et al., 1996; McNamara et
	—	—	—	—	—	—	—	—	NA			

Method	Cet-aceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Discharge spent bait, offal and dead discards during setting and hauling in areas away from where baited hooks are being set or retrieved (understood to decrease seabird catch risk during a single fishing operation but increase catch risk over the long term)	?	?	?	?	▼	?	?	?	Minimize	Y	N	al., 1999; Delord et al., 2005; Gilman et al., 2021
	—	—	—	—	—	—	—	—	NA			
Minimize deck lighting and direct lights inboard during night setting	—	—	—	—	▲	—	—	—	Minimize	Y	Y	ACAP, 2023
	—	—	—	—	—	—	—	—	NA			
Towed buoy: Towing one or more buoy or other objects behind a longline vessel during setting and gear haulback where baited hooks are available to scavenging seabirds may prevent or scare seabirds from entering the area protected by the line and buoy	—	—	—	—	▲	—	—	—	Minimize	Y	Y	Brothers et al., 1999a; McNamara et al., 1999; Goad, 2018; Pierre, 2018
	—	—	—	—	—	—	—	—	NA			
Visual deterrent: Attach a kite or scarecrow-like buoy (with large eyespots and looming movement) above the sea surface to deter seabirds from the area where baited hooks are being set	—	—	—	—	?	—	—	—	Minimize	N	Y	See references in the Gillnet table (**Table 4**)
	—	—	—	—	—	—	—	—	NA			
Branchline length < distance between coiler and stern: To minimize the risk of seabird captures during hauling, avoid having baited hooks trail astern of the vessel by using branchlines of a length that is less than the distance between the stern and the location on deck where the crew stands to coil branchlines into bins (noting that multiple crew may simultaneously coil branchlines)	—	—	—	—	▲	—	—	—	Minimize	Y	Y	Gilman et al., 2014b; Gilman and Musyl, 2017
	—	—	—	—	—	—	—	—	NA			

Method	Cet-aceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Bait casting machine / no setting hooks into propeller turbulence: Cast baited hooks away from the propeller turbulent wash (and under the protection of a tori line if used in combination) by using a hydraulic bait casting machine. Current commercially available bait casting machines, however, do not include settings that enable crew to select the distance or direction of casting, and therefore this method is not currently categorized as having seabird bycatch mitigation efficacy.	—	—	—	—	—	—	—	—	NA	Y	Y	Brothers et al., 1999a; ACAP, 2023
	—	—	—	—	—	—	—	—	NA			
Cast baited hooks outside the turbulent propeller wash	—	—	—	—	▲	—	—	—	Minimize	Y	Y	Brothers et al., 1999a; ACAP, 2023
	—	—	—	—	—	—	—	—	NA			
Bait-swim bladder punctured/species without swim bladders: If species of fish with swim bladders are used for bait, bait with bladders that are not punctured can have a slower sink rate than when punctured	—	—	—	—	▲	—	—	—	Minimize	Y	Y	Brothers et al., 1999a
	—	—	—	—	—	—	—	—	NA			
Branchline automatic coiler: (referred to as a snood puller for demersal longline vessels) Reduce the time for crew to retrieve, coil and store branchlines during gear haulback, reducing the time that baited hooks are accessible to seabirds, and reducing the need for untended lines. (With modern pelagic longline gear, manual coiling into bins may be more efficient and be less likely to result in branchline tangles	—	—	—	—	?	—	—	—	Minimize	N	Y	Brothers et al., 1999a; BirdLife International, 2014; Gilman et al., 2014b; Gilman and Musyl, 2017
	—	—	—	—	—	—	—	—	NA			

Method	Cetaceans	Turtles, hard-shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
during setting than using automatic coilers)												
Bait thaw status: Use fully thawed instead of partially thawed fish bait and use partially thawed instead of fully thawed squid bait to slightly increase the baited hook sink rate (but effect on seabird catch risk when used in combination with branchline weighting is unclear)	–	–	–	–	?	–	–	–	Minimize	Y	Y	Brothers et al., 1995, 1999b; Robertson and van den Hoff, 2010
	–	–	–	–	–	–	–	–	NA			
Bait threading: Bait hooked in the head (fish bait) or tail (fish or squid bait) may have a faster sink rate than when hooked in the mid-back of fish or upper mantle of squid, and possibly faster than a multiple threaded hook (and see entry under marine turtles)	–	–	–	–	▲	–	–	–	Minimize	Y	Y	Robertson and van den Hoff, 2010; ACAP, 2023
	–	–	–	–	–	–	–	–	NA			
Water cannon: Spraying water over the area where baited hooks are being set or retrieved	–	–	–	–	▲	–	–	–	Minimize	N	Y	Brothers et al., 1999a; Kiyota et al., 2001
	–	–	–	–	–	–	–	–	NA			
Oil slick: Deploy shark liver or vegetable oil over the ocean surface area where baited hooks are accessible to seabirds to create an olfactory, taste, chemesthetic or visual deterrent	–	–	–	–	?[8]	–	–	–	Minimize	N	Y	Pierre and Norden, 2005, 2006; Norden and Pierre, 2007
	–	–	–	–	▼[8]	–	–	–	Remediate			
Lasers (There is also a commercially available device manufactured by Mustad and Save Wave, called the Seabird Saver, which uses both a laser and acoustic seabird deterrent, Department of Conservation, 2014)	–	–	–	–	V[9]	–	–	–	Minimize	N	Y	Schrijver, 2014; van Dam et al., 2014; Melvin et al., 2016
	–	–	–	–	▼[9]	–	–	–	Remediate			

