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Bycatch-neutral fisheries through a sequential mitigation hierarchy

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ABSTRACT

Fisheries bycatch is the foremost threat to the conservation of many marine species. Evaluation of alternative bycatch management strategies can account for the relative strength of evidence, contribution to achieving objectives, costs to commercial viability, likelihood of compliance and tradeoffs from multispecies conflicts. This study describes benefits and limitations of a complementary approach of applying a sequential mitigation hierarchy to develop evidence-informed bycatch policy. Measures that avoid bycatch are considered before those that minimize catch risk. These are then followed by remediation interventions that reduce fishing mortality and sublethal impacts. Finally, direct, compensatory banking or in lieu fee-based offsets of residual impacts that were not possible to avoid, minimize and remediate can be implemented as a last resort. However, offset activities can be socioeconomically unjust, and some bycatch impacts are irreversible and cannot be offset. Air-breathing bycatch are exposed to a wide range of anthropogenic hazards across ontogenetic stages, presenting more options for offset conservation activities than fishes. Averted loss offsets, which avoid foregone losses predicted to occur had an intervention not occurred, implemented in combination with true offsets can achieve at least an equivalent gain and contribute to meeting broad, population- and species-level conservation objectives. Robust metrics are needed to determine equivalency, such as in relative reproductive value and population viability, between residual impacts and in-kind versus out-of-kind and on-site versus offsite offsets. Bycatch management strategies guided by a sequential mitigation hierarchy promise to achieve ecological and socioeconomic objectives, including going bycatch-neutral or bycatch-negative through a net biodiversity gain.

1. Introduction

Overexploitation, primarily from fisheries bycatch, is the prime threat to many marine species. Fisheries bycatch of threatened species can be an obstacle to sustainable seafood production and hence to global food, nutrition and livelihood security [1–3]. Fisheries targeting relatively productive species can have profound impacts on co-occurring, incidentally caught, bycatch species that have low reproductive potential due to long generation lengths, low fecundity and other life history traits that make them particularly vulnerable to anthropogenic mortality. They generally have very low maximum population growth rates and low density-dependent compensation [4,5]. As a result, their populations can decline quickly, and once depleted, they may not recover [6–9]. Marine megafauna belong to some of the most threatened taxonomic groups, and include marine apex and mesopredators that, in some systems, contribute to regulating marine ecosystem structure, functions, stability and services [10–12]. Declines in bycatch species' abundance can have cascading effects through food web links [13–16]. Fisheries-induced evolution from selective removals based on heritable traits reduces the population fitness [17–19].

Some species of chondrichthyans (sharks, rays and chimaeras), marine reptiles, marine mammals, seabirds and teleosts are threatened due to fisheries bycatch [9,20–23]. Depending on the fisheries management framework and markets, some threatened megafauna may be targeted or a valuable incidental, secondary catch, used for human consumption, reduction for fishmeal or fish oil, feed for aquaculture and livestock, and other applications. Alternatively, a small portion of threatened catch may be retained such as shark fins, manta and devil ray gill plates, and

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marine snake skins, with discarding of the remaining carcass, or the entire catch may be discarded [9,24–29].

For some gear types and some threatened taxa susceptible to fisheries bycatch, numerous mitigation methods are now available to avoid and minimize their catch and reduce their fishing mortality that are also commercially viable [30,31]. However, there has been mixed progress in their adoption [32–34]. Furthermore, fragmented bycatch management, with taxon-specific instead of integrated, holistic frameworks, can cause unintended multispecies conflicts [35].

To determine which best meets ecological and socioeconomic objectives, alternative bycatch management strategies can be evaluated against several key criteria. This includes accounting for the relative strength of evidence of alternative mitigation approaches [36,37]. The predicted size of the effect of alternative interventions on catch and fishing mortality rates and relative contribution to meeting bycatch management objectives are additional considerations. Bycatch policy development should also account for tradeoffs from multispecies conflicts caused by some mitigation methods, which reduce the catch or mortality rate of some threatened bycatch species but exacerbate catch or mortality of others. Costs to commercial viability (economic viability, practicality and crew safety) is an additional critical consideration. The likelihood of fisher compliance with alternative mitigation methods is also critical, which is determined by enabling conditions. This includes whether crew behavior affects efficacy, whether fishers voluntarily implement the method given commercial viability costs and the catch sector's buy-in and group norm for employing the method, whether there is robust compliance monitoring, and whether other fisheries management framework components are sufficiently robust to deter noncompliance [38–41].

