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Translating the terrestrial mitigation hierarchy to marine megafauna by-catch

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Abstract

In terrestrial and coastal systems, the mitigation hierarchy is widely and increasingly used to guide actions to ensure that no net loss of biodiversity ensues from development. We develop a conceptual model which applies this approach to the mitigation of marine megafauna by-catch in fisheries, going from defining an overarching goal with an associated quantitative target, through avoidance, minimization, remediation to offsetting. We demonstrate the framework's utility as a tool for structuring thinking and exposing uncertainties. We draw comparisons between debates ongoing in terrestrial situations and in by-catch mitigation, to show how insights from each could inform the other; these are the hierarchical nature of mitigation, out-of-kind offsets, research as an offset, incentivizing implementation of mitigation measures, societal limits and uncertainty. We explore how economic incentives could be used throughout the hierarchy to improve the achievement of by-catch goals. We conclude by highlighting the importance of clear agreed goals, of thinking beyond single species and individual jurisdictions to account for complex interactions and policy leakage, of taking uncertainty explicitly into account and of thinking creatively about approaches to by-catch mitigation in order to improve outcomes for conservation and fishers. We suggest that the framework set out here could be helpful in supporting efforts to improve by-catch mitigation efforts and highlight the need for a full empirical application to substantiate this.

KEYWORDS
albatrosses, biodiversity offsetting, economic incentives, no net loss, sharks and rays, turtles

1 | INTRODUCTION

The goal of no net loss (NNL) of biodiversity from economic development is becoming widely adopted by national governments and international lenders, potentially offering a method to limit the impacts of environmental damage in terrestrial and coastal systems (BBOP 2012, IFC 2012). Several large multinational companies have signed up to NNL, or even to producing a net gain of biodiversity as a result of their activities (Bull & Brownlie, 2017; Rainey et al., 2015). Generally, NNL is assured by the use of a mitigation hierarchy, often applied as part of an Environmental and Social Impact Assessment (ESIA). The mitigation hierarchy requires that project proponents first avoid doing harm to biodiversity, for example by sitting the development away from particularly sensitive areas. Subsequently, while carrying out their development, they should minimize the harm done, for example by limiting the footprint of heavy machinery to specific areas and not polluting watercourses. They then remediate the biodiversity loss within the development footprint, for example by replanting cleared areas post-development. The final step is to offset any residual additional damage caused by their development through improvement of biodiversity elsewhere (Gardner et al., 2013), using a range of approaches, for example digging new ponds or clearing invasive vegetation in an adjacent site (Bull, Hardy, Moilanen, & Gordon, 2015). Offsetting is a particularly controversial element of the hierarchy because it requires acceptance of a development that harms biodiversity in a given location and assumes that it is possible to compensate for this harm by biodiversity enhancement elsewhere (e.g. Maron et al., 2016). More generally, there is much debate about whether NNL is attainable, and how it should be implemented in practice (most recently explored by Bull, Lloyd, & Strange, 2017).

Despite its growing use in terrestrial and coastal environments, the mitigation hierarchy has not been so widely applied in near-shore and high seas marine settings, and many questions about its application in the ocean remain (Squires & Garcia, in press, UNEP-WCMC 2016). Marine experience to date has mostly concerned coastal development, for example relating to windfarms, urban development, aquaculture and ports, rather than in the capture fisheries arena (e.g. Kyriazi, Lejano, Maes, & Degraer, 2015; Vaissière, Levrel, Pioch, & Carlier, 2014). The four steps of the mitigation hierarchy are discussed in fisheries, however, and as in the terrestrial literature, the option of offsetting is particularly controversial (e.g. the debate around Wilcox & Donlan, 2007 analysis of the potential for offsetting seabird by-catch by invasive species eradication on nesting islands; Finkelstein et al., 2008; Wilcox & Donlan, 2009; Žydelis, Wallace, Gilman, & Werner, 2009). The use of economic incentives to reduce the amount or impact of by-catch has received attention but has also not yet been fully explored (Dutton & Squires, 2008; Gjertsen, Squires, Dutton, & Eguchi, 2014; Innes, Pascoe, Wilcox, Jennings, & Paredes, 2015). The current FAO International Guidelines on Bycatch Management and Reduction of Discards mention economic incentives only briefly (as the only economic instrument) and refer only to incentives to promote innovation in gear technology (FAO 2011). Many questions remain as to whether it is possible to apply the mitigation hierarchy to marine by-catch, and what measures could be used to incentivize action at each stage in the hierarchy. In particular, there is a need for a conceptual framework that integrates the range of by-catch mitigation measures, and the approaches used to incentivize them, in an holistic way.

This article explores application of the mitigation hierarchy to address a specific fishery concern, that of marine megafauna by-catch. We take "marine megafauna" to encompass long-lived species with low reproductive rates which are therefore potentially sensitive to by-catch, for example marine mammals, turtles, seabirds and large fish, while we define by-catch as catch which is not directly targeted (bearing in mind the complexities in definition highlighted by FAO 2011). We limit our discussion to marine megafauna by-catch for manageability of scope, and because this issue is of particular concern within both the conservation and fisheries realms. However, many of the points we raise are applicable to by-catch more broadly. It is also the issue for which discussion of the applicability of NNL and the mitigation hierarchy to marine systems has been particularly active (e.g. following the paper by Wilcox & Donlan, 2007).

First, we outline a conceptual framework for by-catch mitigation, based on the application of a sequential mitigation hierarchy to achieve NNL. We then discuss some key issues that arise in the application of a mitigation hierarchy to marine megafauna by-catch, and relate them to the equivalent debate in the terrestrial setting. We move on to consider how incentives to mitigate the amount or impact of by-catch can be used to support the application of the framework. Finally, we sum up the potential of our framework for improving by-catch mitigation outcomes.

2 | CONCEPTUAL FRAMEWORK FOR BY-CATCH REDUCTION

To clarify how achieving NNL through a mitigation hierarchy would work for marine megafauna by-catch, we present a conceptual framework relating to the target level of by-catch impact in a fishery. The approach can operate at a range of levels from the global to the stock to the individual animal. The most usual, and most intuitive, scale at which NNL could apply to by-catch is at the scale of a fishery, targeting a given stock or set of stocks, so this is the scale we use in this exploration. Table 1 explains the terms we use to describe the conceptual framework.

