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Title

The mitigation hierarchy for sharks: a risk-based framework for reconciling trade-offs between shark conservation and fisheries objectives

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Running title

A novel framework for shark management

Abstract

Sharks and their cartilaginous relatives are one of the world's most threatened species groups. The primary cause is overfishing in targeted and bycatch fisheries. Reductions in fishing mortality are needed to halt shark population declines. However, this requires complex fisheries management decisions, which often entail trade-offs between conservation objectives and fisheries objectives. We propose the mitigation hierarchy (MH) - a step-wise precautionary approach for minimising the impacts of human activity on biodiversity - as a novel framework for supporting these management decisions. We outline a holistic conceptual model for risks to sharks in fisheries, which includes biophysical, operational and socio-economic considerations. We then demonstrate how this model, in conjunction with the MH, can support risk-based least-cost shark conservation. Through providing examples from real-world fishery management problems we illustrate how the MH can be applied to a range of species, fisheries and contexts, and explore some of the opportunities and challenges hereto. Finally, we outline next steps for research and implementation. This is important in the context of increasing international regulation of shark fishing and trade, which must lead to reductions in shark mortality, whilst managing trade-offs between conservation objectives and the socio-economic value of fisheries.

Key words: adaptive management, conservation, decision-framework, elasmobranchs, fisheries management, socio-ecological systems

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1. Background

Sharks and their relatives (Class Chondrichthyes, herein ‘sharks’) are one of the world’s most threatened species groups (Dulvy et al., 2014). Overfishing in targeted and bycatch fisheries is the primary cause of shark population declines (Baum et al., 2003; Dulvy et al., 2008). This is driven by international demand for shark-derived commodities, alongside a general expansion of global fisheries with high levels of unmanaged shark catch (Dulvy et al., 2017; Lack & Sant, 2011). Policy complexity, insufficient data, socio-economic concerns and limited political will have maintained a cycle of management inaction for sharks (Barker & Schluessel, 2005; Dulvy et al., 2017; Lack & Sant, 2011). Robust management is urgently required to halt population declines for many species.

There are various international frameworks concerned with improving shark management. Forty-one threatened and commercially important shark species are listed on the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (UNEP-WCMC, 2019), which provides a framework for regulating international trade in shark-derived products. The Food and Agricultural Organisation (FAO)'s International Plan of Action for the Conservation and Management of sharks (IPOA-SHARKS) sets a framework for countries to develop national and regional plans of action for sharks (FAO, 1999), and Regional Fisheries Management Organisations (RFMOs) have also banned retention of several shark species in fisheries. However, for these international policy efforts to drive conservation outcomes for sharks they must translate into significant reductions in shark mortality in fisheries, and eventually population recovery (Bräutigam et al., 2015). This requires comprehensive fisheries management reforms throughout global fisheries.

Fisheries management reforms for sharks need to be adapted to specific country and fishery contexts, so that they are effective at the local level. Yet actions must also be scalable to manage shark mortality at seascape, stock and global levels. This necessitates a framework that can guide a coherent network of coordinated actions across multiple levels. Such a framework needs to incorporate the biological and operational complexities of shark fisheries (i.e. many species, mixed fisheries, multiple jurisdictions, compliance and enforcement challenges; Dulvy et al., 2017), and be capable of handling data paucity and uncertainty. In order to support the design of pragmatic policy, management decision-making should also consider socio-economic factors, budgetary constraints, and inevitable trade-offs between conservation objectives and human needs (e.g. food security, livelihoods, income).

There is a need to think beyond silver-bullet technical solutions and direct regulation for shark conservation, towards creative approaches for feasible fisheries management, which can improve outcomes for sharks and people (Booth, Squires, & Milner-Gulland, 2019; Dulvy et al., 2017; Shiffman & Hammerschlag, 2016a, 2016b). Sharks can also serve as a flagship species for improved fisheries management across the globe.

Acknowledging these challenges and opportunities, this article proposes the mitigation hierarchy (MH) as a framework for holistic, risk-based fisheries management for sharks. The MH is a step-wise precautionary approach to reduce the impact of economic development activities on biodiversity (BBOP, 2012). It has been most commonly been applied to development planning in terrestrial ecosystems, however it has recently been proposed as a framework for least-cost management of marine fisheries and bycatch mitigation (Milner-Gulland et al., 2018; Squires & Garcia, 2018). The MH has also been recommended as a global framework to mitigate all negative impacts of human activity on biodiversity, and implement the goal of No Net Loss (NNL) of biodiversity as part of the Convention on Biological Diversity's Post-2020 Global Biodiversity Framework (Arlidge et al., 2018; IUCN, 2018).

We build on efforts to translate the MH to marine fisheries (Milner-Gulland et al., 2018) and delve in to the practical aspects of its application and operationalization for sharks, a challenging species group in urgent need of better management. We develop a conceptual model for shark fishing mortality, which decomposes risk in to several constituent elements. We propose a process for using the MH to make transparent, goal-oriented, data-driven management decisions for reducing these risks. To illustrate its utility, we explore how the process could be applied to a range of different species and contexts using examples from real-world fisheries. In doing so, we outline how existing shark management measures correspond to different stages of the MH, and how existing knowledge on the effectiveness of these measures can be synthesised to make informed management decisions. We also explore practical challenges in applying the MH to sharks, and offer workable solutions and priorities for future research. Overall, we demonstrate how the MH can help to reconcile trade-offs between shark conservation goals and the important role of fisheries in national economies and coastal livelihoods

2. The mitigation hierarchy for sharks

The mitigation hierarchy (MH) is a risk-based precautionary approach for limiting the negative impacts of human activities on biodiversity (Arlidge et al., 2018). The MH was designed for infrastructure development projects in terrestrial ecosystems with effectively irreversible impacts (e.g., housing developments, roads, plantations). It is increasingly incorporated in to infrastructure planning policy, and is most commonly applied as part of Environmental Impact Assessments (EIAs), which seek to assess the environmental consequences of plans or projects prior to their implementation (Bennett, Gallant, & Ten Kate, 2017).

The MH typically proceeds in four sequential steps: (1) avoid, (2) minimise, (3) remediate and (4) compensate. The first step involves avoiding negative impacts on biodiversity from the outset, such as setting damaging human activities away from biodiversity hotspots or critical habitat. The second step requires that the extent of the negative impacts on biodiversity are minimized whilst the damaging activity occurs. The third step involves remediating negative impacts on biodiversity within the footprint of the damaging activity. The final step requires that any residual negative impacts are compensated for, through off-site conservation actions which improve the status of the affected biodiversity elsewhere (Arlidge et al., 2018; CSBI, 2015; Milner-Gulland et al., 2018). If applied successfully, the MH can lead to no net loss (NNL) of biodiversity or even net gain (BBOP, 2012; Bull, Suttle, Gordon, Singh, & Milner-Gulland, 2013; Gardner et al., 2013; Milner-Gulland et al., 2018; zu Ermgassen et al., 2019). For example, wetland mitigation banks in the United States have shown to successfully achieve no-net-loss of wetland area through protection, restoration or creation of wetlands in compensation for loss caused by development projects (Brown & Lant, 1999; zu Ermgassen et al., 2019).

Recently, the MH has been proposed as a framework for managing marine fisheries and mitigating marine megafauna bycatch (Milner-Gulland et al., 2018; Squires & Garcia, 2018). In traditional fisheries management the MH is not explicitly referred to and EIAs are rarely requested, yet the ethos and process share many similarities (Squires & Garcia, 2018; Squires, Restrepo, Garcia, & Dutton, 2018). Building on these similarities, the MH has already been applied to identify and implement least-cost approaches for sea turtle bycatch mitigation (Squires & Garcia, 2018; Squires et al., 2018). However, there is a need to further empirically demonstrate the utility of the MH for other species and fisheries.

The MH is yet to be applied to shark management. However, risk assessments of the vulnerability of sharks to fisheries are already commonly conducted, such as: Productivity-Susceptibility Analyses (PSAs), Sustainability Assessment for Fishing Effects (SAFE) and Ecological Assessment of the Sustainable Impacts by Fisheries (EASI-Fish) (Griffiths, Kesner-Reyes, Garilao, Duffy, & Román, 2019; Hobday et al., 2007; Zhou & Griffiths, 2008). These methods quantify the relative vulnerability of species to fisheries based on susceptibility and productivity parameters, where susceptibility is based on the risk of a species being captured, and productivity is based on intrinsic life history parameters of the affected species. Derived vulnerability scores quantify the extent to which fisheries exceed the species' biological ability to recover, which are used to prioritise management action and research (Arrizabalaga et al., 2011; Braccini, Gillanders, & Walker, 2006; Cortés et al., 2010; Griffiths et al., 2019; Hobday et al., 2007). These assessments can be seen as analogous to EIAs in terrestrial development projects, and the MH an extension of these widely accepted methods to quantify and manage risk. However, the MH also offers several novel advantages. In particular, it provides a framework for defining measurable goals, and structuring existing knowledge about potential management measures to achieve those goals (Milner-Gulland et al., 2018). This can facilitate transparent science-based management decisions, and highlight data gaps and uncertainties which hinder decision-making. Through least-cost implementation, the MH also enables socio-economic trade-offs to be explicitly factored in to decisions (Squires & Garcia, 2018). The MH also provides room for tailored fishery-specific or location-specific management, which can be combined to achieve net goals over a larger area or jurisdiction. This can encourage creative thinking about management measures and their implementation, and a shift of focus towards proactive creation of net outcomes for biodiversity as opposed to reactive avoidance of losses. The setting of measurables targets from the outset can also support monitoring of progress towards goals, and adaptive management (Milner-Gulland et al., 2018). In this paper we seek to demonstrate these advantages, as well as highlighting some challenges in applying the MH to sharks.