Bycatch management policy should also be guided by a sequential mitigation hierarchy [42–44]. This study reviews and discusses the potential benefits as well as limitations of applying a sequential mitigation hierarchy for evidence-informed bycatch management, including obtaining equivalent gains for residual bycatch losses through direct offsets, in lieu fee-based compensatory mitigation and compensatory mitigation banks. Requirements for fisheries to avoid and minimize the catch risk and remediate the mortality of threatened bycatch species are broadly accepted [45]. However, despite the longstanding existence of a no net loss policy for wetlands and terrestrial natural resources, offsetting residual impacts surprisingly remains absent from the fisheries bycatch management toolbox. Incorporating a fisheries bycatch sequential mitigation hierarchy into international guidelines, fisheries management organization's decision-making processes, seafood company's codes of conduct and sustainable sourcing policies, and standards for sustainable fisheries promises to improve the evaluation of alternative bycatch management strategies, increasing the certainty that adopted bycatch policy meets objectives of bycatch management.

2. Sequential bycatch mitigation hierarchy

A sequential mitigation hierarchy framework has been included in environmental impact assessment policies for wetlands and terrestrial natural resources since the 1960s and more recently has been recommended to achieve a goal of no net loss or net gain of biodiversity [42,43,46–53]. Despite being a longstanding principle for managing impacts from human activities, a sequential mitigation hierarchy approach for fisheries bycatch surprisingly remains absent from international guidelines, regional fisheries management frameworks, fisheries sustainability standards, fishing catch sector codes of conduct, and major seafood buyers' sustainable sourcing policies [32,45,54–56]. There are, however, several theoretical and taxon-specific illustrations of the usefulness of a sequential bycatch mitigation hierarchy [42–44,57,58,59].

A sequential mitigation hierarchy can include four tiers, presented here with definitions applicable to mitigating the risk of catch, fishing mortality and sublethal impacts on bycatch species [41,42,44,48,53,60]:

1. Avoiding the risk of capture;
2. Minimizing the risk of capture;
3. Remediating impacts by reducing the probability of one or more of the components of fishing mortality and avoiding and minimizing the risk of sublethal impacts; and
4. Offsetting residual bycatch mortalities and sublethal impacts that could not be avoided, minimized and remediated.

Fig. 1 presents a hypothetical application of a sequential mitigation hierarchy to achieve a bycatch-neutral longline fishery for loggerhead turtles. However, many variations of the hierarchy have been proposed. Some mitigation hierarchies allow for the preservation of existing natural resources as an offset component [50]. Others explicitly exclude preservation as part of the mitigation hierarchy [47]. Under the U.S. Council of Environmental Quality regulations to implement the Clean Water Act, the remediation tier is defined as, "rectifying the impact, by repairing, rehabilitation, or restoring the affected environment" [50], which is similar to the definitions adopted by IUCN [53] and BBOP [52] for biodiversity mitigation. A mitigation hierarchy for the production and adverse effects of abandoned, lost and discarded fishing gear defined the remediation tier as methods that halt one or more of the adverse effects of derelict gear [61]. A sequential exploration of mitigation options was part of the strategy to reduce dolphin bycatch in the eastern Pacific Ocean tuna purse seine-dolphin fishery: (1) adjusting the gear, fishing areas and season to increase selectivity, such as not fishing in areas with larger dolphin herds and where dolphin behavior is less adapted to the fishing operations; (2) modifying deployment conditions, such as making only daytime sets and not fishing in areas with strong subsurface currents; (3) reducing the mortality rate of dolphins released from the gear; (4) reducing the mortality rate of dolphins released from the deck; and (5) utilizing instead of discarding dead dolphin catch, to turn bycatch into catch [62–64].