SHARKS

Method	Cetaceans	Turtles, hard-shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Leader material: Monofilament leaders only (ban wire and multifilament leaders)	?	?	?	?	?	▲	▲	V	Minimize	Y	N	Ward et al., 2008; Vega and Licandeo, 2009; Clarke et al., 2014; Gilman et al., 2016b; Santos et al., 2023
	?	—	—	—	—	?	?	V	Remediate			
Ban shark lines: Branchlines that fish near the surface, through attachment to floats or floatlines, designed to target epipelagic species, including sharks	—	▲	▲	▲	—	▲	—	V	Minimize	Y	Y	Bromhead et al., 2012; Gilman et al., 2008a, 2016c
	—	—	—	—	—	—	—	—	NA			
Ban lazy lines: Attaching sharks or other unwanted catch to a line off the stern where the catch is temporarily attached during the gear haulback while crew are busy processing target catch, which can also be used to temporarily attach untended branchlines with baited hooks if crew get backlogged with coiling into bins	—	—	—	—	▲	—	—	—	Minimize	Y	Y	McNamara et al., 1999; Beverly et al., 2003; Gilman et al., 2008a
	—	—	—	—	—	▲	▲	—	Remediate			
Long branchlines: To increase at-vessel survival rates of obligate ram-ventilating sharks	—	—	—	—	—	—	—	—	NA	Y	N	Gallagher et al., 2014; Ellis et al., 2017; Musyl and Gilman, 2018
	—	▲	▲	—	—	—	▲	V	Remediate			
Ban shark finning: Prohibit the practice of retaining shark fins and discarding the remaining carcass. This policy might cause live captured sharks with no or little value for their meat and other products other than fins to be released alive and might incentivize the use of fishing methods that reduce shark catchability	—	—	—	—	—	—	—	—	NA	Y	N	Clarke et al., 2013; Worm et al., 2013
	—	—	—	—	—	V	V	—	Remediate			

Method	Cet-aceans	Turtles, hard-shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Artificial bait[10]	?	?	?	?	?	▲	▲	▲	Minimize	N	N	Koyama, 1956; Turudome, 1970; Januma et al., 1999, 2003; Mejuto et al., 2005; Bach et al., 2012; Gilman et al., 2020b; Aalbers et al., 2023
	▬	▬	▬	▬	▬	V	V	▬	NA			
Corrodible hooks and rings (and see **Table 1**, ALDFG)	▬	▬	▬	▬	▬	▬	▬	▬	NA	N	N	McGrath et al., 2011; Begue et al., 2020; Gilman et al., 2022b
	?	?	?	?	?	?	?	?	Remediate			
Repellants: Rare earth electropostive metals; olfactory chemicals such as necromones produced by decomposing shark tissue; and electrical, magnetic, light repellants. Also see the record for Active Acoustic Deterrents under cetaceans.	?	?	?	?	?	?[11]	?[11]	?	Minimize	Y	Y	Myrberg et al., 1978; Stroud et al., 2014; Ryan et al., 2018; Chapuis et al., 2019; Broadhurst and Tolhurst, 2021; Doherty et al., 2022; Poisson et al., 2022; Lucas and Berggren, 2023
	▬	▬	▬	▬	▬	▬	▬	▬	NA			
Remote release of hook: Remote release from the branchline when catch is determined, through a sensor that detects line movement (accelerometer, pressure, magnetometer, temperature) from behavior of the catch while hooked on the line to be an at-risk bycatch species	▬	▬	▬	▬	▬	▬	▬	▬	NA	N	Y	Nieblas et al., 2023
	?	?	?	?	**?**	?	?	?	Remediate			

[1] Mitigation hierarchy tiers:
Avoid = Eliminate the bycatch risk of one or more species or assemblage completely within the scope of the intervention
Minimize = Reduce the bycatch risk of one or more species or assemblage
Remediate = Avoid or reduce fishing mortality risk
Offset = obtain an equivalent gain to replace any residual bycatch fishing mortality, or obtain a net gain

[2] Weak hooks reduced the catch rate of unwanted bluefin tuna (Foster and Bergmann, 2012) but can also reduce catch rates of targeted and incidental commercial species (e.g., bigeye tuna, spearfish) (Bigelow et al., 2012). If required to be employed in combination with more

durable leaders, fishing with weak hooks might increase the catch rates of some shark and teleost species by reducing their ability to sever the line. Assessing compliance with regulations specifying that the branchline and mainline remain taught during a capture event to enable a hook to open requires monitoring with an onboard observer or EM system (Gilman et al., 2022).

[3] Two studies found no significant difference in albatross catch rates between wider circle and narrower J-shaped hooks (Domingo et al. 2012; Gilman et al. 2016a). Two studies observed that wider circle hooks had lower catch rates of primarily gulls (Laridae) and shearwaters (Procellariidae) than narrower J-shaped hooks, (Hata, 2006; Li et al., 2012). This suggests that catch risk response to hook type (size and/or shape), and possibly also for larger baits, may only be important for relatively small seabird species (Gilman et al., 2018). Larger hooks may also have more mass and contribute, slightly, to a faster baited hook sink rate.

[4] Night setting benefits seabird species susceptible to longline capture that forage primarily during the day, and therefore changing from night shallow setting to deep day setting is expected to exacerbate seabird catch rates for several at-risk species. But in some regions, night setting, prescribed in some fisheries to protect albatrosses and other primarily diurnal foraging seabird species, has led to higher bycatch of nocturnal foragers (e.g. northern fulmars Fulmarus glacialis, Melvin et al., 2001a,b). In fisheries where baited hooks fish at or very near the surface, deeper fishing could reduce seabird catch risk.