2.1. A conceptual model for risk to sharks in fisheries

Applying the MH to sharks requires an appropriate conceptual model for quantifying fishing mortality and understanding risk. A general model for shark fishing mortality for species X at time t ($F_{X,t}$) can be defined as shark-relevant fishing effort ($E_{X,t}$) multiplied by shark mortality per unit of that effort ($MPUE_{X,t}$; Equation 1, Figure 1).

$$F_{X,t} = E_{X,t} * MPUE_{X,t} \qquad (1)$$

These components can be further decomposed in to several constituent variables (Figure 1). Shark-relevant fishing effort ($E_{X,t}$) is a subset of the overall effort of a fishery (E) that results in volumetric overlap with a population of shark species X within a certain time-period (t). This is a function of the areal overlap of fishing activity with the range of shark species X (P_{Ax}) at time t, and the proportion of effort that will lead to an interaction between the gear and the population of species X (i.e. encounterability) (P_{Ex}; Equation 2, Figure 1).

$$E_{X,t} = E_t * P_{Ax,t} * P_{Ex,t} \qquad (2)$$

Once shark-relevant effort is present for species X, the shark mortality per unit of that effort ($MPUE_X$) depends on the probability of being captured per unit effort ($CPUE_X$) and the probability of mortality once captured (P_{Mx}) (Equation 3, Figure 1). Mortality in fisheries occurs when caught sharks are retained, discarded dead, or discarded alive but suffer post-release mortality (Worm et al., 2013). Collateral mortality also occurs when dead sharks drop out of gears, are depredated after capture, or escape but die later due to exhaustion or injury. The proportion of sharks suffering mortality can therefore be decomposed in to the proportion arriving dead on the vessel (P_{DOAx}), the proportion dying on the vessel (P_{DOVx}), the proportion dying after release (P_{DPRx}) and the proportion dying collaterally (P_{COLx}). Mortality of sharks on the vessel (P_{DOVx}) may be intentional (e.g. due to retention or finning) or unintentional (e.g. due to injury or exhaustion).

$$MPUE_X = CPUE_X \; * \; \overbrace{(P_{DOAx} + P_{DOVx} + P_{DPRx} + P_{COLx})}^{\textit{Post-capture mortality } (P_{Mx})} \qquad (3)$$

The model can be used flexibly to account for targeted and non-targeted shark fishing, or multiple species and scales. For example, for targeted shark fisheries $E_{X,t}$ may be equal to E_t, such that the proportion of fishing effort that overlaps with the range of species X approaches 1. $E_{X,t}$ could also be used for species-complexes in the same area with similar characteristics, or the equation could be extended to sum across multiple species and gear types.

It should be noted that these equations do not represent bio-economic models. Rather we intend to illustrate the different risk factors contributing to shark fishing mortality. In reality these factors are unlikely have an additive, linear relationships, and shark mortality will also be subject to random fluctuations in environmental factors and variation in technical efficiency and skipper skill (Kirkley, Squires, & Strand, 1998).

The components of equations 1-3 are further influenced by a range of direct and indirect factors, which may be operational, biophysical or socio-economic (Table 1). For example, shark-relevant fishing effort, likelihood of capture and likelihood of mortality directly depend on the operational characteristics of a fishery (e.g. fishing ground and gear specifications) the biophysical characteristics of a species (e.g. size, respiratory physiology, locomotor performance), and dynamic interactions between the two (Hobday et al., 2007) (Table 1). Operational factors are determined by active decisions made by fishers and skippers (Figure 2), while biophysical factors are primarily passive (i.e. not actively caused or influenced by fishers). (Table 1). Fisher decisions are in turn driven by indirect factors such as the market and regulatory environment, the perceived legitimacy of regulations, the risk of enforcement, social norms and individual beliefs (Arias, Cinner, Jones, & Pressey, 2015; Barnes, Lynham, Kalberg, & Leung, 2016; Campbell & Cornwell, 2008; Hall et al., 2007) (Figure 2, Table 1). Together, these factors interact and combine to define the overall risk of mortality for a species in a fishery. The primary source of risk will vary for different species and fisheries, while different factors will act at different spatial and temporal scales. A holistic understanding of these different sources of risks, as well as their magnitudes, influenceability, and when and where they can be influenced, will help to identify points of leverage for effective mortality mitigation (Figure 2, Table 1).

2.2 Operationalising the mitigation hierarchy for sharks

A proposed strength of the MH is that it provides a transparent framework for structuring knowledge and monitoring progress towards goals (Milner-Gulland et al., 2018). However, for these benefits to be realised, high-level concepts need to be operationalised in practical terms. User-friendly processes and definitions are required that allow managers to set goals and measurable targets, make informed decisions, and monitor progress. There is also a need for flexibility in order to handle complexity, data paucity and different management priorities.

We expand on the framework by Milner-Gulland et al. (2018) to suggest a process with five key stages: 1) Define the problem, 2) Explore potential management measures, 3) Assess hypothetical effectiveness of management measures, 4) Make decisions, 5) Implement, monitor and adapt (Table 2). This process draws on existing approaches for adaptive fisheries management, including Management Strategy Evaluation (Bunnefeld, Hoshino, & Milner-Gulland, 2011; Fulton, Smith, Smith, & Johnson, 2014) and feasibility assessments (Boo We incorporate the MH in to the process as a framework for structuring knowledge and making decisions.

2.2.1 Defining the problem

2.2.1.1 Preliminary information

Milner-Gulland et al. (2018) start with defining a goal. The goal is the high-level desired change in biodiversity as a result of management. For sharks, the goal will depend on the level of the management unit and the species and fishery(s) of concern. As such, preliminary information on the fishery and species of concern will be required to set reasonable goals and targets. Useful preliminary information includes the species' biological characteristics, the fishery's operational characteristics, the socio-economic context, and constraints such as budget for monitoring, enforcement and implementation (Table 2). This information will help to define the overall mortality risk for a given species-fishery combination, as per equations 1-3 and Table 1. Preliminary information can be collected through a range of methods, including a review of available literature, or primary data collection via on-board observers, landings surveys, socio-economic surveys or key informant interviews (Rigby et al., 2019; Yulianto et al., 2018).

2.2.1.2 Goals

Once background information is clear, a management goal can be set. Goal setting can take place at different scales, from global-, to national-, to fishery-level, or even as a joint goal for RFMOs, shared stocks or the High Seas. The goal can be defined in terms of NNL, net gain, population stability, population recovery, sustainability or simply catch minimization, depending on what is practical given budgetary and operational constraints. For example, a national-level policy goal could be linked to CITES implementation for a species listed on Appendix II, such as silky sharks (*Carchahinus* *falciformis,* Carcharhinidae). The overall goal could be population stability, to avoid utilization of silky sharks that is incompatible with their survival. Another country may seek to restore populations of critically endangered species, such as sawfish (*Pristis spp*., Pristidae), with a goal of net gain or population recovery. Corresponding goals can also be set at finer spatial scales, such as the fishery level. To achieve a national-level goal of silky shark population stability, the goals for all fisheries throughout a national jurisdiction could be no net loss of silky sharks. Alternatively, by thinking in net terms, different goals can be set for different fisheries, acknowledging heterogeneity in fishery impacts, dependence on sharks and adaptive capacity of fishers. For example, vessels taking silky sharks as non-target catch in high-value commercial fisheries could be required to achieve net gain through additional or multiplicative compensatory actions. Small-scale fisheries that are more dependent on silky sharks for income and food security could then be permitted to have a net negative impact on the national silky shark stock, provided the gains and losses across all fisheries combine to achieve net population stability at the national level.

2.2.1.3 Targets

Goals must be operationalised through quantitative targets, for which metrics and baselines can be defined. Expanding on Equation 1, we can develop a general equation for a shark management target where $\Delta_{\lambda T}$ is the target level of net damage inflicted on the species of concern with respect to a baseline (Equation 4).

$$\Delta_{\lambda T} = f\,\underbrace{(M_X) - C_X}_{(E_X * MPUE_X)} \qquad (4)$$

The term $f(M_X)$ is the net damage inflicted by fishing on species X, which is a function of the effort directed at species X and the mortality thus caused. C_X is the net effect of compensatory conservation efforts to improve the viability of the stock or species elsewhere (Milner-Gulland et al., 2018). Milner-Gulland et al. (2018) propose that targets be defined in terms of net change in population growth rate (the metric) with respect to an agreed baseline. A $\Delta_{\lambda T}$ of zero implies no change in population growth rate with respect to the baseline. A positive or negative $\Delta_{\lambda T}$ implies increases or decreases in population growth rate, respectively.

To return to the silky shark example, if the overall goal is population stability a suitable quantitative target could be $\Delta_{\lambda T} \geq 0$, with a static baseline set at zero population growth rate. At fishery levels, a uniform target of $\Delta_{\lambda T} \geq 0$ could also be set across all fisheries. Alternatively, to allow for heterogeneity in fisheries and goals as discussed above, commercial vessels that take silky sharks as non-target catch could be required to achieve $\Delta_{\lambda T} > 0$, while small-scale vessels more dependent on shark catch could be permitted $\Delta_{\lambda T} < 0$, with the net result summing to $\Delta_{\lambda T} \geq 0$. For sawfish recovery, net gain targets ($\Delta_{\lambda T} > 0$) could be set for specific species-fishery combinations, depending on the area of occurrence of different species and the fishery threats.

In theory, once a desired $\Delta_{\lambda T}$ is set, equation 4 can be solved to define acceptable levels of E_X and $MPUE_X$, which could in turn inform effort or catch quotas. Further decomposition of E_X and $MPUE_X$ in to their constituent elements allows identification of management options to achieve to these targets (See Section 2.1.2).

The benefit of adopting targets based on population growth rates is that they focus on the aspirational goal of population health, with a direct relationship between the target and the conservation status of the species. However, such targets require a good understanding of the relationship between population growth rates and mortality. Yet sharks are a data poor group, with limited understanding of population dynamics and fishing mortality for many species (Cashion, Bailly, & Pauly, 2019; Dulvy et al., 2014, 2017). Data paucity is particularly challenging in lower income countries, which represent many of the biggest priorities for management (Momigliano & Harcourt, 2014). As such, targets based on population growth rate may need to be considered the 'gold standard' for data rich, high capacity situations. Simpler targets can be adopted in data poor, lower capacity situations where population models and stock assessments are lacking. Targets could be based on abundance, catch or catch per unit effort, depending on what data is available (Table 3). To return to the silky shark example, the target could be a total catch quota lower than the level required to yield MSY, based on known biological reference points. For sawfish recovery, the target could be based on abundance estimates. Crucially, the target should be quantitative and measurable. In very data poor situations where this is not possible, an aspirational target could be set while more data are collected to inform a revised target (Table 3). Targets can be adjusted over time as the situation changes.