The approach starts by *defining the goal* in terms of a desired change in biodiversity; this is commonly taken to be NNL of biodiversity but that is not necessarily the only goal. For example, in the terrestrial realm, net gain is a widely used goal (Rainey et al., 2015), while in the marine realm, by-catch minimization is often the policy goal (except for totally protected species), which may imply a net loss or gain in biodiversity, depending on the current by-catch level. Another potential goal could be population recovery (cf the US Endangered Species Act; Wolf, Hartl, Carroll, Neel, & Greenwald, 2015).

TABLE 1 Explanation of terms used in the mitigation hierarchy

Term	Explanation
Goal	The desired change in biodiversity, for example no net loss (NNL) of biodiversity as a result of the combined effect of the damaging action (e.g. by-catch) and associated mitigation measures
Target	In our framework, we distinguish between the overall goal at the policy level (e.g. NNL), and the quantitative target which operationalizes the goal, for which a metric can be defined
Metric	The units used to measure gains and losses in biodiversity, in order to evaluate whether the goal has been achieved. In our case, this is net change in population growth rate of the focal species as a result of by-catch + mitigation measures
Baseline	The reference point against which NNL is assessed. This could be static (e.g. current population growth rate), dynamic (projected population growth rate in the absence of by-catch, but continuation of other processes affecting vital rates), or aspirational (desired change in population growth rate)
Counterfactual	The projected change in population growth rate in the presence of by-catch but absence of mitigation measures, against which NNL is assessed (e.g. business as usual). If the baseline is dynamic, the counterfactual is the same as the baseline; otherwise, both are required to fully define the scenario against which NNL is evaluated

The next step is to define a quantitative *target* and associated *metric* by which the goal will be measured. In the case of by-catch of marine megafauna, one relatively intuitive approach is to define the target as zero net change in population growth rate of the focal species caused as a result of by-catch and associated mitigation measures, in the context of all the other factors influencing that population (as was done, e.g., in the studies reviewed by Lewison, Crowder, Read, & Freeman, 2004). The downside of this metric is its requirement for monitoring data that can provide trends in population size over time, decomposed into vital rates (survival, fecundity) so that the contribution of by-catch and mitigation measures to change in population growth rate can be discerned. This may be challenging for many marine megafauna (Caswell, Brault, Read, & Smith, 1998). Other more readily monitored targets could be based on numbers of animals, for example not exceeding a Potential Biological Removal (PBR) threshold (Richard & Abraham, 2013). The downside of numbers-based metrics is their more indirect relationship with the conservation status of the species concerned.

Using the metric of net change in population growth rate, the *baseline* from which gains and losses from different measures taken to mitigate by-catch are assessed could be: a zero population growth rate such that the population remains stable at the current level (a static baseline); the projected population growth rate of the species in the absence of by-catch, which could be positive or negative depending on the relative importance of by-catch in the context of other threats (a dynamic baseline); or an aspirational baseline, such as population growth at X% per year to the point at which it reaches some desired steady-state abundance (which would need to be dynamic given that populations have density-dependent growth). Such a baseline is therefore a type of *counterfactual*, against which any improvement or deterioration in the population of the by-caught species as a result of the implementation of the mitigation hierarchy is compared (i.e. what would have happened in the absence of the by-catch mitigation measures).

Next, the different approaches which can be used to attain NNL (or whatever goal is set) are assessed in terms of their effect on the chosen metric; for example, the reduction in seabird mortality from fitting tori lines in a fishery can be assessed in terms of its effect on the growth rate of a wandering albatross (*Diomedea exulans*, Diomedeidae) population. The four categories of the terrestrial mitigation hierarchy are avoidance, minimization, remediation (also known as restoration or rebuilding) and offsetting. In the case of marine megafauna by-catch, we take “avoidance” to represent measures taken in order 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 potential megafauna by-catch species (see Table 2 for example actions). We take “minimization” as measures which reduce the probability of capture by the gear given that the encounter cannot be realistically “avoided”. These measures occur once there is spatio-temporal overlap between a fishing vessel and a marine megafauna individual. “Remediation” also occurs at sea, but post-capture, and aims to reduce the probability of mortality given capture. “Offsetting” refers to measures to compensate for by-catch mortality that operate separately from the focal fishing activity, but which target the same stock of the by-caught species.

In reality, there are grey areas between each of these stages, and a range of ways in which by-catch mitigation measures can be categorized. For example, here we include restoration and rebuilding activities at the stock level in “offsetting”, because our framework is structured around individual-level capture probability. However, another approach might be to combine remediation at the individual level in a category with restoration/rebuilding measures that improve population viability at the stock level, such as restocking and habitat improvement, leaving offsetting as measures which benefit

TABLE 2 Examples of measures which can be taken under each step of the mitigation hierarchy

Step of the hierarchy	Example measures
Avoidance	Excluding fishing from the areas (no-fishing zones), seasons (closed seasons) or times of day where these species are most vulnerable
Minimization	Using on-vessel technologies which aim to reduce the number of encountered individuals that are captured during fishing operations, such as tori lines for scaring seabirds away from longlines or sonic devices to signal nets to marine mammals
Remediation	Devices which enable individuals to release themselves from the gear (selectivity grids, turtle excluder devices) or to be released (e.g. Medina panels operated in tuna purse-seine fisheries to let dolphins escape before getting on the deck), or releasing them on deck and providing for a safe return to the sea (e.g. a large mesh soft webbing cargo net can be used to "sieve" a ray from the catch and lift it over the side of the vessel; Francis, 2014)
Offsetting	Eradicating invasive predators on islands where seabirds nest, restoring habitat, restocking with hatchery-raised individuals, improving by-catch performance of other gear types in the area

the stock more indirectly or act at the broader species level (such as restoration in other locations or measures to improve compliance and reduce uncertainty). However, we feel that the clarity of the probabilistic approach in our framework, which extends the classification by Hall (1996), is particularly helpful.

Our division of mitigation approaches into these categories can be represented in the following conceptual model, relating to a particular by-catch species, in which the unit is rate of change in population size as a result of by-catch and its mitigation:

$$\Delta\lambda_T = f\left(E_B \times \text{BPUE}\right) - O_T \tag{1}$$

Here, $\Delta\lambda_T$ is the target level of overall net damage inflicted by by-catch on the species concerned, measured in terms of change in population growth rate with respect to the agreed baseline. A zero $\Delta\lambda_T$ implies that the reduction in population growth rate caused by by-catch, after avoidance and mitigation measures have been implemented, is balanced by the gain engendered by offset measures. There is also the possibility for $\Delta\lambda_T$ to be negative (there is still additional population decline as a result of by-catch, even after measures to reduce it) or positive (equivalent to *net gain*, meaning that species population growth is higher than it would otherwise have been, as a result of the combination of measures taken under the mitigation hierarchy).