[5] For example, regulations for the U.S. American Samoa albacore longline fishery require ≥30 m float lines, ≥10 m branchlines, ≥70 m between floatlines and first branchlines, and ≥15 branchlines between two floats to have all hooks fish >100 m to reduce marine turtle catch rates (NMFS, 2011), however the efficacy of the rule has not been assessed. Longer floatlines are not recommended because this reduces the probability that captured marine turtles and other air-breathing species will survive the gear soak.

[6] Lightsticks with certain characteristics increase catch rates of some commercial teleost species such as swordfish and bigeye tuna (Hazin et al., 2002; Murray and Griggs, 2003; Poisson et al., 2010; Anderson et al., 2013; Afonso et al., 2021).

[7] However, see Ochi et al. (2011), which found reduced southern bluefin tuna catch rates with blue-dyed vs. untreated baits. In general, dyeing fish bait to a prescribed blue color might require soaking fully thawed bait in the dye, which can increase fish bait falloff from hooks, and would reduce fishing efficiency across species groups compared to partially thawed fish bait.

[8] Reviewed by WPRFMC (2019), research has been conducted on the effect of dispersing fish and vegetable oils on the sea surface at mitigating seabird bycatch in demersal longline fisheries, finding that efficacy varied by seabird species assemblages (Pierre and Norden, 2005, 2006; Norden and Pierre, 2007). Study periods were too short to test whether habituation to the fish oil occurs. Research has found that exposure to fish oil disrupts feather microstructure, causing the feathers to absorb water and oil, suggesting that seabirds that contact slicks of fish oil will have compromised waterproofing (Morandin and O’Hara, 2014).

[9] Reviewed by WPRFMC (2019) and ACAP (2023), lasers can cause an avoidance response in some seabird species during dark conditions (Schrijver, 2014; van Dam et al., 2014; Melvin et al., 2016). Lasers can cause seabird injury and possibly mortality (ACAP, 2023; Fernandez-Juricic, 2023).

[10] No studies were identified that found an artificial bait to be economically viable for use in pelagic longline fisheries (Gilman et al., 2020b). The objective of using artificial bait is variable, and can include, for example, increasing target species catch rates, reducing bait depredation rates, and reducing catch rates of individual at-risk bycatch species and groups, and thus artificial bait could be included under multiple taxonomic groups.

[11] No study has provided strong evidence of reduced shark catch rates from electrical, magnetic, chemical, lanthanide metal, light emitting or acoustic devices. For example, Doherty et al (2022) found that a battery-powered electrical deterrent device reduced pelagic longline catch rates of sharks (as well as teleosts), but the study design treatments compared only branchlines with and without the electrical deterrent, and did not include a treatment with an inactivated electrical deterrent device, preventing conclusions on the cause of the observed response. The lower catch rates on branchlines with the device might have been caused by the electrical output or possibly because the presence of the device near baited hooks acts as a visual deterrent, as observed in studies on branchline weighting (Rollinson et al., 2016; Jimenez et al., 2019; Gilman et al., 2022c).

Appendix 3. Methods to Mitigate the Catch and Fishing Mortality of At-risk Bycatch Species by Tuna Purse Seine Fisheries

Table 3 is a database of methods to mitigate the catch and fishing mortality of at-risk bycatch species by tuna purse seine fisheries. For each method, the species group-specific effects on catch and fishing mortality risk, compliance monitoring requirements, and whether the method is in broad commercial use are identified. Methods are sorted into taxonomic groups for which they are typically prescribed as a bycatch mitigation approach, and then by mitigation hierarchy tier. For each method, the first row is catch rate response, and the second row is fishing mortality rate response. Catch rate refers to the number or weight of captures per unit of effort. Fishing mortality rate is used here to refer to the proportion of the catch that dies due to the fishery interaction. A catch rate response, particularly for elasmobranch and teleost species, can have variable economic consequences depending on the fishery, individual vessel within a fishery, season, fishing grounds, etc. See ISSF (2012) for a description of tuna purse seine gear components and vessel equipment.

There were no identified methods primarily designed to mitigate the capture or mortality rate of billfishes. See measures listed under other taxonomic groups that affect bycatch of these groups as well as cross-gear type approaches in **Table 1**. Seabird bycatch is not problematic in tuna purse seine fisheries (e.g., see Peatman et al., 2019), and hence seabirds are not included in the table. Billfishes are included as an at-risk bycatch group, where tuna purse seine fisheries capture mainly marlins and sailfish (*Istiophorus platypterus*). Main teleost species captured in tuna purse seine fisheries are not considered to be at risk, and include kawakawa (*Euthynnus affinis*) and other small tuna species, ocean triggerfish (*Canthidermis maculate*), mackerel scad (*Decapterus macarellus*), dolphinfish (*Coryphaena hippurus*), rainbow runner (*Elagatis bipinnulata*) and other carangids, as well as undesirable sizes of target tuna species (Dagorn et al. 2013; Hall and Roman 2013; ISSF 2017b).

Several mitigation methods are not included in **Table 3** that hold promise but currently lack evidence of efficacy at reducing catch or mortality rates of at-risk species. These include: using sorting grids (Nelson, 2007; ISSF, 2010) including manta grids (Murua et al., 2023); using intermittent or continuous lights, including in combination with sorting grids (Kawamoto et al., 2012a,b; Oshima et al., 2019); using chum or bait to attract sharks away from FADs prior to setting (IATTC, 2007; Restrepo et al., 2018); installing shark escape panels (Itano et al., 2012); towing FADs out of the net prior to pursing; and using multiple adjacent or stacked FADs (ISSF, 2010).