Finally, acknowledging trade-offs and societal limits, some targets may need to be set based on regulatory, cultural and economic constraints. For example, 'minimise mortality of species X whilst maintaining the economic viability of the fishery' or 'minimise mortality of species Y whilst maintaining income of vulnerable fishers'. For these targets, the equation for $\Delta_{\lambda T}$ could be solved by expressing E_X, $MPUE_X$ and C_X as functions of cost, and including budgetary or socio-economic constraints. We discuss this further in Section 2.1.3.

2.2.2 Exploring management measures

Once goals and targets are set, management measures need to be identified and assessed. If the data are adequate, this can be done quantitatively through solving equation 4 and considering the various determinants of M_X and C_X. However, in most cases, the data may be insufficient for a full quantitative assessment.

Existing measures for shark mortality mitigation can be categorised in to the first three steps in the MH: avoid, minimise and remediate, as outlined in Table 4. These steps also correspond to the different sources of fishing mortality risk outlined in equation 1-4 and Table 1, and the different steps in fisher decision-making (Figure 2). Avoidance strategies are measures to reduce the probability of encounter between potentially harmful gear and a potentially (by)-caught individual, by separating fishing activity from individuals or stocks of concern. This can be considered equivalent to a reduction in $E_{X,t}$. Examples of avoidance strategies include, no-fishing zones, depth restrictions or closed seasons (Milner-Gulland et al., 2018, Table 4). To translate avoidance in to a reasonable risk-based definition for sharks, we propose that measures leading to <5% probability of a potentially harmful gear being within 1km of a shark stock of concern (for vessel i, during time t, operating in spatial extent j) are considered avoidance. While measures such as marginal reductions in fishing effort within an area of shark availability are minimization. Using this definition, fishing zonation or closures for avoidance could be defined according to overlap between the spatial and temporal extent of the fishery and accepted habitat distribution maps for the species of concern (Table 4).

Where avoidance is neither feasible nor necessary, minimisation strategies can reduce the probability of sharks being captured, given that shark-relevant effort is present. These measures are equivalent to a reduction in $CPUE_X$. Minimisation strategies can reduce capture of species of concern, while allowing for sustainable exploitation of co-occurring species with healthier populations. Existing fisheries management measures that qualify as minimisation include reductions in effort or technology and gear specifications to reduce capture of particular species and sizes (Table 4). For example, in gill nets, modifications to net size and tension can minimise of susceptibility of certain species and life history stages to meshing and entanglement (Harry et al., 2011; Thorpe & Frierson, 2009). For purse seine vessels fishing on fish aggregation devices (FADs), attractants, deterrents, backdown procedures and FAD design can reduce capture of pelagic sharks (Restrepo et al., 2017) (Table 4).

Remediation strategies facilitate live release of individuals, their safe return to the sea, and their post-release survival (Table 4). Remediation includes pre- and post-haul measures that reduce the probability of mortality, given a shark is captured in a gear. This includes steps to increase pre-haul escape, and increase survival if brought on deck and subsequently released. Remediation is equivalent to reductions in P_{DOA}, P_{DOV}, P_{DPR} and P_{COL}. Examples of pre-haul remediation measures include use of nylon monofilament leaders in pelagic longlines to allow sharks to bite off and escape before haul back (Ward, Lawrence, Darbyshire, & Hindmarsh, 2008), and the use of exclusion devices to allow escape of large sharks and rays from trawls (Brewer et al., 2006) (Table 4). Once on the vessel, post-capture handling such as reducing time out of the water, cutting the line off quickly and close to the hook, and gentle handling, can facilitate post-release survival (Kaplan, Cox, & Kitchell, 2007) (Table 4). Use of circle hooks instead of J are also promote easy hook removal and reduce severity of injury, and corrodible hooks may minimise long-term damage or injury once sharks are released (Cooke & Suski, 2004). Finning bans or retention bans also apply to this category, since they effectively reduce the probability of sharks dying on-board vessels (Table 4).

Finally, compensation occurs to offset unavoidable residual damage to the population once all reasonable measures have been taken to avoid, minimise and remediate. Compensation may be particularly important for high vulnerability, low survivability pelagic species, which are caught in commercially important fisheries that cannot feasibly be closed. To our knowledge compensation has not been applied in a shark management context, though it is used for sea turtle bycatch mitigation. A bycatch tax is levied on tuna processors via the International Seafood Sustainability Foundation (ISSF), which then funds high-priority sea turtle conservation projects in the Atlantic, Indian, Eastern Pacific, and Western and Central Pacific Oceans, including nesting site protection, bycatch and subsistence take reduction in small-scale fisheries, and educational and research (Squires et al., 2018). Interestingly, these compensatory conservation efforts are estimated to have a higher conservation benefit, in terms of turtle population growth rate, per dollar cost than other measures to avoid and minimise capture (Gjertsen, Squires, Dutton, & Eguchi, 2014). A similar mechanism could be adopted for shark mortality mitigation, through bycatch taxes on commercial fisheries which are invested in conservation actions to improve the status of the fishing-affected population elsewhere. For example, payments could be instituted to support the protection and management of pupping and nursery grounds, and reduce take in small-scale fisheries, as has been demonstrated for sea turtles (Gjertsen et al., 2014; Squires et al., 2018). Though in order to be true compensation, the increase in survival probability as a result of compensatory conservation must be at least equivalent to the mortality probability of the harmful gear. To address this uncertainty, high offset multipliers could be applied to bycatch taxes, as has proven to be a key success factor for delivering ecological outcomes in terrestrial applications of compensatory mitigation (zu Ermgassen et al., 2019).

2.2.3 Assessing effectiveness

Once potential management measures have been explored, the hypothetical effectiveness of measures in achieving the target can be analysed. This should include an assessment of technical, biophysical and socio-economic risks (Table 1), and how they can be alleviated.

2.2.3.1 Technical effectiveness

As illustrated in Table 4, different management measures have varying degrees of effectiveness depending on the fishery and species. Assessments of technical effectiveness of can be conducted by estimating quantities for the magnitude of avoidance (reduction in E_X), minimization (reduction in $CPUE_X$), remediation (reduction in $MPUE_X$) and compensation (increase in C_X) that can be achieved for a management measure or combination of measures (Figure 3).

For some species-fisheries combinations, in which habitat, selectivity and survivability studies have been conducted, data will be available to inform a quantitative technical assessment. For example: several studies identify specific geographic areas with higher catch rates for certain species (e.g. Oliver et al., 2015; Yulianto et al., 2018). These data could help to identify priority areas for avoidance, and quantify hypothetical reductions in E_X. Catch and post-haul survival rates have been quantified for several species caught in longlines and gill nets, as well as the impacts of operational variables such as soak time and set depth on these rates (Braccini, Van Rijn, & Frick, 2012; Braccini & Waltrick, 2019; Dapp, Huveneers, Walker, Drew, & Reina, 2016; Gallagher, Orbesen, Hammerschlag, & Serafy, 2014; Gilman et al., 2008). Studies have also quantified the effectiveness of different minimization approaches, such as by-catch reduction devices (BRDs) in prawn trawls (Brewer et al., 2006), and circle- hooks and nylon leader lines in longlines (Gilman et al., 2008; Ward et al., 2008). These figures could be used to quantify the hypothetical effectiveness of these measures in terms of $CPUE_X$ and P_{Mx}.

However, the effectiveness of many existing technical measures is not well quantified. For example, the hypothetical effectiveness of compensation schemes may be particularly difficult to estimate due to a limited understanding of how conservation actions quantitatively influence shark populations, which gives rise to issues related to equivalence, additionality and time lags (Bull et al., 2013). Even for measures that are quantified, the observed or tested efficacy may not always be replicated in practice, or may only apply to the conditions in which they were observed or tested (Campbell & Cornwell, 2008). As such, quantitative assessments of the hypothetical impact of management measure on a target will be challenging, particularly in small-scale fishery and low capacity contexts. In these situations, it may be necessary to elicit expert opinion or fisher knowledge to explore hypothetical effectiveness. Methods such as the IDEA protocol (Hemming et al., 2018), Value of Information Analysis and Bayesian belief networks (Milner-Gulland & Shea, 2017) could be adopted as part of this process. During recommendations and implementation, precautionary multipliers could be applied to technical measures to account for uncertainty. For example, large offset areas relative to impacted areas are key factor in determining successful ecological outcomes in terrestrial biodiversity compensation schemes (zu Ermgassen et al., 2019).

2.2.3.2 Feasibility

The conceptual model and management measures we have presented thus far predominantly focus on the technical factors that influence risk of shark mortality. However, given the socio-economic complexities of shark fisheries, shark management is much more than a biological and technical issue: it is a human issue (Booth et al., 2019). Risk of post-capture mortality (P_{DOV} and P_{DPR}) and choices about fishing locations and gear deployment will depend on the behaviour and decision-making of fishers and skippers (Figure 2). As such, management decisions need to consider the fishery context and constraints, in order to avoid unintended consequences (Baum et al., 2003; Jenkins, 2006; Sarmiento, 2006), unacceptable costs (Campbell & Cornwell, 2008; Gilman et al., 2007; Jaiteh, Loneragan, & Warren, 2017) and implementation failure (Fulton, Smith, Smith, & Van Putten, 2011). Accordingly, potential measures at different steps in the MH need to be assessed in terms of their likely effect on people. Building on previous work on conservation opportunity, conservation likelihood and cost-effective conservation (e.g. Ban, Hansen, Jones, & Vincent, 2009; Dickman, Hinks, Macdonald, Burnham, & Macdonald, 2015; Gjertsen et al., 2014; Knight, Cowling, Difford, & Campbell, 2010) we define these considerations as feasibility (Booth et al., 2019). Explicitly considering feasibility can highlight opportunities and barriers to implementation, as well as identify where novel instruments such as financial incentives and intrinsic motivations may be used to overcome implementation gaps (Booth et al., 2019; Gjertsen et al., 2014; Selinske et al., 2017; Ward-Paige & Worm, 2017).