$f(E_B \times \text{BPUE})$ is the effect on population growth rate of the by-catch-relevant component of fishing effort, broken down into the by-catch-relevant effort itself, E_B, and the by-catch taken per unit of that effort, BPUE, where $f()$ is the effect of this effort on the by-caught species' population dynamics. This would generally be calculated as the output of a population model. A reduction in E_B is equivalent to a fishery *avoiding* by-catch, partially or completely. It could include restricting the fishery to particular areas or seasons, modification of fishing practices and operations (e.g. setting the gear deeper to avoid depths where by-caught species are prevalent). A reduction in BPUE is the result of the at-sea measures encompassed in the "minimize" and "remediate" steps of the mitigation hierarchy.

By-catch-relevant effort E_B is a subset of the overall fishing effort that occurs in the area in which there is risk of by-catch (E). Given the complexities of estimating E_B, in many cases it will be necessary to approximate it by E (e.g. Tuck, Polacheck, & Bulman, 2003). This may be problematic; for example, Báez et al. (2007) show that loggerhead turtle (*Caretta caretta*, Cheloniidae) by-catch in the Mediterranean was not correlated with fishing effort (measured as number of hooks); by-catch was instead strongly related to distance from the coast. They suggest that this was not because turtle abundance is a function of distance (which would have implied a gradient in E_B), but because fisher behaviour varied, although they left investigation of the mechanisms for further research. BPUE is a function of catchability of the by-caught species as well as E_B; for example, Ward, Lawrence, Darbyshire, and Hindmarsh (2008) carried out a multispecies analysis of the effects of nylon leaders on catch rates and showed that catch reduced with nylon for sharks, blue marlin (*Makaira nigricans*, Istiophoridae) and snake mackerel (*Gempylus serpens*, Gempylidae), and increased for bigeye tuna (*Thunnus obesus*, Scombridae) and black marlin (*Istiompax indica*, Istiophoridae). The relationships between E, E_B and BPUE are likely to be complex and confounded. There have been limited explorations of these relationships in by-catch datasets, which typically suffer from low sample sizes and zero-inflation requiring specialized modelling techniques (e.g. the spatially explicit Bayesian hierarchical models of Sims, Cox, & Lewison, 2008). By-catch mitigation may use a suite of interacting measures from several levels of the mitigation hierarchy (Table 2), which change over time, adding further to the complexity of separating E, E_B and BPUE (as discussed for target fishery data by Bishop, 2006). We do not here attempt further to clarify these relationships, but a key research need is to disentangle these variables in an empirical setting.

O_T is the net effect on population growth rate of policies aiming to improve the overall viability of the by-caught species' population, representing "offsetting" of the damage caused. It represents the expected effects of measures to improve conditions for individuals which would not have been at risk of by-catch at that particular stage in their lives or location. For example, supplementation in nesting areas (for turtles); restoration of nesting habitat (for seabirds); or implementation of protected areas aimed at demographic groups not directly impacted by fishing (calving areas for cetaceans; juvenile concentrations for fish).

3 | OPERATIONALIZING THE FRAMEWORK

In Table 3, we illustrate the application of the by-catch mitigation framework using four examples from different fisheries and by-catch taxa. Specific solutions to Equation 1 could come from taking into account the regulatory, cultural and economic conditions in a particular fishery. For instance, once the focal by-catch population has been defined, then it is possible to solve the equation by assigning factors affecting decision-making, including cost. If a least-cost approach to by-catch goals is appropriate, E_B, BPUE and O_T could be expressed as functions of cost to solve the equation for a given $\Delta\lambda_T$. Another approach would be to maximize $\Delta\lambda_T$ subject to a budget constraint.

Table 3 highlights that there is not always potential for effective action at each level of the hierarchy; for some species (e.g. oceanic whitetips/longlines), there may be limited potential at all levels. The framework is a way of organizing and structuring thinking about by-catch mitigation, and enabling mitigation effectiveness to be assessed against a concretely defined and measurable target. Its function is not to propose new ways of doing by-catch mitigation for cases like these. If, on using the framework to analyse the effectiveness of the measures available for a given by-caught stock, it is found that it is not possible to reach the chosen target (e.g. NNL), then difficult decisions must be made. For example, the target may need to change, which could imply an acceptance of continuing decline of the by-caught stock. Or the fishery must be restructured in a way that reduces by-catch effectively (maybe even closed down). Or investment must be made into technological innovation to develop new ways to reduce by-catch. If it is found that the data are inadequate for the analysis required, then the decision must be made either to invest in improving the evidence base or to recognize that it is not possible to evaluate whether by-catch mitigation has been effective in reaching the agreed goal. The framework's main utility, therefore, is to make these choices explicit.

Equation 1 could be extended to handle multiple species, varying gear types, or heterogeneous by-catch reduction methods. For instance, BPUE can be decomposed into several components representing the different stages of the process. If BPUE represents the sum of individuals dead on arrival, individuals captured and dying on the vessel, and individuals dying after live release, we can rewrite BPUE as a series of factors:

$$\mathrm{BPUE} = B_{\mathrm{DOA}} + P_{\mathrm{DV}} \times B_{\mathrm{OB}} + (1 - P_{\mathrm{DV}}) \times B_{\mathrm{OB}} \times P_{\mathrm{DR}} \quad (2)$$

where B_{DOA} is the by-catch per unit effort that arrives to the boat dead, B_{OB} is the by-catch per unit effort that arrives to the vessel alive, P_{DV} is the proportion dying on the vessel, and P_{DR} is the proportion dying after release. For instance, a higher proportion of by-catch of sea turtles and other species arrives to the boat dead when using longlines that are set deep, such as those used for bigeye tuna that can be set more than 300 m deep, when compared to a shallow set longline such as those used in many nearshore artisanal fisheries (Andraka et al., 2013; Hall, Swimmer, & Parga, 2012; Swimmer et al., 2006). This difference would appear in the B_{DOA} term. Such a decomposition illustrates the flexibility of this framework in handling fishery- and species-specific features and also serves to highlight areas where different mitigation methods would have the greatest influence (e.g. Shiode, Hu, Shiga, Yokota, & Tokai, 2005). Another extension to the basic framework would be to consider explicitly the uncertainty surrounding different elements of the conceptual model, and the impact of this uncertainty on which element of by-catch mitigation should be a focus (Table 3).