3. Bycatch avoidance, minimization and remediation

Measures that avoid unwanted bycatch prevent one or more extrinsic factors that explain capture risk. Attributes for susceptibility to capture include areal overlap, encounterability (probability of encountering the gear based on the vertical habitat distribution of the species relative to the fishing depth of the gear) and selectivity [65,66]. Area-based management tools, including static, permanent no-take marine protected areas and temporally and spatially dynamic ocean management measures, could avoid bycatch risk of a threatened species if they completely eliminate areal or temporal overlap between fishing vessels and the species' distribution [67,68]. Changing gear type is another approach that can completely avoid catchability, such as changing from driftnet to troll to eliminate leatherback turtle bycatch [69].

Bycatch minimization methods reduce, but do not eliminate, the risk of capture by reducing one or more capture susceptibility attributes. Methods that reduce bycatch either reduce effort or bycatch rates through (Table 1) [31,64,70]:

1. Input controls on effort;
2. Output controls on catch levels or rates, and trade bans, which may reduce fishing effort and increase selectivity; and
3. Changes in fishing methods and gear designs that reduce bycatch rates either by reducing areal or temporal overlap, reducing encounterability (vertical overlap) or increasing selectivity (i.e., making the gear more selective by reducing its ability to catch bycatch species).

For example, under certain enabling conditions, output controls such as shark finning bans, bycatch thresholds, retention limits and bans and trade bans may cause fishers to modify gear designs and fishing methods or reduce effort in order to reduce catch of threatened bycatch species [74–77].

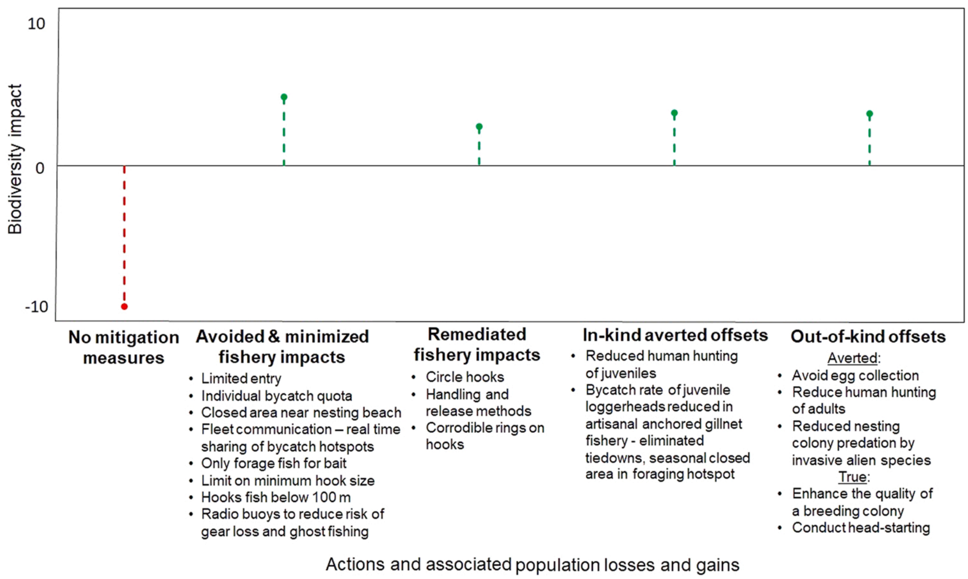

Fig. 1. Hypothetical application of a sequential mitigation hierarchy for a tuna longline fishery's bycatch of pelagic juveniles of a loggerhead turtle population to achieve a bycatch-neutral impact. The y-axis value of − 10 represents the population impact if no bycatch mitigation measures were implemented and value of 0 represents no net impact to the loggerhead population, where the losses from fishing (direct and collateral bycatch mortalities and sublethal effects from injuries, disease and stress) are offset by conservation activities – such that the value of the combined sum of the green positive biodiversity impacts is equal to the value of the red negative impact from bycatch. For this example, in-kind offsets are activities that achieve gains in juveniles of the same population that is exposed to the fishery, and out-of-kind offsets benefit either other age-classes of the same population or other loggerhead populations.