Our proposed approach to feasibility assessments draws on principles from least-cost conservation, which seeks to achieve desired conservation goals at lowest total cost to society (Gjertsen et al., 2014; Squires & Garcia, 2018; Squires et al., 2018). In this approach, the marginal costs of mitigation measures (MC) are traded-off against the marginal benefits of biodiversity gains (MB). In principle, the economically optimal level of conservation occurs when the MC of each additional unit of mitigation reduction is equal to the MB of biodiversity gains (Figure 4). Though in practice, the benefits of management measures will be based on physical conservation outcomes as opposed to their economic value. For example, if population models are available MB could be measured in terms of estimated increases in shark population growth rates as a result of mitigation measures, as had been used in cost-effectiveness assessments for sea turtles (Gjertsen et al., 2014). Alternatively, estimated reductions in shark mortality as a result of mitigation, such as estimated change in total catch, catch per unit effort or bycatch ratios, could also be used as a measure of the conservation.

benefit. Summing and comparing ratios of MBs to MCs for different management measures can help to identify which measures (and combinations of measures) are most cost-effective. The least-cost approach is powerful, as it acknowledges that most real-world conservation projects take place within socio-economic constraints, and explicitly incorporates trade-offs in to the management decision-making process (Figure 4). In the case of shark fisheries, feasibility can encompass the direct economic costs of implementing a management measure for fishers (e.g. purchasing new gear) and managers (e.g. monitoring, enforcement, compliance management), the opportunity costs of profits foregone (e.g. from lost marketable catch), and the indirect and social costs (e.g. intangible impacts on culture, social networks, livelihood and food security, and well-being). As such, the MC curves illustrated in Figure 4 represent this holistic definition of cost (i.e. feasibility).

As with the technical assessment, quantifying feasibility poses a number of challenges in terms of data availability and uncertainty. We propose a potential approach for assessing and quantifying feasibility in shark fisheries in Booth et al. (2019), which could be applied here. This component of the assessment would need to be informed by social research methods, such as socioeconomic surveys, focus group discussions and predictive conservation approaches (Travers et al., 2019). As with goal and target setting, the methods used for assessing feasibility can be adapted to suit different levels of data availability, capacity and budget. For example, costs could be defined quantitatively in economic terms, based on statistically-robust surveys of household income from shark fishing and market prices of shark products, or more qualitatively, based on fisher perceptions of the likely impacts of management measures on their lives (e.g. using scenario interviews or Likert scale questionnaires).

Feasibility assessments could be operationalised through a least-cost approach by considering catch reduction per unit cost (Gjertsen et al., 2014; Squires & Garcia, 2018) or per unit feasibility (Booth et al., 2019). The equation for $\Delta\lambda_T$ could be solved quantitatively by expressing E_X, $MPUE_X$ and C_X as functions of cost. For example, if the direct and opportunity costs of management measures can be estimated, in terms of income foregone due to reduced catches, then cost curves could be constructed for each unit of conservation benefit (i.e. mortality reduction (Figure 4)). This would also allow for the cost-effectiveness of different management measures to be compared, as conducted for the Pacific Leatherback Turtle (Gjertsen et al., 2014). However, caution should be exercised with quantitative feasibility assessments. The methods used by Gjertsen et al. (2014) consider the overall economic costs to the fishing industry, yet there may be many intangible costs of shark conservation to small-scale fisher communities, which can be highly heterogenous across space, time and demographic groups. A holistic approach to social costs and benefits, which captures the multiple facets of human well-being (Woodhouse et al., 2015) beyond income foregone may be required to ensure that people are no worse off (Booth et al., 2019; Bull, Baker, Griffiths, Jones, & Milner-Gulland, 2018). In principle, these holistic social costs could be calculated using social prices, which are commonly applied in social cost-benefit analyses for development project appraisals, and are calculated on a case-by-case basis to account for economic efficiency as well as equity and distributional concerns (Drèze & Stern, 1990; Little & Mirrlees, 1990; Squires & Vestergaard, 2015). More work is required to apply social prices to a fisheries management context, yet they have been applied to design equitable benefit sharing for deep sea mining, with potential lessons for fisheries management, particularly in high seas fisheries (Lodge, Segerson, & Squires, 2017).

2.2.3.3 Determining thresholds

Combining these two types of analyses would help to explicitly acknowledge trade-offs between shark conservation goals and socio-economic fisheries objectives, and thus define thresholds for feasible mortality reduction. These thresholds are illustrated by the yellow arrows and lines in Figures 3 and 4. Thresholds will be determined by what is technically possible, based on the biology of the species, the operational characteristics of the fishery and available technical measures; and what is feasible, given the socio-economic context and key constraints. Determining thresholds and constraints can identify which management measures are likely to be most impactful and cost effective. In some cases, management measures which are technically possible may be unacceptably costly or unfeasible. These cases may require hard choices or adjusted expectations regarding goals and targets. However, through making socio-economic costs explicit in the planning phase, the MH can help to identify potential causes of implementation failure, and facilitate creative thinking about policies and instruments that could alleviate socio-economic constraints (e.g. training, building institutions or establishing performance-based incentives) (Figure 4).

2.2.4 Making decisions

Finally, all information and options need to be drawn together to make management decisions. Acknowledging the inherent complexity and data paucity of shark management, we propose a simple, low-tech approach for using the MH to make robust management decisions (Table 5). The approach uses an integrated framework based on informed judgement. A simple high-to-low or traffic light categorization system enables semi-quantitative assessments of effectiveness and feasibility, which can be used flexibly to handle multiple types of information and uncertainty. A semi-quantitative assessment is deemed appropriate here, as such approaches are already widely applied to risk and stock assessments for sharks and other fish species (e.g. Braccini et al., 2006; Cortés et al., 2008; Cortés et al., 2010; Arrizabalaga et al., 2011), and in other biological risk assessments (e.g. the IUCN Red List Assessment (Mace et al., 2008); the World Organisation for

Animal Health risk assessment (Beauvais, Zuther, Villeneuve, Kock, & Guitian, 2018)). The framework can be used in conjunction with robust stock assessments and quantitative population models under different management scenarios, or informed by expert elicitation and stakeholder consultation where data is lacking. Populating the framework with available data can also help to highlight key uncertainties and data gaps to inform management-relevant research priorities.

The utility of the framework is illustrated in Table 5. We offer worked examples from four real-world fishery problems: a commercial purse seine tuna fishery taking pelagic sharks as by-catch in Western and Central Pacific Oceans, a small-scale coastal gillnet fishery taking wedgefish (Rhinidae spp.) as valuable secondary catch in Aceh, Indonesia, a small-scale longline fishery taking pelagic sharks as target catch in Lombok, Indonesia and commercial shrimp trawls taking sawfish as bycatch in the Gulf of Mexico, USA. This diversity of examples show how the MH can be used for a range of species and fisheries, in complex socio-economic contexts, and with varying degrees of data availability. For each fishery problem, management options at different levels of the MH are listed sequentially, and assessed in terms of their technical effectiveness and feasibility, based on existing knowledge. For some species-gear combinations the technical effectiveness of different measures can be quantified. For example, for silky sharks caught in tuna purse seines, studies have shown that avoiding purse seine setting on schools of tuna less than 10 tons can reduce amount of silky shark catch by 21%-41%, that at least 21% of silky shark bycatch can be fished out of purse seine nets and released, and that post-release survival of silky sharks in can increase by 20% with good handling (Restrepo et al., 2017). This can be used to quantify or categorise to what degree a given measure could contribute towards achieving the target (Table 5). In addition, the sequential impact of these measures can be summed to estimate an overall technically achievable level of mortality reduction, and how this would contribute towards achieving the management goal. Where information is limited, it may be possible to make informed judgements based on studies for similar species. For example, while we are not aware of any studies on the effectiveness of by-catch reduction devices for sawfish in trawls, Brewer et al. (2006) showed that turtle exclusion devices (TEDs) can be effective at reducing catch rate of large sharks and rays, which could be used as a reasonable proxy of effectiveness sawfish. If appropriate proxies are uncertain or unavailable research priorities can be highlighted (Table 5).

Socio-economic context and practical constraints are explicitly considered through feasibility. This can highlight areas where there are mis-matches between what is technically possible and socio-economically feasible. It can also highlight opportunities where incentives or new institutions could be used, such as bycatch taxes in commercial fisheries or payments for ecosystem services in small-scale fisheries (e.g. Gjertsen et al., 2014; Selinske et al., 2017), to address these mis-matches.

For example, rhinidae species exhibit fairly high post-capture survival rates (Ellis, McCully Phillips, & Poisson, 2017; Fennessy, 1994). This suggests that remediation through post-capture release is technically achievable for wedgefish captured in gillnets. However, in small-scale gillnet fisheries in Indonesia, wedgefish represent high value secondary catch, and play an important role in income and food security. As such, release protocols represent an unacceptable cost to fishers (Table 5). In this case incentives such as payments for ecosystem services and collaborative research could better align conservation objectives with fishers' socio-economic needs. Feasibility can also help to highlight management measures that should not be pursued, since they are ineffective or non-implementable. For example, captured hammerhead sharks (*Sphyrna* spp., Sphyrnidae) exhibit high at-vessel mortality and low post-release survival rates. In addition, in many fisheries, particularly those targeting sharks, there are strong socio-economic incentives to retain them on board due to their high value. As such, post-capture remediation strategies for hammerhead sharks are unlikely to yield meaningful impacts on fishing mortality. Management efforts should instead focus on avoiding and minimising capture as far as possible (Table 5). For targeted shark fisheries this may require measures which shift fishing effort away from hammerhead aggregation sites while allowing for sustainable increases in exploitation of less threatened species such as milk sharks (*Rhizoprionodon acutus,* Carcharhinidae) and blue sharks (*Prionace glauca,* Carcharhinidae).

These various pieces of information can then be drawn together to make an overall assessment and management recommendation, which can include technical measures, policy design and research needs (Table 5).

2.2.5 Implement, monitor and adapt

Once a management decision has been made, measures need to be implemented. This will likely entail a combination of technical measures, with appropriate policies and instruments to facilitate uptake. Alongside this, research and monitoring can fill data gaps and assess progress towards goals. Monitoring will enable continuous updating of models and assessments to verify assumptions and uncertainties and respond to dynamic changes in the socio-ecological system. This can inform changes in management strategies based on updated information (i.e. adaptive management) and progress towards more aspirational and quantifiable targets over time. On-going stakeholder engagement will be crucial throughout to understand the socio-economic impacts of management actions. This can help to ensure people are no worse off as a result of management, and drive change and commitment towards bolder actions (Bull et al., 2018; Hall et al., 2007). In more intractable cases, where trade-offs between social and ecological objectives are acute, the MH approach can support incremental change, with goals becoming more ambitious over time.