It is important to note that this equation is not a true bioeconomic equation to be solved. Rather, it is a conceptual framework in which we make the components of the mitigation hierarchy explicit, in order to guide thinking towards a more holistic approach to addressing by-catch. It also does not represent a hierarchy such as is required in terrestrial systems. To make this equation into a hierarchy, rather than a model for least-cost mitigation of by-catch, it could be set up as a goal programming function, with sequential solutions to each element, summed to produce the final mitigation outcome. In operational terms, this translates into a presumption that investment and effort should be focussed differentially on sequential elements of the model, starting with E_B, then BPUE, then O_T, so that offsetting relates only to the unavoidable residual harm once all other steps have been taken. This may be reflected in the emphasis placed on the incentives given to fishers to change behaviour pertaining to sequential elements of the hierarchy, in the timing of the offset, or in the disposition of the funding for research and conservation action allocated by government.

Research is currently ongoing to operationalize Equation 1 to reduce turtle by-catch of a small-scale gillnet fishery operating out of San Jose port, Peru (Alfaro-Shigueto et al., 2010). Currently, a small-scale certification scheme is under trial by the NGO ProDelphinus, which aims to give premium prices for fish caught by skippers abiding by best-practice by-catch reduction guidelines (J. Alfaro-Shigueto and J. Mangel, personal communication). The research entails collecting detailed economic data from all gillnet vessels to understand the economic costs involved in fishing operations, to calculate the potential additional costs of measures at each stage in

TABLE 3 Summary of options for by-catch mitigation, structured according to the mitigation hierarchy, for four case-studies

	Case-study			
Framework step	**Albatrosses/longlines**	**Turtles/longlines**	**Rays/purse seines**	**Oceanic whitetips/longlines**
Defining the problem				
Fishery and spatial extent	Brazilian domestic industrial coastal longline fleet	Eastern Pacific (coastal and pelagic) small-scale commercial longline fishery	Tuna purse-seine fishery of the eastern Pacific	Asian and EU longline tuna fisheries in the Indian ocean
Target species	Various species of shark and swordfish	Mahi-mahi (*Coryphaena hippurus* Coryphaenidae; seasonal), tuna, sharks (mostly silky; *Carcharhinus falciformis*, Carcharinidae), billfish	Various species of tuna	Various species of tuna
By-catch species of concern	Albatross & petrel species; particular concern for critically endangered Tristan albatross (*Diomedea dabennena*, Diomedeidae)	Olive ridley (*Lepidochelys olivacea*, Cheloniidae), green/black (*Chelonia mydas*, Cheloniidae), hawksbill (*Eretmochelys imbricata*, Cheloniidae), loggerhead (Peru and Mexico) and leatherback (*Dermochelys coriacea*, Cheloniidae)	Seven mobulid species, including CITES-listed *Manta birostris* (Mobulidae) and *M. alfredi* (Mobulidae), caught mostly alive in dolphin-associated or free-school sets	Oceanic whitetip shark; Vulnerable on IUCN red list, retention banned by tuna RFMOs, listed on CITES Appendix II
By-catch target ($\Delta\lambda_T$)	Brazilian government: Minimize by-catch. Rules focus on targets for use of minimizing measures, rather than on by-catch numbers	Not well defined. RFMOs suggest minimizing by-catch. Could consider PBR for olive ridleys, zero catch for leather-backs (reflecting their respective population status)	IATTC (2015): zero retention, storing or selling and live release of by-caught rays when possible. Implies by-catch minimization	Target by-catch level not defined due to uncertainty; RFMOs ban retention, landing and trans-shipment
Mitigation hierarchy element				
Avoid	✓✓ [time/area closures, night-time setting]	✓ [time/area closures, deeper lines]	✓ [time/area closures]	✓✓ [deep setting]
Minimize	✓✓✓ [tori lines, line weights]	✓✓✓ [monofilament line, circle hooks (not leatherbacks)]	– [hard to avoid catching]	✓ [monofilament line, circle hooks, ban on steel leaders]
Remediate	– [hard to release alive]	✓✓ [improved handling]	✓✓✓ [improved handling]	✓ [short sets]
Offset	✓✓ [invasive eradication]	✓✓ [beach protection]	✓ [illegal trade]	✓ [information gathering, illegal trade]
Factors affecting operationalization				
Scope for incentives	Participatory research on barriers to uptake of minimization measures. Positive incentives for those using new measures, paid for by, for example, fisheries-wide levy	Certification/sustainability standards in export markets	Transitional payments to promote better handling on deck, hence improving survival	If information gathering seen as a valid offset due to high uncertainty, funding a tagging scheme could incentivize fishers to collect data on shark catch rate, survival of released sharks, by-catch hotspots, to support improvements across the whole mitigation framework

(Continues)

TABLE 3 (Continued)

Framework step	Case-study: Albatrosses/longlines	Turtles/longlines	Rays/purse seines	Oceanic whitetips/longlines
Major uncertainties	Lack of species-level identification of by-catch, lack of understanding of compliance	Lack of ecological knowledge of turtle population trends & distribution. Potential for significant additional by-catch from coastal gillnet fishery	Impact of catch on mobulid survival. Predictors of mobulid distributions	Lack of observers or reporting so very limited understanding of by-catch levels, spatio-temporal encounter hotspots, post-release survival, compliance
Key obstacle	Compliance with existing rules must be improved	Funding for alternatives to fishing at a large enough scale. Long time lag and uncertainty in offset effectiveness	Limited knowledge of mobulid distributions makes avoidance difficult	Lack of monitoring limits options
Overall assessment	Existing measures for improving implementation of minimization step already exist but need incentivizing; offsetting could provide short-term gains to complement these	Targeted funding could facilitate improvements throughout the hierarchy. Best approach may differ by species (particularly leatherbacks vs others)	Focus on remediation step is currently the main option available	Some potential for minimization through deep setting, but challenging to change behaviour in this fishery; electronic monitoring systems would help
Key references	Bugoni, Mancini, Monteiro, Nascimento, & Neves (2008); Wanless et al. (2009)	Alfaro-Shigueto, Dutton, & Mangel (2007); Hall et al. (2012); Andraka et al. (2013)	Jones & Francis (2012); Hall & Roman (2013); Croll et al. (2016); Fowler (2016)	Tolotti et al. (2015)

Ticks indicate the potential for action at different steps of the hierarchy, based on feasibility, current knowledge and impact on mortality (✓✓✓ = high potential; ✓✓ = some potential; ✓ = limited potential; - = no potential). Text in brackets gives suggested measures at each level of the hierarchy; these are illustrative rather than definitive. The information for the case-studies is based on the expert knowledge of the authors through their involvement in management of the by-catch issue in these fisheries. RFMO, regional fisheries management organization; PBR, potential biological removal.