However, some bycatch avoidance and minimization methods can cause multispecies conflicts. For example, eliminating gillnet tiedowns reduces turtle catch risk, but this increases the net's vertical profile, increasing the catch risk of small cetaceans [78]. Using pelagic longline circle hooks in place of J-shaped hooks of the same size benefits marine turtles (reduces leatherback catchability and reduces leatherback and hardshelled turtle mortality) but increases shark catch rates [35,79]. Area-based management measures can reduce catch rates of some threatened species but the temporal and spatial distribution of fishing effort may unintentionally exacerbate catch rates of other threatened species [80]. Bycatch management strategy evaluation enables identifying and accounting for these conflicts so that any unavoidable trade-offs are intentional and acceptable, where the selected management framework is simulated to best meet objectives on multispecies bycatch management and predicted ecosystem-level effects [41]. However, the availability of requisite data inputs and robustness of population and ecosystem models required for these assessments will determine the relative certainty of simulations of bycatch management strategy evaluation for different fisheries, affected bycatch populations and ecosystems.

Remediation, the third step in the bycatch mitigation hierarchy, increases the probability that threatened bycatch survive fishing gear interactions while avoiding and minimizing sublethal impacts [44,60]. This is the fisheries equivalent to the restoration step of terrestrial and biodiversity mitigation hierarchies [44,48,52]. Injuries, disease and stress from sublethal fisheries interactions can reduce an individual's fitness, growth and reproductive investment and output. Repeated sublethal interactions can eventually cause or contribute to collateral mortalities [81,82]. The six components of total fishing mortality are [83,84]:

- Pre-catch mortalities, where live catch that escapes or catch that is removed from the gear, due to mechanical action or depredation, prior to capture die as a result of the interaction;
- Retained catch;
- Dead discarded catch, where this non-retained catch may have been dead when the crew retrieved it upon the haulback of the gear, or retrieved alive but died by time the crew discarded it;
- Post-release mortalities, where catch that crew retrieve and then release alive later die from stress and injury from the interaction;
- Ghost-fishing mortalities by gear that was abandoned, lost or discarded; and
- Collateral mortalities indirectly caused by fishing.

For some taxa and gear types, effective measures that manage gear designs and fishing methods have been identified to reduce the risk of fishing mortality. For instance, for species that ingest hooks, relative to J-shaped hooks, circle hooks can increase the probability of pre-catch, haulback and post-release survival by causing the hook to lodge in the mouth or body instead of being ingested deeply [31,85], which reduces fishing mortality of non-retained species. Longline branchline length affects mortality rates of obligate ram-ventilating elasmobranchs, where shorter branchlines impair movement and increase mortality risk [86,87]. Soak duration also affects mortality risk, where the longer the capture duration, the higher the morality risk [86]. Capture depth affect the risk of barotrauma and determine environmental parameters, such as temperature, dissolved oxygen and salinity, that affect mortality rates due to physiological stress responses and tolerance thresholds for survival [87,88]. Fishing depth also affects whether air-breathing marine species can reach the surface to breath during the gear soak. Various informative predictors, including handling and release methods, condition upon release, anatomical hooking position and gear remaining attached, also affect the probability of post-release survival [89–91].

Bycatch thresholds, retention limits and bans and trade bans for threatened bycatch species and shark finning bans have been documented to reduce fishing mortality in some fisheries [76], but may not be effective under certain management frameworks and market conditions [74,75,77]. For example, bans on shark finning, where fins are retained and the remaining carcass is discarded, might reduce the retention of sharks without market value other than for the fins, so that sharks that are retrieved and released alive might survive, especially when crew employ prescribed handling-and-release practices. However, for shark species with high haulback and post-release mortality rates, and for fisheries where certain shark species are retained for their meat and other products, finning bans likely will not affect fishing mortality rates [74,87]. Authorities may adopt programs that pay fishers to release captured threatened species [92,93].