***Table 3**. Database of methods to mitigate the catch and fishing mortality of at-risk bycatch species by tuna purse seine fisheries.*

Key

▲ = reduces catch or fishing mortality risk
— = no effect
▼ = increases risk
? = inconclusive/unknown
V = response is variable
O = offset residual bycatch mortalities that could not be avoided, minimized and remediated

Method	Marine mammals	Turtles, hard-shelled	Turtles, leather-back	Rays	Sharks	Billfishes	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
MULTISPECIES										
Free school sets compared to drifting fish aggregating device (FAD) sets, in terms of catch per set[2]	—	▲	▼	▼	▲	▲	Minimize	Y	N[3]	Dagorn et al., 2013; Hall and Roman, 2013; ISSF, 2017b, Peatman et al., 2019
	—	—	—	—	—	—	NA			
Non-entangling drifting FADs compared to entangling and less-entangling designs[4]	—	▲	—	—	▲	—	Minimize	Y	Y	Restrepo et al., 2018; ISSF, 2019; Escalle et al., 2023; Moreno et al., 2023; Murua et al., 2023c
	—	—	—	—	—	—	NA			
Hopper, release ramps, release doors: Use of a hopper, release ramps (slides, from the edge of the hopper tray or brail's edge to the release door), release doors, and stretchers to carry large organisms such as mobulid rays, to the side of the vessel to increase discarding from the top deck and to reduce the time spent handling catch that will be released. And, use of conveyor belts and gutters to release small sharks and other bycatch that accidentally reach the lower deck.	—	—	—	—	—	—	NA	Y	Y	Poisson et 2014a,b, ISSF, 2016; Hutchinson et 2015, 2017; Murua et al., 2021, 2023a,b
	?	▲	▲	▲	▲	—	Remediate			

MARINE MAMMALS

Method	Marine mammals	Turtles, hard-shelled	Turtles, leather-back	Rays	Sharks	Billfishes	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Ban intentional sets on live cetaceans	▲	—	—	—	—	—	Minimize	Y	Y	Escalle et al., 2015, 2016; Gilman et al., 2024
	—	—	—	—	—	—	NA			
Backdown maneuver, ban on night sets: Tilt down the purse seine net at one end to let encircled dolphins escape from the net, for sets made on yellowfin tuna schools associated with a dolphin school. Used in combination with daytime (no later than 30 minutes after sunset) or use of high-intensity floodlights. (Optimal if used in combination with a Medina panel and a speed boat to herd dolphins)	▲	—	—	—	—	—	Minimize	Y	Y	Bratten and Hall, 1996, 1998; Hall et al., 2000, 2003, 2017; Ballance et al., 2021; FAO, 2021
	? [5]	—	—	—	—	—	NA			
Medina dolphin safety panel: A panel of fine mesh netting sewn into the purse seine net to surround the apex of the backdown area, where dolphins are most likely to contact and become entangled in the net	—	—	—	—	—	—	NA	Y	N	Hall, 1998; Ballance et al., 2021; FAO, 2021
	▲	—	—	—	—	—	Remediate			
Rescue divers to release large at-risk bycatch, such as dolphins and mobulid rays, from the net, including during backdown when releasing dolphins (increasing pre-catch survival)	—	—	—	—	—	—	NA	Y	Y	Hall, 1998; Ballance et al., 2021; Murua et al., 2023b
	▲	▲	▲	▲	▲	—	Remediate			
SHARKS										
Ban intentional sets on live whale sharks	—	—	—	—	▲	—	Minimize	N	Y	Escalle et al., 2016; Gilman et al., 2024
	—	—	—	—	—	—	NA			
Reduced depth of drifting FAD appendages (designed to reduce bigeye tuna catch)	—	—	—	—	—	—	Minimize	N	Y	Lennert-Cody et al., 2008; Satoh et al., 2008; Schaefer et al., 2021
	—	—	—	—	—	—	NA			

Method	Marine mammals	Turtles, hard-shelled	Turtles, leather-back	Rays	Sharks	Billfishes	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Reduced depth of the purse seine net (designed to reduce bigeye tuna catch)	?	?	?	?	?	?	Minimize	N	Y	Lennert-Cody et al., 2008
	—	—	—	—	—	—	NA			
Real-time, remote estimates of target and bycatch number or biomass at FADs through acoustic and video discrimination: Use estimates derived from automated real-time machine learning analyses of data from satellite-linked echosounder buoys or of video from satellite-linked cameras attached below a buoy located at a FAD to inform decisions on which drifting FADs sets are to be made, including when the: (1) school biomass exceeds a minimum threshold (e.g., 10 tons), (2) ratio of the weight of at-risk bycatch species to the weight of target species is below a threshold, and (3) number or biomass of at-risk bycatch species is below a threshold	—	—	—	—	▲	▲	Minimize	N	N	Dagorn et al., 2012; ISSF, 2016; Moreno et al., 2019; Mannocci et al., 2021; Forget et al., 2022; Murua et al., 2023b
	—	—	—	—	—	—	NA			
Catch and release sharks from the net using handlines prior to pursing the net	—	—	—	—	V	—	Minimize	N	Y	Restrepo et al., 2018; Hutchinson et al., 2019; Murua et al., 2023b
	—	—	—	—	—	—	NA			
Time of day of setting: Manage the time of day of sets made at FADs to coincide with periods when predominantly target species are present and bycatch species, including sharks and teleosts, are not. May vary by region. Unfortunately, evidence suggests that both silky sharks and target tuna species have similar behaviors in diel attendance at drifting FADs	—	?	—	?	?	?	Minimize	N	N	Forget et al., 2015; Itano et al., 2016; Lopez et al., 2017
	—	—	—	—	—	—	NA			