3 Conclusions

Many shark species and populations are threatened by overfishing (Dulvy et al., 2008, 2014). Precautionary approaches for mitigating shark fishing mortality are required throughout global fisheries. Yet robust science-based management is hindered by the inherent complexity, uncertainty and data paucity of shark fisheries (Dulvy et al., 2017). A key source of complexity and uncertainty in fisheries management stems from humans (Fulton et al., 2011). There is a need to think more explicitly about the human dimensions of shark fisheries, and the trade-offs between conservation objectives and socio-economic objectives, during management decision-making (Booth et al., 2019)

We have presented a novel process and framework for holistic risk-based shark management which can help to address this gap. It builds on efforts by Milner-Gulland et al. (2018) and Squires and Garcia (2018) to apply the MH to marine fisheries management and by-catch mitigation, as well as previous work by Hall (Hall, 1996; Hall, Alverson, & Metuzals, 2000) and BBOP (2012). The framework draws from existing concepts of risk-based management for sharks (Arrizabalaga et al., 2011; Cortés et al., 2010; Griffiths et al., 2019; Zhou & Griffiths, 2008) and extinction risk assessments (Dulvy et al., 2014), but offers several novel advantages. In particular, the MH encourages thinking in net terms, and summation of different actions across multiple sites and scales to meet higher-level aspirational goals. This can facilitate a move away from one-size-fits all policies for shark conservation, towards context-specific fisheries management. The MH also provides a structured framework to bring together a range of potential management measures. The process we propose enables evaluation of each potential measure, in the context of the whole suite of measures, in terms of their likely combined effectiveness in achieving a management goal. The framework can highlight which measures could have the greatest conservation impact (e.g. Milner-Gulland et al., 2018; Shiode, Hu, Shiga, Yokota, & Tokai, 2005) and the lowest cost (e.g. Gjertsen et al., 2014), thus facilitating practical science-based decision making. With quantitative targets and metrics, the actual effectiveness of management actions can then be monitored to enable adaptive management. The framework is also flexible and user-friendly. It can handle multiple types of information, and can be adapted to different levels of data availability and capacity. Further, by explicitly acknowledging uncertainty, the framework can highlight data gaps and research priorities. Finally, by integrating socio-economic feasibility, the framework explicitly considers trade-offs and constraints. This can facilitate creative thinking about least-cost shark conservation, and identify novel instruments to improve implementation. As for any fisheries management issue, poor regulation, limited capacity for monitoring and enforcement, and limited compliance could hamper implementation. Yet we hope that taking constraints in to account during management planning can better align shark conservation objectives with the socio-economic needs and constraints of fishers, and minimise implementation failure (Fulton et al., 2011; Hall et al., 2007; Squires & Garcia, 2018).

Moving forwards, it will be important to provide a proof of concept for this framework by empirically demonstrating its utility in real-world fisheries, particularly in data-poor situations. This will require an inter-disciplinary approach, which incorporates fisheries science with social science, and considers shark fisheries as integrated socio-ecological systems (Ostrom, 2009). As well as filling data gaps on fundamental biological and fisheries factors to answer management questions, there is a need to better understand the broader socio-economic factors that drive shark fishing behaviour and fisher decisions. This holistic understanding will be crucial for designing management measures that are tailored to context and create better outcomes for sharks and people.

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5 Data Availability Statement

No data have been made available for this manuscript, since no data have been used or analysed in its preparation.

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7 Tables

Table 1. Direct and indirect factors affecting shark mortality at the point of catch

Equation components				**Factors affecting components of fishing mortality**		
				Operational (direct, active)	**Biophysical (passive)**	**Socio-economic (indirect)**
Shark-relevant fishing effort for species x ($Ex_{,t}$)	Areal overlap of fishing activity with shark population ($P_{Ax,t}$).			- Target species - Fishing location	- Geographic range - Season - Climate	- Availability and value of marketable non-shark catch - Economic value and importance of sharks for income or subsistence - Regulations, perceived legitimacy and fairness of regulations, risk of enforcement - Economic costs - Incentives for compliance
	Encounterability. Proportion of effort that will lead to an interaction between gear and shark population ($P_{Ex,t}$).			- Set depth - Gear type and specifications - Soak time	- Maximum depth and depth range - Habitat-type - Habitat use (e.g. site fidelity, schooling)	
Mortality Per Unit Effort (MPUEx)	Number of sharks captured by gear per unit of shark-relevant effort (CPUEx)			- Gear type and specifications - Soak time - Mesh size - Hook size	- Size - Morphology - Locomotor performance	
	Proportion of sharks that die due to capture (P_{Mx})	Proportion arriving dead on vessel (P_{DOAx})		- Soak time - Target species - Gear type, and specifications - Set depth - Post-capture handling	- Morphology - Locomotor performance - Respiratory and metabolic physiology	
		Proportion dying on vessel (P_{DOVx})	Unintentionally			
			Intentionally (due to retention or finning)			

	Proportion dying after release (P_{DPRx})	- Post-capture handling - Gear type and specifications - Hook type	- Locomotor performance - Respiratory and metabolic physiology
	Proportion dying collaterally (P_{DOLx})	- Gear type and specifications - Soak time	- Size - Locomotor performance - Predators

Table 2. A multi-stage process for using the mitigation hierarchy to make science-based management decisions for sharks at the fishery level

Stage in the assessment	Key questions/considerations
1. Define the problem	
1.1. Understand the fishery	Fishery footprint, market-type, target species, targeting of sharks
1.2. Define the species of management concern	Single species, taxonomic group or species complex
1.3. Assess the risks	
1.3.1. Biological (species)	Size, fecundity, biological reference points, extinction risk
1.3.2. Technical (fishery)	Encounterability, catchability and survivability of species in fishery
1.3.3. Socio-economic (context)	Uses and values of sharks, target markets
1.3.4. Constraints (context)	Budget for monitoring, enforcement and implementation. Societal limits on acceptable damage to species or costs to people.
1.4. Set goals and quantitative targets	
1.4.1. Goal	Desired change in biodiversity (e.g. no net loss, net gain, population recovery, mortality minimization, population stability, fishery sustainability).
1.4.2. Target	Quantitative target which operationalises the goal
1.4.3. Metric	Units to measure gains and losses in biodiversity to evaluate progress (e.g. population growth, total mortality, number of animals).
1.4.4. Baseline	Reference point against which progress is assessed.
1.4.5. Counterfactual	Projected change in metric in business-as-usual scenario.
2. Explore management measures	Which management options are available for achieving the target at each step? What data are available for estimating their impact on the target? What are the uncertainties?
2.1. Avoid	Options for avoiding encounters (i.e. reducing E_X)
2.2. Minimise	Options for minimising capture, given E_X is present (i.e. reducing CPUE_X)
2.3. Remediate	Options for minimisng mortality, given sharks are captured (i.e. reducing MPUE_X)
2.4. Compensate	Options to compensate for residual mortality (i.e. increasing C_X)

3. Assess hypothetical effectiveness of management measures	
3.1. Technical assessment	To what degree could management measures reduce risks to the species, based on biophysical and operational factors?
3.2. Feasibility assessment	To what degree could management measures be feasibly implemented, given costs, benefits, social context and resources for implementation? Is there scope for incentives to address gaps?
4. Make a management decision	Which mix of measures and instruments are likely to have the greatest impact?
5. Implement, monitor and adapt	Implement measures and encourage uptake. Monitor progress towards target. Adapt management.

Table 3. Examples of different goals and targets that could be used, depending on the fishery, data availability and capacity.

Key: F_{MSY} = fishing mortality that achieves maximum sustainable yield (MSY). $F_{40\%}$ = fishing mortality at 40% MSY.

Example Fishery	Species of management concern	Data availability	Goal	Target	Methods	Key references
Commercial mixed gear fishery for spiny dogfish in Northwest Atlantic, USA	Spiny dogfish (*Squalus acanthias*)	Very good – population models, life-history and total fishing mortality	Fishery sustainability	Total fishing mortality ≤ F_{MSY}	Define based on stocks and modelled projections of stocks under different fishing mortality rates. Monitor based on catch and mortality data.	Simpfendorfer & Dulvy, 2017; Sosebee & Rago, 2017
Commercial shrimp trawls taking sawfish as bycatch in Gulf of Mexico, USA	Smalltooth sawfish (*Pristis pectinata*)	Good – abundance estimates	Net gain	Abundance increases at 2% per year relative to baseline until 10% increase achieved.	Define and monitor based on estimated abundance from shark tagging studies.	NOAA Fisheries, 2019b
Commercial tuna purse seine taking pelagic sharks as by-catch in Western and Central Pacific Oceans	Silky sharks (*Carcharhinus falciformis*)	Moderate – catch and catch per unit effort time series	Net gain	Total fishing mortality < $F_{40\%}$	Defined based on precautionary biological reference points, monitor based on catch.	Restrepo et al., 2017
Small-scale longlines taking mixed pelagic sharks in Lombok, Indonesia	Scalloped hammerheads (*Sphyrna lewini*)	Moderate – catch and catch per unit effort time series	Population stability	Catch ≤ $F_{40\%}$	Defined based on precautionary biological reference points, monitor based on catch.	Yulianto et al., 2018
Small-scale coastal gill	Wedgefish	Poor – patchy catch	Catch	Total wedgefish catch	Define and monitor based on	M. Ichsan pers

More aspirational. Suitable in data rich and high capacity situations

More pragmatic. Suitable in data poor and limited capacity situations

nets taking wedgefish as secondary catch in Aceh, Indonesia	(*Rhynchobatus* spp.)	data	minimization while maintaining household income of fishers	and bycatch ratio decline by 30%, while maintaining total value of catch.	catch data and fisher interviews.	comm
Artisanal multi-gear fishers taking reef-associated species in Fiji	Reef sharks	Very poor – no catch data	Catch minimization while maintaining food security	Shark catch declines by 10% each year, while maintaining total catch weight.	Define based on fisher interviews, monitor and refine based on catch data.	Glaus et al., 2018