the mitigation hierarchy. In the absence of high quality population data with which to parameterize a model, a PBR-based approach is being used to set a target by-catch level in terms of number of individuals of each of the turtle species caught in the fishery. Expert opinion from fishers and Prodelphinus staff, supplemented by data from a long-running by-catch observer programme operating out of the port (Alfaro-Shigueto et al., 2011), gives the potential reduction in turtle by-catch numbers as a result of a given mitigation approach. Interviews and focus groups with fishers provide understanding of their preferences for different by-catch mitigation approaches, barriers and constraints to implementation, and potential participation in different incentive schemes; this can be supplemented by Discrete Choice Experiments providing empirical estimates for preferences for combinations of by-catch reduction measures (cf Rogers, 2013). This field research produces a short-list of feasible mitigation measures at each stage in the mitigation hierarchy, for costing and testing (e.g. specific areas or times for fishery closure under avoidance, combinations of hook types and net modification under minimization, training in turtle handling and release for remediation, and improving by-catch performance of other gear types in the area for offsetting). This enables the analysis of the effectiveness and cost of various combinations of by-catch reduction strategies, framed within the four steps of the mitigation hierarchy (avoid, minimize, remediate, offset), with a clear target by-catch reduction goal in mind.

4 | COMPARING KEY DEBATES BETWEEN TERRESTRIAL NNL AND BY-CATCH MITIGATION

4.1 | The hierarchical nature of mitigation

Terrestrial situations are usually viewed as requiring a strict hierarchy with avoidance, minimization and remediation taking precedence over offsets. Part of the reason for this hierarchy may be societal values and expectations, but also it is a reflection of reversibility and uncertainty. The terrestrial mitigation hierarchy was set up to address habitat destruction caused by development, which is effectively irreversible, hence avoidance is strictly preferred from a conservation perspective. In practice, avoidance has been a neglected step, and much of the disquiet about biodiversity offsetting has been because of the tendency to pay lip service to avoidance and focus instead on offsets, which then may be implemented on paper only (Hough & Robertson, 2009; Phalan et al., 2017). Even with perfect enforcement and compliance with measures further down the mitigation hierarchy, the strict avoidance of habitat loss is more certain to limit impact than reducing losses in the course of a potentially damaging action, which is more certain than restoring damage after the fact or compensating for it with actions elsewhere. Often in terrestrial systems multipliers are used at the offset stage to reflect this uncertainty, requiring that an additional amount of equivalent land is protected in an offset over and above the amount that is lost during the development (with the ratio of land offset to land destroyed in the 10 s to 100 s depending on the circumstances; Moilanen, Van Teeffelen, Ben-Haim, & Ferrier, 2009). By contrast, in fisheries settings there have been suggestions that, depending on the legal environment, it may be more appropriate for offsets to be used as part of a least-cost conservation approach alongside more traditional mitigation methods, rather than as the last step in a mitigation hierarchy (Dutton, Joseph, Squires, & Williams, 2011; Dutton & Squires, 2008; Wilcox & Donlan, 2007).

4.2 | Out-of-kind offsets

Out-of-kind offsets are those which do not act to increase the impact-affected biodiversity. In terms of our conceptual framework, they are offsets which do not act to increase the population growth rate of the by-catch-affected focal population (Equation 1). For example, one suggested benefit of raising funds for offsetting from a by-catch tax on fishers is that the proceeds from such a tax can finance offsets elsewhere within the range of the by-catch-affected population (Dutton & Squires, 2008): Although not a true offset under a mitigation hierarchy, funds from the California drift gillnet industry in 2002 financed sea turtle nesting site conservation in Baja California for compensatory mitigation of sea turtle by-catch (Jannise, Squires, Seminoff, & Dutton, 2010). In terrestrial (and marine) systems, it can be more challenging to define the impact-affected biodiversity, because impact is rarely as clearly linked to a given species and stock as it is for by-catch. Because of this, the location and biodiversity target of conservation actions falling under the "offset" heading has sometimes been loosely related to the actual impact. Best-practice standards state that offsets must be implemented as close to the damaging activities as possible and focus on biodiversity as similar as possible to that which has been impacted (BBOP 2012). However, there have also been calls for "out-of-kind" offsets that give more conservation bang-for-buck by focussing on threatened species or rare habitats, or areas in need of conservation, rather than the impacted areas or species which may be considered less "valuable" for conservation (Bull, Hardy et al., 2015). This has led to substantial debate as to the appropriate limits on the geographic scale and biodiversity focus for offsetting (e.g. Apostolopoulou & Adams, 2017). It also draws attention to the subjective and user-defined nature of the word "biodiversity" (Morar, Toadvine, & Bohannan, 2015). As it is impossible fully to operationalize the concept, implementers of the mitigation hierarchy have latitude to interpret biodiversity according to, for example, ease of measurement, perceived societal value or mitigation cost (Maron et al., 2016). In our case, we take a narrow focus on the by-caught species itself; this is in line with much of the literature on by-catch, but not with the broader discourses on ecosystem-based approaches to marine management and ecosystem services (Rosenberg & McLeod, 2005). These discourses suggest the need for a more functional, ecosystem-based approach to no net loss of biodiversity; this has yet to transpire either in the marine or in the terrestrial literature, possibly because substantial challenges in defining impact-affected biodiversity then inevitably ensue.

As marine megafauna stocks are often transboundary and migratory, defining the appropriate spatial unit for offsetting may be a challenge because the most effective location for an offset may or may not be within the area of influence of a given fishery. Clearly and precisely defining the spatial unit within which the mitigation hierarchy will be implemented, during the process of defining the overall goal (such as NNL), is vital. This unit should reflect the scale over which an action will affect λ_T; offsets which are within the distribution of the focal stock of the by-caught species (as defined for Equation 1) are not out-of-kind. However, challenges emerge when the appropriate spatial unit for offsetting activities is different to the appropriate spatial unit for other elements of the mitigation hierarchy, which are likely to be defined instead by jurisdictional area or target fish stock distribution. In many fisheries, the species affected by by-catch may not be well enough known, and offsets may accordingly need to be broadly targeted to benefit any potentially affected species. True out-of-kind offsets would include funding the conservation of unaffected species or stocks, of habitats not used by the focal stock, or contributions to a conservation fund without a clear commitment that the funds are to be spent on increasing λ_T for the focal by-caught stock. These are unlikely to form part of best-practice guidance for by-catch offsets.