Method	Marine mammals	Turtles, hard-shelled	Turtles, leather-back	Rays	Sharks	Billfishes	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
(usually make excursions away from FADs at night) in the Indian and Atlantic Oceans. (See **Table 1** for other spatiotemporal control measures)										
Active acoustic deterrents: Acoustic deterrents including acoustic harassment devices and broadcasting killer whale and other predator sounds could be used on instrumented aggregating devices prior to making sets	? ▬	? ▬	? ▬	? ▬	? ▬	? ▬	Minimize NA	N	Y	Myrberg et al., 1978; Chapuis et al., 2019; Lucas and Berggren, 2023
Active acoustic attractants: Broadcast low-frequency sound to attract sharks away from floating objects	? ▬	? ▬	? ▬	? ▬	? ▬	? ▬	Minimize NA	N	Y	Myrberg et al., 1978; Restrepo et al., 2018; Poisson et al., 2022
Repellants attached to FADs and other floating objects. Repellants include: rare earth electropostive metals, chemical/olfactory, electrical, magnetic, light, acoustic harassment devices and other active acoustic deterrents. (Also see Visual Deterrents in the Turtles section)	? ▬	? ▬	? ▬	? ▬	?[6] ▬	? ▬	Minimize NA	N	Y	Myrberg et al., 1978; Ryan et al., 2018; Stroud et al., 2014; Chapuis et al., 2019; Broadhurst and Tolhurst, 2021; Doherty et al., 2022; Poisson et al., 2022; Lucas and Berggren, 2023
RAYS										
Ban intentional sets on live Mobulid rays	▬ ▬	▬ ▬	▬ ▬	▲ ▬	▬ ▬	▬ ▬	Minimize NA	N	Y	Escalle et al., 2016; Gilman et al., 2024
TURTLES										
Remove turtles from net during haulback: Crew on speedboats spot turtles entangled in the net. As the	▬	▬	▬	▬	▬	▬	NA	?	Y	FAO, 2010; Hall and Roman, 2013; ISSF, 2016; Hall et al., 2017

Method	Marine mammals	Turtles, hard-shelled	Turtles, leather-back	Rays	Sharks	Billfishes	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
purse seine net is being retrieved towards the power block, crew on speedboats or on deck halt hauling the net to disentangle and release turtles	—	▲	▲	—	—	—	Remediate			
Visual deterrent: Incorporate shark or other predator shapes (models, silhouettes) into FADs and other floating objects	?	?	?	?	?	?	Minimize	N	Y	See citations in the Gillnet table (**Table 4**)
	—	—	—	—	—	—	NA			
Do not intentionally make a set when a turtle is detected in a school or aggregation	—	▲	▲	—	—	—	Minimize	N	Y	FAO, 2010
	—	—	—	—	—	—	NA			

[1] Mitigation hierarchy tiers:

Avoid = Eliminate the bycatch risk of one or more species or assemblage completely within the scope of the intervention

Minimize = Reduce the bycatch risk of one or more species or assemblage

Remediate = Avoid or reduce fishing mortality risk

Offset = obtain an equivalent gain to replace any residual bycatch fishing mortality, or obtain a net gain

[2] Catch rate comparison is in terms of catch per set and not per unit weight of catch of target tunas. Does not compare other set types, such as other floating objects (anchored FADs; drifting logs; algae; live and dead large marine organisms such as whale sharks, whales and Mobulid rays; and marine debris) and sets on dolphin schools. Different school set types can have substantially different catch compositions but are lumped together here for simplicity. There is large regional variability in purse seine catch rates by set type and taxonomic group, but regions are lumped here for simplicity (Dagorn et al., 2013; Hall and Roman, 2013; ISSF, 2017b, Peatman et al., 2019).

[3] Observer and EM data are primarily used by management authorities to determine set type. However, the catch composition, length data, operational data (Hare et al., 2015; Lennert-Cody et al., 2023) and comparison of VMS and satellite buoy data can also be used to determine set type.

[4] While FADs have been interpreted by some to be a fishing aid and by others to be a component of the fishing gear, sharks, turtles and fishes can be entangled in the appendage and turtles in the netting on the rafts of drifting FADs (FAO, 2018b). While the mortality from entanglement in FADs could be categorized as pre-catch, ghost fishing or catch, the entanglement risk can be eliminated by transitioning from entangling- and less-entangling to non-entangling designs.

[5] There is uncertainty over indirect, collateral effects on dolphins from release from tuna purse seines such as from the stress of repeated chase and capture, and purse seine sets on dolphin schools have been hypothesized to cause miscarriages and separation and loss of calves, however, experiments designed to test these hypotheses have not found supporting evidence (Archer et al., 2004; Edwards, 2006, 2007; Ballance et al., 2021).

[6] No study has provided strong evidence of reduced shark catch rates from use of electrical, magnetic, chemical, lanthanide metal, light emitting or acoustic devices. For example, Doherty et al (2022) found that a battery-powered electrical deterrent device reduced pelagic longline catch rates of sharks (as well as teleosts), but the study design treatments compared only branchlines with and without the electrical deterrent, and did not include a treatment with an inactivated electrical deterrent device, preventing conclusions on the cause of the observed response. The lower catch rates on branchlines with the device might have been caused by the electrical output or possibly due to the presence of the device near baited hooks, as observed in studies on branchline weighting (Rollinson et al., 2016; Jimenez et al., 2019; Gilman et al., 2022c).