Table 4. Summary of technical measures for managing shark mortality for each steps in the mitigation hierarchy, and examples of their use in existing fisheries management/policy for sharks, where applicable. *Key: LL = Longlines; GN = gill nets, PS = purse seine, TR = trawl. Ex = shark-relevant fishing effort for species X, CPUEx = catch per unit effort of species X,* P_{DOA} *= proportion of sharks dead on arrival,* P_{DOV} *= proportion of sharks dying on vessel,* P_{DPR} *proportion of sharks dying after release,* P_{COL} *proportion of sharks dying collaterally,* C_X *= the positive impact of compensatory conservation measures for species X. FMP = Fisheries Management Plan. FAD = Fish Aggregation Device.)*

Operational fishery variables	**Example effects on sharks** (Applicable gears)	**Examples of use in existing fisheries management plans and policy**	**Key references**
<u>Avoidance:</u> Avoid encounters of sharks with fishing gear, given sharks are present. Equivalent to a reduction in Ex. (Avoid defined as <5% probability of a potentially harmful gear being within <1km of a shark of management concern)			
Spatial location of fishing activity	Spatial trends in catch rates related to habitat preferences, movement patterns and aggregating	No-take MPAs (e.g. Raja Ampat, Indonesia), permanent closures to particular vessels (e.g. shark sanctuaries ban commercial shark fishing), species-specific area-based	Afonso et al., 2011; Bromhead et al., 2012; Gray, Broadhurst,

	behaviour (LL, GN, PS, TR).	management (e.g. time-area closures to protect gummy sharks migrating to pupping grounds in Australia).	Johnson, & Young, 2005; Jaiteh et al., 2016; Oliver, Braccini, Newman, & Harvey, 2015; Poisson, Gaertner, Taquet, Durbec, & Bigelow, 2010; Sepulveda & Aalbers, 2018; Shiffman & Hammerschlag, 2016b; Sybersma, 2015; Ward-Paige & Worm, 2017; Yulianto et al., 2018
Depth of fishing activity	Depth trends in catch rates related to habitat preferences and movement patterns (LL, GN, PS, TR).	-	
Time of year or season of fishing activity	Seasonal time/area closures avoid seasonally migrating or aggregating species (LL, GN, PS, TR).	Direct regulation of fishing seasons (e.g. Canada's Atlantic Fisheries Regulation establishes closed seasons for commercial and recreational shark fishing), time-area closures once catch limits have been met (e.g. shark FMPs for Gulf of Alaska and NW Atlantic & Gulf of Mexico in USA).	
Minimisation: Minimise capture of individuals in fishing gear, given shark-relevant effort is present. Equivalent to a reduction in CPUEx.			
Gear type	Different total catch and bycatch ratios for different gears (LL, GN, PS, TR).	Direct regulation of permitted gear (e.g. coastal GN ban in California in 1994 led to increases in soupfin shark (*Galeus galeus*) and leopard shark (*Triakis semifasciata)* numbers; ban on GN in Florida to minimize capture of smalltooth sawfish (*Pristis pectinata*).	Afonso, Santiago, Hazin, & Hazin, 2012; BMIS, 2015; Brill et al., 2009; Gilman et al., 2008; Gray, Johnson, Broadhurst, & Young, 2005; Harry et al., 2011; NOAA Fisheries, 2019a; Ramírez-Amaro & Galván-Magaña, 2019; Restrepo et al., 2017; Thorpe & Frierson, 2009;
Gear deployment depth	Species-specific effects of fishing depth on catch rate (LL, GN, PS, TR).	-	
Gear deployment time	Species-specific effects of time of day on catch rate (LL).	-	
Bait	Mackerel style bait instead of squid bait reduces bycatch of pelagic sharks (LL).	-	

Attractants/deterrents	Species-specific effects of chemical cues, light cues and magnetic or electropositive metals on gear interactions (LL, GN, PS).	-	Wakefield et al., 2016; Ward et al., 2008; Watson, Epperly, Shah, & Foster, 2005; Yulianto et al., 2018
Mesh size, design and tension	Mesh size and tension influences selectivity for species and life history stage (GN)	-	
Fishing effort	Higher effort (vessels, gears, hook number) leads to higher catch rates (LL, GN, PS, TR).	Direct regulation of fishing effort through limited entry and permits (e.g. U.S. Atlantic Highly Migratory FMP for sharks requires fishers to obtain permits), direct regulation of fishing outputs through quotas and trip limits (e.g. U.S. Atlantic Highly Migratory Species shark fishery has a trip limit of 36 large coastal sharks).	
FAD management	Setting on FADs can cause higher levels of shark catch. Higher levels of collateral mortality associated with entangling FADs (PS).	Regulation of FAD design (e.g. several RFMOs require a transition to non-entangling FADs).	
Tickler chain	Tickler chain on bottom trawls increases catch rate of bottom-dwelling sharks and skates	-	
<u>Remediation:</u> Remediate individuals by ensuring their safe return to the ocean and post-capture survival, given capture has occurred. Includes steps to increase escape if captured, prior to being brought on deck; and increase survival if brought on deck and subsequently released. Equivalent to reductions in P_{DOA}, P_{DOV}, P_{DPR} and P_{COL}.			
Setting depth	Survival rates of some species vary with setting depth (LL, GN).	-	Braccini, Van Rijn, & Frick, 2012; Brewer et al., 2006; Brewer, Rawlinson,
Soak time	Survival rates of some species vary with soak time (LL,	-	

	GN).		Eayrs, & Burridge, 1998; Cooke & Suski, 2004; Dapp, Huveneers, Walker, Drew, & Reina, 2016; Gallagher, Orbesen, Hammerschlag, & Serafy, 2014; Godin, Wimmer, Wang, & Worm, 2013; Kaplan et al., 2007; Kerstetter & Graves, 2006; NOAA Fisheries, 2019; Pacheco et al., 2011; Patterson, Hansen, & Larcombe, 2014; Poisson et al., 2010; Serafy, Orbesen, Snodgrass, Beerkircher, & Walter, 2012; Wakefield et al., 2016
Gear type	Survival rates of some species vary with gear type (LL, GN, PS, TR).	Direct regulation of authorised gears (e.g. Shark FMP for NW Atlantic and Gulf of Mexico establishes gear restrictions to reduce bycatch mortality).	
Hook type	Circle hooks promote easy removal/reduce severity of injury. Corrodible hooks promote ejection and minimise negative impacts of hooks on released individuals (LL)	Direct regulation of hook type (e.g. Shark FMP for NW Atlantic and Gulf of Mexico stipulates that bottom LL vessels must have non-stainless-steel corrodible hooks)	
Leader material	Nylon monofilament leaders can increase bite-off and escape of pelagic sharks (LL)	-	
Exclusion/ escape devices	Exclusion devices reduce capture of large sharks and rays in TR, escape grates reduce capture of spiny dogfish (*Squalus acanthias*) in TR, escape panels may promote release of sharks in PS (PS, TR).	Direct regulation of gear specifications (e.g. All TR nets in Western Australia required bycatch reduction devices)	
Post-capture handling	Reducing time out of the water, cutting the line quickly and close to the hook in LLs, and gentle handling can increase post-capture survival (LL, GN, PS, TR).	Direct regulation of handling procedures or equipment on board to promote safe handling (e.g. Shark FMP for NW Atlantic and Gulf of Mexico stipulates that bottom LL vessels have dehooking device, line-cutters, and dipnet. All TR in Western Australia require onboard in-water sorting systems).	
Retention	Retaining sharks on board for landing and sale causes 100% mortality (LL, GN, PS, TR).	Retention bans, quotas.	
Finning	Removing fins and discarding carcass at sea causes 100% mortality (LL, GN, PS, TR).	Finning bans, fin-to-carcass ratios, or fins naturally attached.	

Compensate: Compensate for residual damage caused through off-site conservation efforts that increase in the probability of another individual in the same stock living to the same age/stage. Equivalent to increases in C_x.			
By-catch tax or fines	Finance off-site conservation efforts within the range of the catch- affected population	International Seafood Sustainability Foundation (ISSF) voluntary by-catch tax to finance sea turtle nesting habitat	Dutton & Squires, 2008; Finkelstein et al., 2008; Gjertsen et al., 2014; ISSF, 2016; Milner-Gulland et al., 2018; Pascoe, Wilcox, & Donlan, 2011; Squires & Garcia, 2018
Payments in kind	Fisher time, resources and knowledge could contribute to monitoring, management and research within the range of the catch- affected population.	-	

Table 5. A simple framework for using the MH to assess the effectiveness of potential measures and make management decisions, with real-world example case study fisheries. Key: A= Avoid, M= Minimise, R= Remediate, C= Compensate. [✓] = low, [✓✓] = moderate, [✓✓✓] = high. [$] = potential for incentives. LL = longline, GN = gillnet, TR = trawl, PS = purse seine, FAD = fish aggregation device, TED = turtle exclusion device. SS = silky sharks, HH = hammerhead sharks, WF = wedgefish, , SW = sawfish.