4.3 | Research as an offset

A related area of active controversy for marine by-catch is whether research or information gathering should be seen as a valid offset mechanism. The rationale is that this research could be used to reduce uncertainty, promote innovation and thereby improve outcomes for by-caught species, albeit indirectly. An offset could be used to incentivize better data collection, for instance, using a by-catch levy to pay for tagging or to put by-catch observers or electronic monitoring systems on boats. This might be a prelude to later mitigation or avoidance activities once more is known about the biological setting. Whether research activities could appropriately be considered as part of an "offset" is controversial—in some cases, an indirect benefit to the by-caught stock might be clearly apparent (e.g. the oceanic whitetip (*Carcharinus longimanus*, Carcharinidae) case-study in Table 3), while in other cases using investment in research as an offset could be seen as a case of moral hazard, potentially compromising scientists' independence and having at best a highly indirect relationship to NNL of the by-caught species. Another view is that reducing uncertainty is a core responsibility of operating a fishery, which therefore should be borne by the management authority or fishing businesses. In terrestrial systems, these dilemmas also exist, but the sentiment is much more clearly expressed that research activities are not appropriate offsets (Bull, Gordon, Watson, & Maron, 2016).

4.4 | Incentivizing implementation of mitigation measures

The factors that drive decision-making about megafauna by-catch reduction (by skippers, companies, fishery managers, policymakers and other stakeholders) include legal obligations to minimize by-catch at the national or international levels (e.g. FAO, 2011; Rice, 2014), the availability and quality of technical fixes, associated costs to fishers, limits on access to seafood markets, as well as societal pressures. However, much research on by-catch reduction focuses on identifying and implementing technical measures to reduce BPUE, rather than on the social and economic barriers to implementation (Campbell & Cornwell, 2008). Technological innovation to improve BPUE needs to be appropriately incentivized, with efforts made to ensure that such measures are as cost-effective as possible for fishers (Gjertsen, Hall, & Squires, 2010; Lent & Squires, 2017). However, it often happens that even apparently suitable by-catch measures are not widely implemented (e.g. Damalas & Vassilopoulou, 2013; Orphanides & Palka, 2013; Radzio, Smolinsky, & Roosenburg, 2013). In these cases, the degree of non-implementation, and the reasons behind it, needs to be understood so it can be addressed (Cox et al., 2007). These types of consideration are also not well researched in the terrestrial offsetting literature, because compliance is poorly monitored (Bull, Suttle, Gordon, Singh, & Milner-Gulland, 2013), and there is little support for research on the barriers to implementation of a mitigation hierarchy, and how to support developers to address these barriers (Bull, Bryant, Baker, & Milner-Gulland, 2015). The social impacts of implementing a biodiversity mitigation hierarchy on resource users are mentioned in guidance (e.g. BBOP 2012) but how to measure and account for them is very poorly understood. The few studies investigating delivery of promised offset measures in terrestrial systems suggest a very poor record (Quétier, Regnery, & Levrel, 2014). Therefore, the social side of implementing the mitigation hierarchy and incentivizing compliance is an area that needs more, and more active, research within both the terrestrial and marine realms (Fulton, Smith, Smith, & van Putten, 2011). This is particularly true when the burden of implementing mitigation approaches is borne by relatively small-scale producers rather than governments or multinationals (e.g. the pelagic longline fisheries in Table 3).

4.5 | Societal limits

For a species at high risk of extinction, complete avoidance of by-catch might be the most desirable policy from both a management agency and societal perspective. In addition, with emblematic or highly threatened marine megafauna it may be viewed by members of the public as morally wrong to kill any individuals even if mitigation is in place (e.g. Maui's dolphin; Hamner et al., 2014), leading to pressure on governments to reflect this ethical concern in regulations. These dilemmas echo the issue of thresholds in terrestrial offsets, which recognizes that there are some critical areas in which development is not societally appropriate, regardless of the potential for mitigation, and other areas in which the mitigation hierarchy can be appropriately applied (Bull et al., 2013). Examples of locations where a threshold approach is seen as appropriate in terrestrial systems include the habitat of highly endangered species, or ecosystems which are limited in extent and irreplaceable (such as old growth forest). In terrestrial systems, therefore, the mitigation hierarchy is seen as most appropriate for application in more common and degraded habitats such as farmland. Similarly, in fisheries, there may be some situations in which the stocks subject to by-catch are so precious or threatened that no level of threat from fishing can be contemplated, and others where fishing subject to NNL and the mitigation hierarchy is a socially acceptable approach. In situations in which trade-offs between conservation and development are seen as necessary or acceptable by wider society, a social licence to operate may be gained through adopting offsets in the absence of regulation. For example, in sub-Saharan Africa, several large development projects are attempting to offset their impacts on great apes and their habitats (Kormos et al., 2014). A by-catch equivalent might be fishing companies voluntarily donating funds for turtle nesting beach restoration in their area of operation, in addition to complying with regulatory by-catch mitigation measures. These measures may improve the image of the company with the general public, but to avoid accusations of "greenwashing", their effectiveness needs to be properly scrutinized (Bull et al., 2016). Transparently embedding these types of actions within a mitigation hierarchy such as we are proposing and critically evaluating their contribution to increasing the population growth rate (as per Equation 1), would be one way to prompt such scrutiny.

4.6 | Uncertainty

The nature of the uncertainties surrounding biology and enforcement in the marine setting raises questions about the ordering of steps in the mitigation hierarchy, in a way that is dissimilar to terrestrial systems where the hierarchy of uncertainties may be clearer and uncertainty is generally lower. For example, it may be that the impact on overall population growth rate of an offset measure like eradicating invasive species from a seabird nesting habitat is both less uncertain and more cost-effective than avoidance measures such as closing areas which may or may not be frequented by adult seabirds in a given time-period. Generally, though, it might be assumed that measures which target life stages subject to high levels of natural mortality, or within which individual contribution to overall population growth rate is low (e.g. headstarting juvenile turtles) may be less effective in achieving NNL than measures which target reproductively mature adult females (such as live releases; Heppell, Crowder, & Crouse, 1996). However, before implementing an offset that aims to improve the survival of one lifestage in order to compensate for the by-catch mortality of another, a robust assessment of the consequences (with associated uncertainties) should be carried out through detailed population modelling, based on strong empirical studies (c.f. Wallace, Heppell, Lewison, Kelez, & Crowder, 2008). In terrestrial systems, the requirement sequentially to apply the mitigation hierarchy is broadly unchallenged, but actually similar arguments apply. For example, habitat restoration sits above offsetting in the hierarchy, and yet it is a long-term, uncertain process, which may in some circumstances be much less preferable to an offset using a well-established approach which is highly likely to lead to conservation gains.