Appendix 4. Methods to Mitigate the Catch and Fishing Mortality of At-risk Bycatch Species by Drift Gillnet Fisheries

Table 4 is a database of methods to mitigate the catch and fishing mortality of at-risk bycatch species by drift gillnet fisheries. For each method, the species group-specific effects on catch and fishing mortality risk, compliance monitoring requirements, and whether the method is in broad commercial use are identified. Methods are sorted into taxonomic groups for which they are typically prescribed as a bycatch mitigation approach, and then by mitigation hierarchy tier. For each method, the first row is catch rate response, and the second row is fishing mortality rate response. Catch rate refers to the number or weight of captures per unit of effort. Fishing mortality rate is used here to refer to the proportion of the catch that dies due to the fishery interaction. A catch rate response, particularly for elasmobranch and teleost species, can have variable economic consequences depending on the fishery, individual vessel within a fishery, season, fishing grounds, etc. See FAO (2016) for descriptions of gillnet gear components.

There were no identified methods primarily designed to mitigate the capture or mortality rate of rays or teleosts. See measures listed under other taxonomic groups that affect the bycatch of these groups as well as the cross-gear type approaches listed in **Table 1**.

Table 4. *Database of methods to mitigate the catch and fishing mortality of at-risk bycatch species by drift gillnet fisheries.*

Key

▲ = reduces catch or fishing mortality risk
— = no effect
▼ = increases risk
? = inconclusive/unknown
V = response is variable
O = offset residual bycatch mortalities that could not be avoided, minimized and remediated

Method	Marine mammals	Turtles-hard, shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
MARINE MAMMALS												
Stiffer netting and floatlines: Increase the tension of net webbing and floatlines. Nets are made stiffer by: (a) increasing filament diameter, (b) using a different weave such as multifilament in place of monofilament, (c) using larger/more buoyant floats on the top rope and heavier weights or lead-core on the bottom rope, (d) infusing compounds (e.g., barium sulfate), and (e) lower profile (narrower, reduced vertical height). Increased net stiffness reduces entanglement risk for large organisms, and may reduce the time required for crew to disentangle and release catch	?	▲	▲	▲	—	▲	▲	V	Minimize	Y	Y	Werner et al., 2006; Larsen et al., 2007; Mooney et al., 2007; Price and Van Salisbury, 2007; Thorpe and Frierson, 2009; Gilman et al., 2010; White et al., 2013; FAO, 2018
	▲	▲	▲	▲	—	▲	▲	▲	Remediate			
Active acoustic alert and deterrent devices: Active acoustic devices that alert marine mammals of the presence of the fishing gear, including pingers, and deterrents that broadcast killer whale and other predator sounds	V[2]	?	?	—[3]	—	—[3]	—[3]	—[3]	Minimize	Y	Y	Kraus et al., 1997; Bordino et al., 2002, 2004; Barlow and Cameron, 2003; Hodgson et al., 2007; Doksaeter et al., 2009; Carretta and Barlow, 2011; Dawson et al.,
	—	—	—	—	—	—	—	—	NA			

Method	Marine mammals	Turtles-hard, shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
												2013; Werner et al., 2015; FAO 2018, 2021; Lucas and Berggren, 2023
Active acoustic harassment device: Emit sounds that cause pain or distract pinnipeds and other marine mammal species, using frequencies above the detection thresholds of target fish species.	V	?	?	—	—	—	—	—	Minimize	Y	Y	Long et al., 2015; Lucas and Berggren, 2023; Veneranta et al., 2024
	—	—	—	—	—	—	—	—	NA			
Passive acoustic devices: Designed to increase the acoustic target strength (reflectivity) of the fishing gear in order to increase detection by echolocating cetaceans, such as by incorporating air-filled objects or metallic compounds (e.g., metal oxide nets containing barium sulphate or iron oxide), which may increase reflectivity. Observed reduced catch rates however may be due, in part, to the increased net tension/stiffness and visibility. (See Seabirds, Increased Net Visibility).	?	—	—	—	▲	—	—	—	Minimize	N	Y	Trippel et al., 2003; Mooney et al., 2007; Bordino et al., 2013; Kratzer et al., 2021, 2022
	—	—	—	—	—	—	—	—	NA			
Less durable gear: Weak ropes and webbing made of less durable materials that produce a lower breaking strength can increase escapement rates of large marine megafauna such as baleen whales, and possibly turtles and sharks. Weak links on floatlines located immediately below the float — or possibly using a floatline with a lower breaking strength across the rope or with multiple weak links	▲	?	?	?	—	?	?	?	Minimize	?	N	Gilman et al., 2010; Pace et al., 2014; Knowlton et al., 2018; FAO, 2018, 2021
	—	—	—	—	—	—	—	V	Remediate			

Method	Marine mammals	Turtles-hard, shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
incorporated along the floatline — can reduce baleen whale entanglement												
Reduced vertical lines: Reduce the ratio of the number of vertical lines to units of gear (e.g., number or length of panels, length of strings) to reduce entanglement risk of mysticete whales. (If fishers use wider-diameter floatlines in response to using fewer floatlines, this could increase entanglement risk and adverse effects on entangled whales). Ropeless gear designed for pot gear could also potentially be employed for gillnets, but to date the ropeless gear technology is not yet sufficiently reliable.	?	▬	▬	▬	▬	▬	▬	▬	Minimize	N	Y	FAO, 2018a, 2021; Stevens, 2021
	▬	▬	▬	▬	▬	▬	▬	▬	NA			
TURTLES												
Deeper subsurface fishing (could also be listed as primarily relevant to cetaceans group): Setting gillnets deeper so that the floatline (headline) is set deeper, achieved either by shifting the entire panel deeper or by using lower profile panels. Can reduce vertical depth overlap with some marine mammal species, marine turtles and other epipelagic species, and non-diving and possibly diving seabirds. In some fisheries, deeper driftnets might reduce commercial teleost and squid species catch rates. Shifting panels to fish deeper might increase the haulback	▲	▲	▲	?	▲	▲	▼	V	Minimize	Y	Y	Hayase and Yatsua, 1993; Hembree and Harwood, 1987; Gearhart and Eckert, 2007; Eckert et al., 2008; Price and Van Salisbury, 2007; Gilman et al., 2010; FAO, 2021; Kiszka et al., 2021; Moazzam, 2019, 2022; Rouxel et al., 2023
	▼	▼	▼	▬	▼	?	?	?	Remediate			