Methods to avoid and minimize the production of abandoned, lost and discarded fishing gear include temporal and spatial separation of mobile and passive gear types to avoid gear conflicts and gear marking to increase gear visibility or identify ownership. Approaches to remediate ghost fishing mortality risk, efficiency and duration include disabling or removing derelict gear, using degradable and less durable gear, using non-toxic materials, using escape panels and cords in traps, using non-entangling designs of tuna purse seine fish aggregating devices and other approaches that increases ghost fishing selectivity of passive fishing gear [94]. The relevant interventions depends on the

Table 1
Approaches to minimize catch rates of threatened bycatch species, the second tier of a sequential mitigation hierarchy [31,71,72].

Susceptibility attribute	Minimization mitigation approach	Examples
Spatial and temporal overlap	Static and dynamic area-based management tools	● Restrictions on the time of day of fishing ● Permanent static closures; seasonal closures, such as dynamic sites important for critical life history stages ● Quasi-real time measures, based on real-time habitat suitability and species distribution models and fisheries-dependent observations implemented through move-on rules and voluntary industry fleet communication programs
Vertical overlap	Depth and time of day of fishing	● Gillnets set deeper, with a reduced profile, to avoid cetaceans, turtles and coastal seabirds ● Deeper daytime pelagic longline fishing reduces bycatch rates of threatened epipelagic species compared to shallow night-time fishing without costs to target tuna catch rates ● Ban on shark lines – pelagic longline branchlines that fish near the surface to target epipelagic sharks
Selectivity	Increased escapement	● Elimination or reduced length of gillnet tiedowns to reduce turtle entanglement ● Backdown procedure to release dolphins from tuna purse seine nets ● Excluder devices in trawls to allow turtles, marine mammals, juvenile and 'trash' fishes to escape ● Monofilament instead of wire pelagic longline leaders to enable sharks to sever the line and escape
	Shielded gear	● Streamer lines to avoid seabirds ● Entrance and bait barriers to prevent pinnipeds and sea otters from entering pots
	Repellents	● Electrical, chemical, magnetic and rare earth electropositive metals to repel sharks ● Acoustic harassment devices to deter marine mammals
	Mismatch between morphological characteristics and gear design	● Wider hooks to reduce the probability that organisms with small mouth dimensions will ingest the hook ● Smaller gillnet meshes to reduce the catchability of larger organisms ● Fish aggregating devices without netting to reduce the entanglement risk of sharks and other megafauna
	Reduced gear attractiveness and attraction to the gear	● Bait species and artificial bait - different species and sizes of marine predators have different bait preferences, based on chemical, visual, acoustic and textural characteristics and size of the bait ● Restrictions on discharges of offal and spent bait ● Ban on lightsticks
	Reduced gear detection	● Camouflaged gear ● Dyed bait ● Acoustic masking of vessels
	Increased gear detection	● Acoustic pingers for small cetaceans and seabirds ● Gillnet illumination for marine turtles ● White upper meshes in gillnets for seabirds
All	Input controls	● Limited entry (number of vessels in a fishery) ● Buyback programs ● Vessel size limits ● Limit on the amount of gear that can be deployed ● Limit on number of fishing days ● Limit on the number of fishing operations ● Limit on soak duration
All	Output controls	● Bycatch thresholds ● Retention limits, either individual or fleet-based, for marketable species ● Retention bans ● Shark finning bans
All	Trade ban	● Several elasmobranchs are listed on Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora, which establishes control of their international trade, and all sawfishes (Pristidae) are listed in Appendix I, which prohibits international trade [73]
All	Minimize production and ghost fishing efficiency and duration of abandoned, lost and discarded fishing gear	● Zone to prevent gear conflicts, e.g., when passive gear is towed away or buoy lines cut by mobile fishing gear ● Gear supply chain traceability system and Extended Producer Responsibility schemes for fishing gear ● Technology to track gear position ● Disablement of ghost fishing efficiency of detected derelict gear

fishery-specific drivers for derelict gear production and enabling conditions that determine the likelihood of industry uptake [61].