Example fishery	**Species of concern, management goal and target**	**MH Step**	**Potential measure**	**Technical assessment**		**Feasibility assessment**		**Overall assessment/ management recommendation**
Commercial purse seine tuna fishery taking pelagic sharks as by-	Silky sharks (*Carcharhinus falciformis*) Net gain	A	Spatio-temporal closures	✓✓	Parts of range could be closed to fishing, but species is wide-ranging, circum-global. Critical habitat and impact of closures on mortality unclear.	✓	Direct overlap with target species, closure of large areas of fishing ground not economically viable. Off-shore monitoring and enforcement is costly.	A: Spatio-temporal closures where feasible. M: Species-specific fishing restrictions or low quota, with FAD regulations.

catch in Western and Central Pacific Oceans	(Total fishing mortality < MSY)	M	Escape panel	?	Effectiveness varies – measure needs to be explored.	✓ ✓	Tested in some fisheries, commonly adopted to reduce dolphin bycatch.	R: Best practice live release protocols. Trade interventions to reduce incentives to retain. C: Mandatory on-vessel monitoring. By-catch tax for mortality over and above quota to incentivize good performance and compensate for unavoidable mortality. Needs: Research on effectiveness of escape panel, attractants and post-release survivability, and conservation measures.
			Make fewer sets on FADs, especially with low tuna abundance	✓ ✓	Sets on tuna schools >10 tons can reduce SS catch by 21%-41%	✓ ✓	May lead to loss of target catch by 3-10%.	
			Attract sharks away from FADs	?	50% of sharks can be lured away with bait, though not tested on sets.	✓ ✓	Luring requires time and resources.	
		R	Fish and release sharks	✓ ✓	100% of fished and released sharks survive, though only 21% of those encircled could be fished.	✓ ✓	SS not target species, though are marketable catch. Some incentives to retain. On-vessel monitoring and enforcement is costly.	
			Use best handling and release protocols	✓ ✓	High at-vessel mortality, post-release survival can increase by 20% with good handling.	✓ ✓		
		C	By-catch tax	?	Off-site conservation measures to be assessed.	✓ ✓	Commercial fishery has business risk and resources to pay, but requires costly monitoring. [$]	
Small-scale coastal gillnet fishery taking wedgefish as valuable secondary catch in Aceh, Indonesia	Wedgefish (*Rhynchobatus* spp.) Minimise mortality	A	Spatio-temporal closures	✓ ✓ ✓	Known critical habitat could be closed to fishing.	✓ ✓	WF co-occur with target species, degree of overlap needs to be confirmed.	A: Managed GN use in areas with highest by-catch ratios. M: Restrictions or low quota. R: Live release protocols and improved handling C: Compensation in kind Needs: Performance-based
		M	Mesh size and tension to reduce entanglement, electro-sensory deterrents	?	Species-specific effectiveness to be explored.	✓ ✓	Limited capacity to purchase new gear. Potential impacts on target species need to be understood. [$]	

		R	Live release protocols and improved handling	🟩 ✓ ✓ ✓	WF robust to capture in GN, high survivability.	🟥 ✓	WF high value marketable catch. On-board monitoring of SSFs is challenging and costly [$].	incentives – training and transitional payments to promote safe handling and release. Participatory research in to survivability. Free gear swaps with participatory testing. Trade interventions to reduce value.
		C	Payments in kind	⬜ ?	Fishers could contribute time and knowledge to conservation efforts.	🟧 ✓ ✓	Fishers have limited resources, but may be able to pay in kind.	
Small-scale longline fishery taking pelagic sharks as target catch in Lombok, Indonesia	Scalloped hammerhead sharks (*Sphyrna lewini*) Population stability	A	Spatio-temporal closures	🟧 ✓ ✓	HH co-occur with other target species, though exhibit schooling. Closures may be possible for aggregations.	🟧 ✓ ✓	HHs high value target species, though other species available. Off-shore monitoring and enforcement is costly.	A: Spatio-temporal closures at aggregation sites M: Vessel permits and species-specific catch quotas to reduce E_{HH}. Gear restrictions/modifications to minimize $CPUE_{HH}$. C: Compensation in kind Needs: Performance-based group incentives to reduce mortality, individual awards for exceptional fishers/vessels. Gear swap. Trade interventions to reduce value.
		M	Hook number and setting depth	🟧 ✓ ✓	Hook number and setting depth influences CPUE.	🟧 ✓ ✓	HHs are high value target species, some cultural attachment to fishing gear. [$]	
		R	Live release protocols and improved handling	🟥 ✓	High at-vessel mortality and low post-release survival.	🟥 ✓	HHs are high value, incentives to retain once on board. On-board monitoring and enforcement is costly.	
		C	Payments in kind	⬜ ?	Fishers could contribute time and resources to protecting pupping grounds.	🟧 ✓ ✓	Fishers have limited resources, but may be able to pay in kind	
Commercial shrimp trawls taking sawfish as bycatch in Gulf of	Smalltooth sawfish (*Pristis microdon*) Net gain	A	Spatio-temporal closures	🟩 ✓ ✓ ✓	Critical habitat could be closed to fishing.	🟧 ✓ ✓	Co-occurrence with target species, complete avoidance would close fishery. Enforcement is costly.	A: Spatio-temporal closures where feasible. M: Species-specific prohibitions and gear-based regulations. R: Best practice live release protocols
		M	By-catch reduction devices - TED	🟧 ✓ ✓	TEDs can reduce capture of large sharks and rays by >60%. SW specific effect unclear.	🟧 ✓ ✓	Reduces capture of prawns by 2-12%.	

Mexico, USA		By-catch reduction devices – tickler chain removal	✓ ✓	Removal of tickler chain can increase escape of demersal sharks and rays by ~30%. SW specific effect unclear.	✓	Reduces capture of other commercially valuable/marketable species.	C: By-catch tax or fines for failure to comply. Needs: Mandatory on-board monitoring. Research on effectiveness of TEDs, post-release survivability, and potential conservation measures.
	R	Use best handling and release protocols	?	Post-release survival rates of SW unclear.	✓ ✓ ✓	Prohibited species/non-marketable in USA.	
	C	Fine or by-catch tax	✓ ✓	Funds for critical habitat protection, enforcement and abundance surveys.	✓ ✓	Industry have resources to pay, requires monitoring and enforcement.	