4.7 | Temporal considerations

The timing of offsets in relation to other elements of the mitigation hierarchy has been the subject of debate within the terrestrial literature. The main suggestion for addressing the temporary loss of biodiversity while offsets come to fruition has been adopting mitigation banking, whereby offsets are implemented in advance of potentially damaging activities, providing biodiversity credits which can be used to compensate for later losses. This both removes an element of uncertainty from the offset implementation and reduces the time lag between loss and gain (Mann, 2015). With respect to marine megafauna by-catch, flexibility in timing provides additional scope for cost reduction and benefit enhancement which may not be present in traditional habitat-based terrestrial offsets. For example, temporary measures such as a short-term by-catch tax to fund an offset may be used if mitigation or avoidance methods take time to come online, or if a temporary nudge is enough to cause behavioural change. This might be the case if a policy was needed to induce fishers to take up new gear to avoid the cost of an offset, or if concerns about safety or yield reductions during the transition to new gear could be allayed by a temporary subsidy for early adopters or a paid participatory monitoring programme to inform wider implementation (e.g. the mobulid and shark case-studies in Table 3). Just as for habitat restoration (Zedler & Callaway, 1999), by-catch offset strategies which target juvenile stages of long-lived species (e.g. turtle headstarting or invasive removal from seabird nesting islands) may take many years for their effects to become apparent in an increase in population growth rates. Additional uncertainty is introduced by the difficulty in monitoring populations of many by-catch species (e.g. seabirds; Hatch, 2003), leading to uncertain estimates of the impact of offset activities on population growth (see case-studies in Table 3). These problems are not insuperable, however; positive trends have been reported in turtle populations over decades as a result of nest protection (e.g. Dutton, Dutton, Chaloupka, & Boulon, 2005).

5 | USING INCENTIVES TO REDUCE BY-CATCH

Many of the examples and principles discussed above either implicitly or explicitly relate to the economic, social, institutional or moral incentives operating on different actors inside and outside the fishery, which can be positive or negative. We now turn to a discussion of how incentives can be used to reduce by-catch within our framework. Incentives can be put in place to change fisher behaviour with respect to any of the elements of the framework (avoid, minimize, remediate and offset; Table 3). Although discussed in the literature, most of these incentive approaches are yet to be implemented in the real world, particularly for by-catch. Therefore, until empirical evidence of their effectiveness is available, these suggestions come with a caveat.

Financial costs of by-catch mitigation actions can arise, for instance, from lost catch, capital investments in new gear or mitigation equipment, or the loss of access to a fishery. Costs may also arise from the deployment of by-catch observers or training in the use of new gear. These costs can be paid by fishing companies or individuals, or by governments, NGOs or seafood consumers. Whether or not compensation for costs incurred by fishers is seen as appropriate depends on whether by-catch reduction is seen as a social good that fishers are providing (in which case they should be compensated for it), or as putting right the harm that they are doing to biodiversity while generating their own private gain (in economic language, whether by-catch is viewed as an unpriced externality, in which case they should pay). It also depends on whether economic hardship will ensue; a case for compensation of by-catch reduction costs incurred by people dependent on fishing for their livelihoods may be more sympathetically received by other actors than a case made by a large multinational fishing company.

If by-catch is seen as an unpriced externality, it might be socially optimal to tax fishers for their by-catch so that this externality is internalized. This places an explicit price upon by-catch (Boyce, 1996; Pascoe et al., 2010; Squires & Garcia, 2014). The by-catch price is likely to be incorporated into the price of the target species, and thereby becomes part of the target species cost. This price could be set differently for different demographic classes of the by-caught species, depending on the impact the loss of an individual would have on the population. All else being equal, putting a price on by-catch means that the seafood product that is the target catch becomes more expensive and consumers have to pay more for their seafood, reducing demand. Then, in principle, every firm in the supply chain, every vessel and every consumer have an incentive to reduce by-catch until each economic actor's marginal cost of by-catch reduction equals the common price of by-catch that they all face. Offsets are one way to price and internalize the by-catch externality cost. If an offsetting action is costly to implement and must be paid for with each unit of by-catch, it implicitly prices the residual by-catch. In this circumstance, the effect from a financial standpoint is the same as a by-catch tax, with the level set based on the cost of the offset. Various institutional structures to support this charge per unit of by-catch are possible, with different implications in terms of the distribution of costs and benefits. For example, an insurance scheme could be paid into by fishers that pays out in the event of a by-catch event, thereby spreading the cost of unavoidable, rare, by-catch events. Or a tradable permit scheme could operate, such that fishers who experience a by-catch event can buy a permit, with the cost varying depending on demand for permits (hence providing a vessel-level incentive to innovate to reduce by-catch).

If there is demand for conservation in an international market, then price premiums and market access (through eco-labelling, supply chain certification, other food sustainability campaigns; Ward & Phillips, 2010), or boycotts acting as strategic threats from consumers (Kotchen, 2013; Segerson, 2010), could act as positive or negative economic levers on the fishery, providing an incentive for fishers to reduce their by-catch voluntarily (as has been suggested for the Brazilian mahi-mahi fishery; Table 3). For example, the Marine Stewardship Council now includes by-catch mitigation in their certification process (MSC 2014). Demand-led levers may be more or less applicable at different levels in the hierarchy; for example, avoidance may be relatively hard to evidence, while offsetting may be less easy to sell to a consumer than minimization or remediation. Concerns about the unintended consequences of positive incentives (particularly for direct subsidies, rather than conditional incentives) may determine whether they are an appropriate instrument in a given case. For example, they may be inappropriate if there is a risk that the additional money is reinvested in increased fishing capacity, or if there may be consumption, production or conservation leakages (transfer of the problem somewhere else), whether at the vessel, fishery or trans-national level. High transactions costs may also limit the benefits of incentives schemes.