Method	Marine mammals	Turtles-hard, shelled	Turtles, leatherback	Rays	Seabirds	Sharks, epipelagic	Sharks, mesopelagic	Teleosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
mortality rate of air-breathing species.												
Illumination: Add lights (chemical lightsticks and LEDs of various wavelengths) to gillnets	▲	▲	▲	▲	▲	▲	▲	V	Minimize	N	Y	Wang et al., 2010, 2013; Ortiz et al., 2016; Virgil et al., 2017; Mangel et al., 2018; Kakai, 2019; Lucchetti et al., 2019; Bielli et al., 2020; Darquea et al., 2020; Gautama et al., 2022; Senko et al., 2022; Snape et al., 2024
	—	—	—	—	—	—	—	—	NA			
Visual deterrent within gear: Incorporate shark or other predator shapes (models, silhouettes) into the gear	?	▲	?	?	?	?	?	▲	Minimize	N	Y	Wang et al., 2010; Bostwick et al., 2014
	—	—	—	—	—	—	—	—	NA			
Mesh size: As mesh size decreases, catchability of large organisms such as sea turtles, marine mammals, and some elasmobranchs and seabirds generally decreases, while catchability of smaller organisms, including in some fisheries juvenile age classes of target fish species, increases. Both maximum and minimum mesh sizes could be regulated to reduce bycatch of larger and smaller sharks.	▲	▲	▲	V	▲	V	V	V	Minimize	Y	N	Dagys and Zydelis 2002; McAuley et al., 2007; Price and Van Salisbury 2007; Murray 2009; Orphanides 2010; Salerno et al. 2010; Northridge et al., 2017; FAO, 2018
	—	—	—	—	—	—	—	—	NA			

Method	Marine mammals	Turtles-hard, shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
No buoys or buoy lines: Gillnet with no buoys/buoy lines, but headlines with floats. Might reduce marine mammal entanglement risk. Might reduce the profile and increase the depth of the headline (see above, deeper headline), reducing vertical overlap with epipelagic species. Might also reduce the gear's acoustic target strength and therefore reduce the catch rate of some echolocating cetacean species such as harbor porpoises by reducing their detection of the gear, but might increase the catch rate of other echolocating cetaceans (see above, passive acoustic devices).	V	▲	▲	V	▲	▲	▼	▼	Minimize	N	N	Peckham et al., 2009; SMRU, 2001; FAO, 2021
	—	—	—	—	—	—	—	—	NA			
SEABIRDS												
Increased net visibility: Blue-dyed metal oxide nets containing barium sulphate; replace transparent nylon netting with a color that is highly visible to at-risk bycatch species (but not target catch), in the upper portion of gillnet panels for seabirds. Luminous vertical lines or flexible rope whiskers in floatlines for marine mammals. (And see Illumination under Turtles)	?	?	?	?	▲[4]	?	?	?	Minimize			Melvin et al.,1999; Trippel et al., 2003; Kot et al., 2012; Kraus et al., 2014; Hanamseth et al., 2017; FAO, 2018; Field et al., 2019
	—	—	—	—	—	—	—	—	NA			
Ban offal discharge during shooting/hauling: Prohibit discharge of offal during shooting and hauling	?	?	?	?	?	?	?	?	Minimize	N	Y	Wiedenfeld et al., 2015; Northridge et al., 2017
	—	—	—	—	—	—	—	—	NA			

Method	Marine mammals	Turtles-hard, shelled	Turtles, leather-back	Rays	Sea-birds	Sharks, epi-pelagic	Sharks, meso-pelagic	Tel-eosts	Mitigation hierarchy tier[1]	Commercial use?	Compliance monitoring requires observers or EM?	Citations
Visual deterrent above the sea surface: Attach a scarecrow-like floating device (with large eyespots and looming movement) or kite above the sea surface and near the gillnet	?	–	–	–	▲	–	–	–	Minimize	N	Y	Almeida et al., 2023; Rouxel et al., 2021, 2023
	–	–	–	–	–	–	–	–	NA			
SHARKS												
Repellants: Includes rare earth electropostive metals, olfactory, electrical, magnetic, and light repellants. (Also see active acoustic deterrents and acoustic reflection under marine mammals).	?	?	?	?	?	?[5]	?[5]	?	Minimize	N	Y	Myrberg et al., 1978; Brill et al., 2009; Jordan et al., 2013; Stroud et al., 2014; FAO, 2018; Ryan et al., 2018; Chapuis et al., 2019; Broadhurst and Tolhurst, 2021; Garagouni et al., 2022; Lucas and Berggren, 2023
	–	–	–	–	–	–	–	–	NA			

[1] Mitigation hierarchy tiers:
Avoid = Eliminate the bycatch risk of one or more species or assemblage completely within the scope of the intervention
Minimize = Reduce the bycatch risk of one or more species or assemblage
Remediate = Avoid or reduce fishing mortality risk
Offset = obtain an equivalent gain to replace any residual bycatch fishing mortality, or obtain a net gain

[2] Pingers with effective designs can reduce catch rates of harbor porpoises and other small cetaceans, but have no effect on some marine mammals (e.g., dugong, North Atlantic right whale, humpback whale), and may attract and increase the catch risk of some species such as bottlenose dolphins and sea lions (Kraus et al., 1997; Bordino *et al.*, 2002, 2004; Barlow and Cameron, 2003; Hodgson et al., 2007; Carretta and Barlow, 2011; Dawson et al., 2013; FAO 2018, 2021). Sea lion attraction might be able to be reduced using a higher pinger frequency (Bordino et al., 2004).