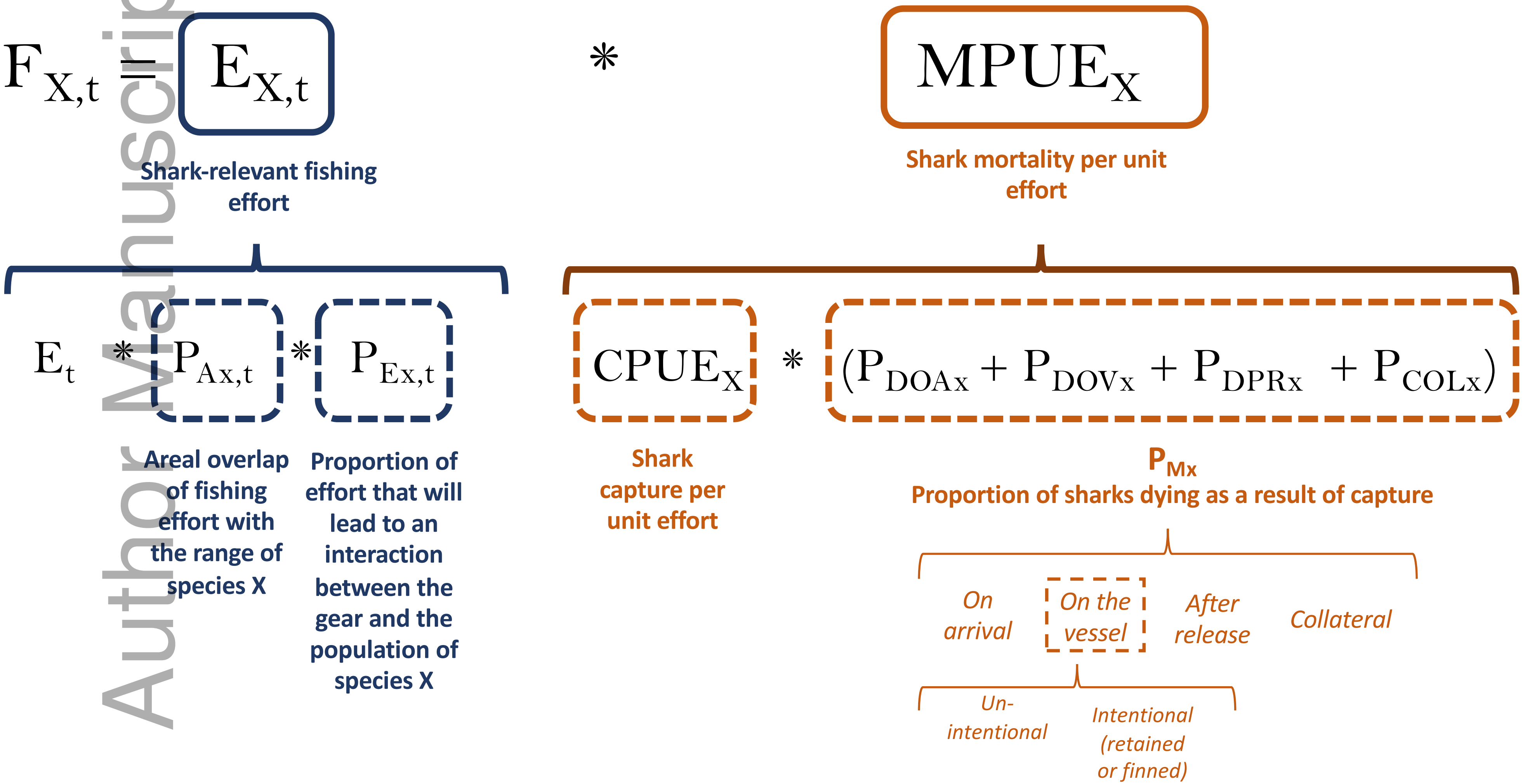
8 Figure legends

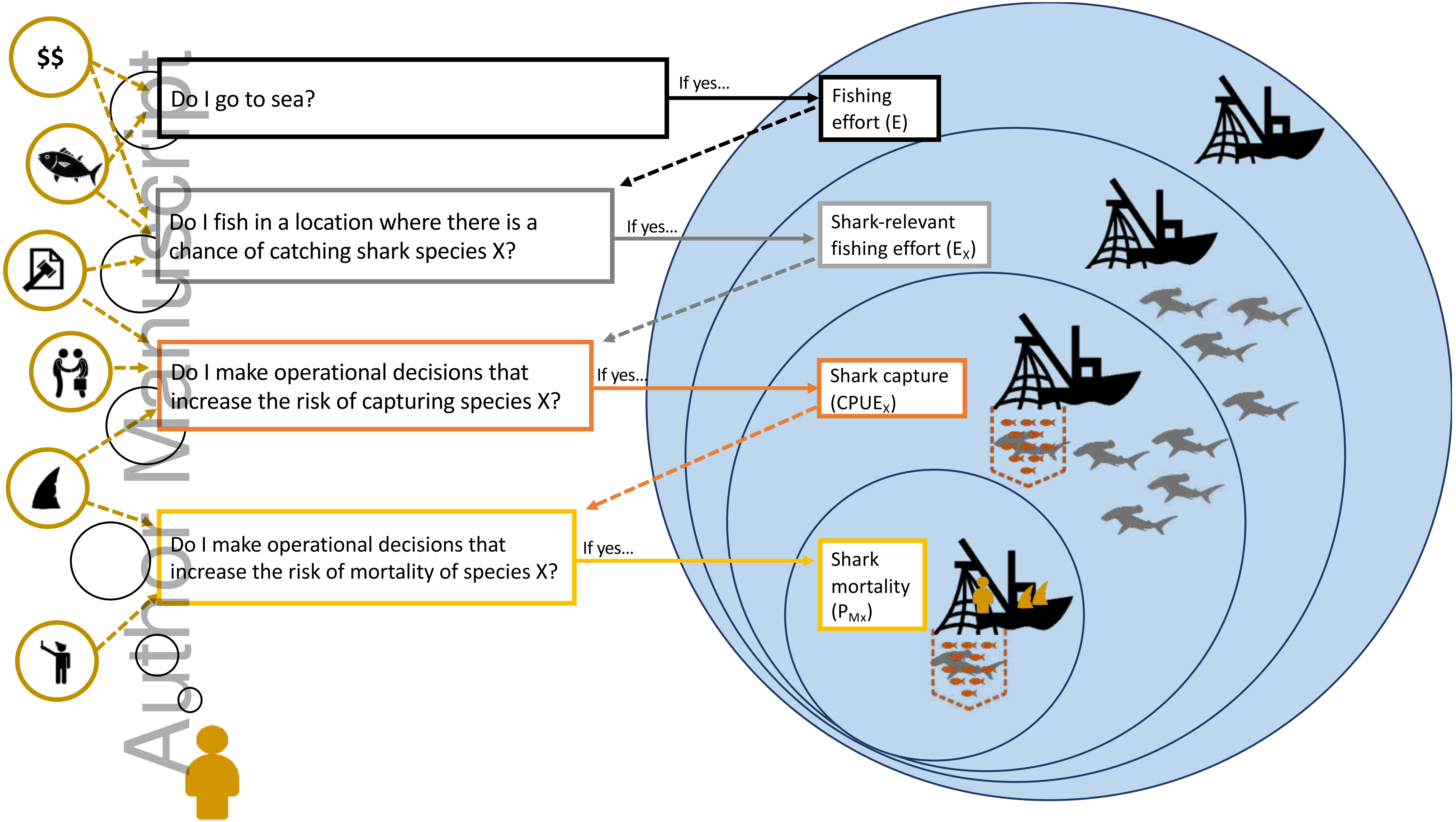
Figure 1. A conceptual model for shark fishing mortality, to decompose risks to sharks in fisheries.

Figure 2. A schematic of the fisher decision-making process that leads to shark mortality. Fisher decisions influence the proximate technical causes of shark mortality, and fisher decisions are in turn influenced by a range of distal socio-economic factors (See Table 1 for factors).

Figure 3. A step-wise decision framework for feasible shark management, based on the mitigation hierarchy (after BBOP (2012)). Thresholds for feasibility at each step will be determined by species- and fishery-specific constraints, including what is technically possible and socio-economically acceptable.

Figure 4. Cost and benefit curves for assessing socio-economic feasibility of management measures at each step in the mitigation hierarchy (after Squires and Garcia (2018)). Solid white lines represent the marginal conservation benefit (MB) of management measures at (i.e. reduction in mortality) at a given step. Dotted white lines represent the full marginal cost (MC) to the fishery (i.e. economic and social) of implementing management measures at a given step. Thresholds for feasibility at each step will be determined by socio-economic constraints. These constraints influence the marginal costs of potential management measures, and the instrument mix required to mitigate costs and achieve a desired management target. For least-cost conservation, the optimal management strategy occurs where the desired conservation benefits are achieved at lowest total cost.


$F_{X,t} = E_{X,t} * MPUE_X$
Shark-relevant fishing effort
Shark mortality per unit effort
$E_t * P_{Ax,t} * P_{Ex,t}$
$CPUE_X * (P_{DOAx} + P_{DOVx} + P_{DPRx} + P_{COLx})$
Areal overlap of fishing effort with the range of species X
Proportion of effort that will lead to an interaction between the gear and the population of species X
Shark capture per unit effort
P_{Mx}
Proportion of sharks dying as a result of capture
On arrival
On the vessel
After release
Collateral
Un-intentional
Intentional (retained or finned)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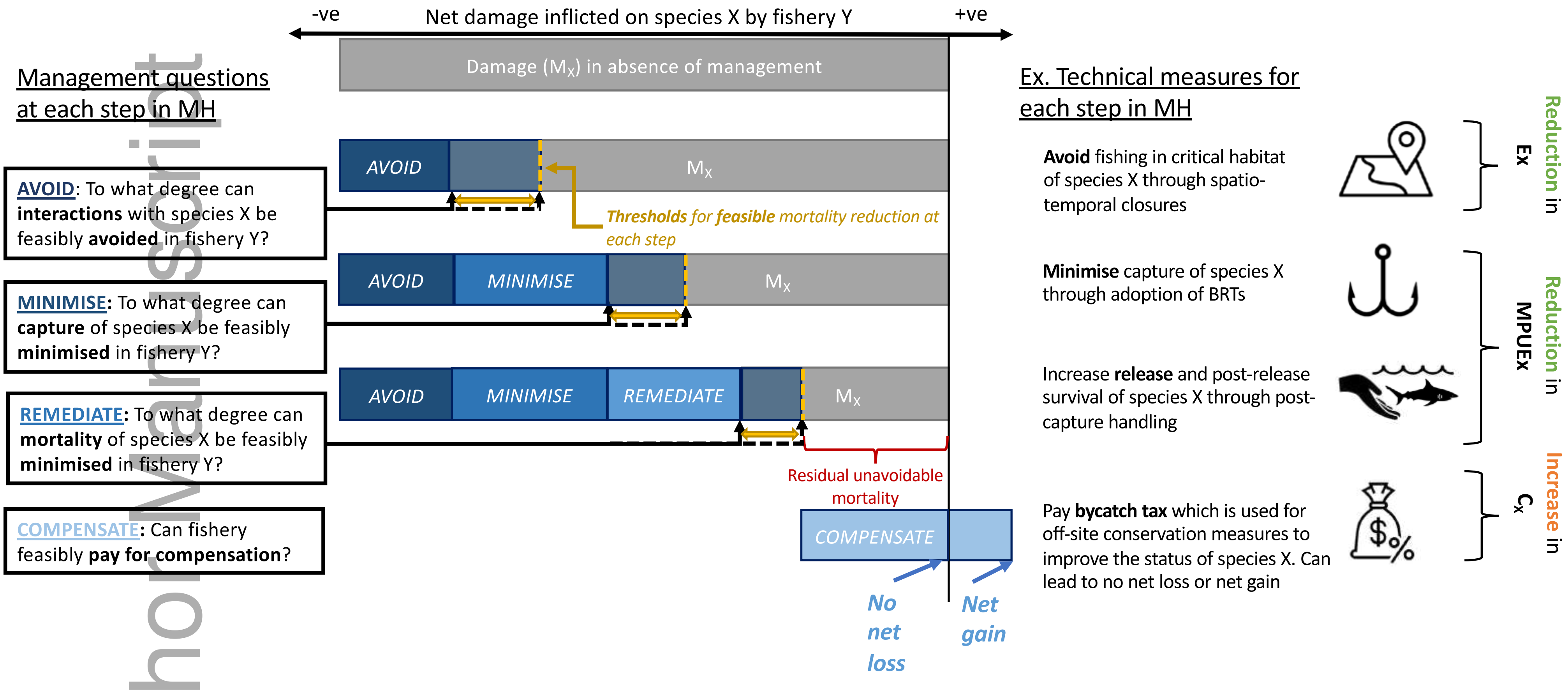
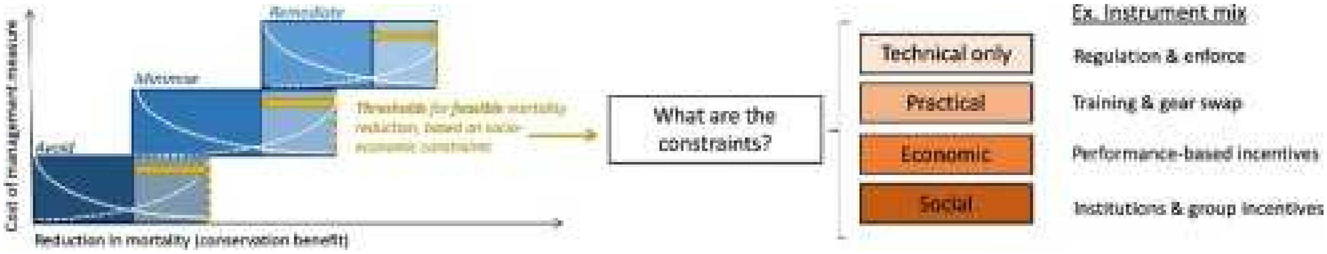
Do I go to sea?
If yes...
Fishing effort (E)
Do I fish in a location where there is a chance of catching shark species X?
If yes...
Shark-relevant fishing effort (E_X)
Do I make operational decisions that increase the risk of capturing species X?
If yes...
Shark capture ($CPUE_X$)
Do I make operational decisions that increase the risk of mortality of species X?
If yes...
Shark mortality (P_{MX})


-ve
Net damage inflicted on species X by fishery Y
+ve
Damage (M_X) in absence of management
Management questions at each step in MH
AVOID: To what degree can interactions with species X be feasibly avoided in fishery Y?
MINIMISE: To what degree can capture of species X be feasibly minimised in fishery Y?
REMEDIATE: To what degree can mortality of species X be feasibly minimised in fishery Y?
COMPENSATE: Can fishery feasibly pay for compensation?
AVOID
M_X
Thresholds for feasible mortality reduction at each step
AVOID
MINIMISE
M_X
AVOID
MINIMISE
REMEDIATE
M_X
Residual unavoidable mortality
COMPENSATE
No net loss
Net gain
Ex. Technical measures for each step in MH
Avoid fishing in critical habitat of species X through spatio-temporal closures
Minimise capture of species X through adoption of BRTs
Increase release and post-release survival of species X through post-capture handling
Pay bycatch tax which is used for off-site conservation measures to improve the status of species X. Can lead to no net loss or net gain
Reduction in
Ex
Reduction in
MPUEx
Increase in
C_x



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