Other changes which may need to be incentivized for successful implementation of by-catch reduction policies may be less amenable to financial measures, at least partly because it is less clear how to assign financial value to the actions, or to the benefits and losses which they produce. For example, perceived reductions in safety for fishing crews (from weighted longlines, for instance) are costs that may be hard to value financially. Other prerequisites for long-term sustainable behaviour change, such as changes in social norms so that fishing communities see by-catch reduction as appropriate behaviour, or technical skill acquisition so that they can use new methods, may be incentivized by carefully designed interventions working with fishers (Hall et al., 2007). Conservation policies based on economic incentives (extrinsic motivation) are not always superior to those based upon intrinsic motivation. In fact, incentive-based by-catch reduction policy instruments could even be counterproductive by reducing the effectiveness of intrinsic motivation, depending upon the situation (although the empirical evidence on this topic is weak; Rode, Gómez-Baggethun, & Krause, 2015). If the change required for by-catch reduction to work meets cultural resistance, then participatory research might be especially effective in breaking down barriers between those who want by-catch reduction to take place and those who actually have to implement it (the fishers). For example, in Australia, the government-funded body Oceanwatch facilitates engagement between communities, the fishing industry, seafood suppliers and government to improve knowledge sharing (www.oceanwatch.org.au). Innovation is crucial in fisheries, and fishers are accustomed to adopting new technology or processes, potentially making an incentivized participatory research programme especially fruitful.

Sometimes the most efficient way to solve problems is a social instrument or an institutional change in place of, or as well as, an economic instrument. For example, supporting development of fisher organizations rather than instituting a vessel-level tax or subsidy might provide the impetus needed to change behaviour. Instituting catch shares (individual transferable quotas) may provide an enabling environment for by-catch reduction, for example by promoting more effective monitoring (Grimm et al., 2012). Experience in terrestrial system produces similar insights; incentive-based schemes which also build community cohesion and support the development or strengthening of local management institutions, are more effective in the longer run than direct economic incentives (Clements et al., 2010).

6 | CONCLUSIONS

The framework we present here is novel. It draws upon and extends the frameworks for conceptualizing by-catch developed by Hall (1996) and Hall, Alverson, and Metuzals (2000). It amalgamates Hall's framework with the mitigation hierarchy as used in the Environmental Impact Assessment literature (BBOP 2012). The suggestions about goals, metric and mitigation actions are drawn from the empirical by-catch literature, and the issues we discuss integrate the concerns of the extensive terrestrial and nascent marine offsetting literature with the by-catch literature. The framework makes clear that an early, crucial, step is to clarify the goal of any by-catch reduction policy. Overarching goals, like those issued by the Convention on Biological Diversity (e.g. Aichi Target 11 that 10% of marine habitat should be under protection by 2020), need to be translated into operational terms within each fishery. Currently, legislated or agreed by-catch reduction goals tend to be less specific than they could be, and this leads to problems in interpreting these goals in order to plan a by-catch mitigation strategy (see the case-studies in Table 3 for examples). This ambiguity is to be expected within negotiated targets, but it is a challenge nonetheless (Maxwell et al., 2015). Using a common unit of by-catch impact, such as the $\Delta\lambda_T$ which we use here, would be helpful both in clarifying expectations, and evaluating the effectiveness of elements of the mitigation hierarchy.

Once the by-catch goal is known, options for implementing avoidance, minimization, remediation and offsets can be clarified (as in Table 2). However, outside of the interconnected biology of the ecosystem, by-catch is embedded within social and economic systems. Different units of analysis may be needed at different levels of the hierarchy, to cope with the challenges of incomplete overlap between jurisdictional units, fisheries, target stocks and by-catch stocks. Jurisdictional issues are important and complex, potentially impeding implementation. Fleets interact, raising the risk of policy leakage, for example if people shift to other fisheries, gear or livelihoods. Therefore, the scale at which each element of the mitigation hierarchy is implemented is likely to vary, with incentives to mitigate often being best applied at the vessel level, focussed on reducing individual mortality, while offsetting is implemented at the scale of the by-catch species' stock. With transboundary species, unilateral conservation in one jurisdiction creates the potential for production, trade and conservation leakages. For example, a conserving State could implement the avoidance step and shut down or dramatically curtail its own production of swordfish to reduce sea turtle by-catch, but the knock-on effect may be more importation of swordfish from fleets with higher sea turtle by-catch (Rausser, Hamilton, Kovach, & Stifter, 2009).

Translating the framework from a species to an ecosystem level will require consideration of the potential interactions between by-catch mitigation approaches targeted at different species (Serafy et al., 2012). Actions to mitigate by-catch for one group of species can increase or decrease it for others, and so a system-wide approach is needed. For example, changing from J-hooks to circle hooks to reduce mortality of turtles may decrease or increase shark mortality (Andraka et al., 2013; Godin, Carlson, & Burgener, 2012). In terrestrial systems, similar interactions arise, and value judgements are made (whether explicitly or implicitly) as to what loss and gain of "biodiversity" translates to in operational terms, and what elements of biodiversity matter most to implementers.

Uncertainty is high in ocean ecosystems, creating both challenges and opportunities in applying the concept of NNL through a mitigation hierarchy that includes offsetting. In particular, for marine megafauna, there is high uncertainty in the processes linking any element of the mitigation hierarchy through to changes in population growth rate. Furthermore, impacts can be long-term, hard to measure and spatially diffuse, and uncertainty is not predictably spread through the hierarchy. This creates a different set of challenges to those faced in terrestrial systems, where at least for some types of environmental impact, the links between action and impact are relatively direct and measurable, and uncertainty generally increases through the mitigation hierarchy (from avoid through minimize/remediate to offset).

By-catch reduction measures have had significant successes over the last decades, as a result of substantial investment of time and funding by researchers, management authorities, conservation organizations and fishers (Cox et al., 2007). However, this success is not universal. Just as for any fisheries management issue, a poor regulatory regime, limited compliance and lack of information hamper efforts to reduce by-catch. In some places, high levels of by-catch, limited options for mitigation and weak governance (leading to poor enforcement) can combine to make the by-catch problem intractable. Our framework will not solve these problems. However, it brings together the full range of approaches for by-catch mitigation in a structured and systematic way, which requires a target to be expressed against which outcomes can be evaluated. By exposing areas of uncertainty and data deficiency, it could challenge scientists and managers to obtain the data required properly to evaluate the effectiveness of mitigation measures. This could then support and encourage clearer decision-making and prioritization of actions. Our framework demonstrates that the principle of implementing the goal of no net loss through a mitigation hierarchy is as applicable to marine megafauna by-catch as to terrestrial systems, where it is already widely used in challenging, data-poor, circumstances.

There is untapped potential for cost-effective by-catch mitigation, which could be realized with the adoption of this framework, and with consideration of new approaches to incentivizing by-catch mitigation within the steps of the hierarchy. Applying it to a few case-studies in practice will demonstrate empirically where and how the potential for improved effectiveness could best be realized. Existing legal frameworks often preclude approaches which implicitly or explicitly permit by-catch, including the use of economic incentives or new approaches such as offsets. However, in this context of dynamic uncertainty, the dividends of thinking more creatively about by-catch mitigation could be high.

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