[3] Pingers with effective designs can have no effect on catch rates of commercial teleost species, however, broadcasts of recordings of killer whale calls in addition to reducing some marine mammal species catch rates might also reduce fish catch, including commercial species (Werner et al., 2015; Doksaeter et al., 2009).

[4] Effective in some regions and seabird species, however, see Field et al. (2019).

[5] No study has provided strong evidence of reduced shark catch rates from use of electrical, magnetic, chemical, lanthanide metal, light emitting or acoustic devices. For example, Doherty et al (2022) found that a battery-powered electrical deterrent device reduced pelagic longline catch rates of sharks (as well as teleosts), but the study design treatments compared only branchlines with and without the electrical deterrent, and did not include a treatment with an inactivated electrical deterrent device, preventing conclusions on the cause of the observed response. The lower catch rates on branchlines with the device might have been caused by the electrical output or possibly due to the presence of the device near baited hooks as observed in studies on branchline weighting (Rollinson et al., 2016; Jimenez et al., 2019; Gilman et al., 2022c).

Appendix 5. Draft RFMO Decision or Resolution on Holistic Bycatch Management Strategy Evaluation

The [*name of RFMO*];

Recalling that the United Nations Food and Agriculture Organization (FAO) adopted *International Guidelines on Bycatch Management and Reduction of Discards*, which calls upon States and regional fisheries management organizations and arrangements to be aware of key considerations for effectively implementing an ecosystem approach to fisheries through managing impacts on non-target, associated and dependent species (NADs) or bycatch, and minimizing discards;

Recognizing further that FAO also adopted an *International Plan of Action for the Conservation and Management of Sharks*, an *International Plan of Action for Reducing the Incidental Catch of Seabirds in Longline Fisheries*, and *Guidelines to Reduce Sea Turtle Mortality in Fishing Operations*;

Cognizant that fisheries targeting tuna and tuna-like species and billfishes can adversely affect NADs, particularly those with low maximum per-capita population growth rates, late maturity and other life history traits that make them especially vulnerable to fishing mortality;

Noting that legal instruments establishing international responsibility to conserve NADs first became an obligation under the 1982 Law of the Sea Convention, and it is now well recognized that the mandates and conservation and management measures of regional fisheries management organizations and arrangements are expected to include ecosystem-based management and a precautionary approach in accordance with Article V of the United Nations Fish Stocks Agreement;

Recognizing that assessments of alternative bycatch management strategies should account for key factors, including: multispecies conflicts, strength of evidence of efficacy when employed in real-world conditions, magnitude of effect on species-specific catch and fishing mortality rate, tier in a sequential mitigation hierarchy, costs to components of commercial viability, likelihood of compliance, and commercial availability.

Aware that a fragmented, piecemeal fisheries management system can cause unintended multispecies conflicts, where some measures that are designed to manage the catch or mortality of one NAD species of conservation concern can unintentionally exacerbate the catch or mortality of others;

Concerned that the lack of implementation of holistic, multispecies bycatch management strategy evaluation might be causing multispecies conflicts that are unplanned, with unintended consequences;

Acknowledging that holistically managing the direct and collateral impacts of tuna fisheries on endangered, threatened and other at-risk NADs supports carefully considered, intentional tradeoffs when cross-taxa conflicts cannot be avoided;

Resolves to:

1. Implement holistic, multispecies bycatch management strategy evaluation.

2. Coordinate with other fisheries management organizations and arrangements to establish and maintain a comprehensive global database of bycatch management methods, available through a webtool, where each record of a bycatch mitigation method contains fields on key criteria that inform bycatch management strategy evaluation identified in the subsequent paragraphs.

3. Evaluate and identify conflicts as well as mutual benefits among species and taxonomic groups caused by alternative bycatch management methods. To inform this evaluation, the recommended webtool database will identify the effects of alternative bycatch mitigation methods on taxa-specific catch rates and fishing mortality rates.

4. Identify and account for the relative strength of evidence of efficacy when a bycatch mitigation method is employed in practice. Recognize that evidence from meta-analytic studies ideally should inform the development of global- and regional-level bycatch management strategies. Otherwise, given too few studies to support robust meta-syntheses, decisions should rely on qualitative syntheses of accumulated studies. For bycatch mitigation methods whose efficacy is affected by crew behavior, analyses of observer and electronic monitoring program data may provide more certain estimates of responses during commercial fishing operations relative to estimates derived from experiments. It therefore can be important to validate that the efficacy of an intervention when used under controlled conditions is of similar effectiveness when employed in real-world conditions through “pragmatic” studies.

5. Account for the predicted species-specific size of the effect on catch and fishing mortality rates of at-risk NADs caused by alternative bycatch management methods, including the tier in a sequential mitigation hierarchy (avoid, minimize, remediate, offset), and hence how alternative methods would contribute to meeting bycatch multispecies management objectives.

6. Account for the costs to commercial viability of alternative bycatch mitigation methods, including costs to economic viability, practicality and crew safety.

7. Account for the relative compliance likelihood of alternative bycatch management approaches. This includes assessing whether: (a) A method is expected to achieve voluntary compliance based on costs to commercial viability and degree of change from conventional fishing practices; (b) A method’s efficacy at mitigating the catch or fishing mortality rate of at-risk NADs relies on crew behavior; and (c) The monitoring, control, surveillance and enforcement framework provide for robust surveillance of a particular bycatch mitigation method and incentives fisher compliance with prescribed employment of the method.

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