Collateral sources of fishing mortality are more difficult to document as well as to remediate [84,95]. We provide four illustrative examples:

- Some pelagic apex predators bring baitfish to the surface. Reducing their abundance decreases the availability of prey to seabirds, potentially increasing their vulnerability to starvation and other stressors that could result in mortality [84].

- Fishing mortality of an albatross of a breeding pair usually results in starvation of the chick, and reproductive output is further reduced as the remaining albatross may require years before mating again [96].
- Capture, handling and release may induce premature birth, abortion and maternal mortality following abortion in live-bearing elasmobranchs, and possibly premature egg laying in oviparous elasmobranch species [97,98].
- Fishing mortalities indirectly modify trophic food web structure and processes as well as functionally-linked systems, which can result in regime shifts [99–101].

4. Direct and compensatory bycatch offsets

Offsets, a longstanding practice in terrestrial and wetlands management [51,102,103], could be applied to fisheries bycatch. Similar to carbon offset programs, to meet a bycatch-neutral no net loss objective, residual adverse impacts on biodiversity that are not avoided and minimized may be offset, as a last resort, by obtaining an equivalent gain. Or, a more-than-equivalent net biodiversity gain can be obtained to meet a bycatch-negative objective [53,104–107]. Offset programs could be designed to achieve equivalent or more-than-equivalent gains for ecological as well as socioeconomic residual bycatch impacts [52]. Three general approaches for achieving offsets are [104,108,109]:

- Direct offsets, also referred to as permittee-responsible offsets under wetlands and conservation offset programs, where the entity responsible for a biodiversity loss directly implements the offset activity;
- In-lieu fee-based compensatory mitigation, also called offset funding, where the entity responsible for the biodiversity loss pays a public or private body to implement conservation activities; and
- Banking, a type of compensatory mitigation, where restored, enhanced, created and, in rare cases, preserved biodiversity units are quantified as credits that can be debited to provide compensation in advance of authorized impacts of similar biodiversity units.

Bycatch compensatory offset approaches are types of 'polluter pays' systems where an entity is required or voluntarily pays an entity that implements interventions to offset residual bycatch impacts [60,70,107]. An entity representing the fishing industry (e.g., fishing company, association of fishing companies, other seafood supply chain companies or associations) could be responsible for bycatch offsets. Direct offsets would likely be small, individual conservation projects implemented directly by the entity responsible for residual bycatch. In lieu fee-based compensatory offset activities could also be implemented as individual, small conservation projects, but more likely would be implemented by a public agency or environmental non-governmental organization that manages well-established and large conservation programs [110]. Regardless of the offset approach, the conservation activities to achieve the offset are the same. However, unlike direct offsets, with mitigation banks, and possibly with in-lieu fee-based compensatory mitigation, fees from multiple entities could be pooled to implement larger, coordinated conservation activities [104,108].

Direct offset programs and in lieu fee-based offsets that are implemented through new, individual projects could be designed to charge fixed amounts for individual categories of residual bycatch impacts - such as by relative reproductive value (based on age-class and sex), population, and condition - that, as a precautionary approach, are set conservatively higher than the predicted cost for offset conservation activities. This precautionary approach would ensure that at least equivalency is achieved that may also result in a net biodiversity gain. However, bycatch mitigation banks and in lieu fee-based compensatory mitigation programs that use existing, established conservation programs would assess an in lieu cost and establish bank credit costs in advance of residual impacts, such as in a legal enabling instrument, where these compensatory offset fees are based on actual costs, incurred prior to the bycatch residual impacts, to achieve equivalency between residual impacts and offset gains.

A mitigation bank is one approach for compensatory offsets [108,109,111]. When management authorities determine that bycatch has been adequately avoided, minimized and remediated, they could authorize an entity to purchase (debit) credits from the bank to achieve an equivalent or more-than-equivalent gain to offset their residual bycatch losses. A mitigation bank can be owned and operated by a government agency, be a privately-sponsored bank (publicly owned, managed by a private entity), or be an entrepreneurial bank (both privately owned and managed) [109,112]. The bank may have an endowment fund from which investment income is used, in perpetuity, to monitor and manage conservation activities, such as the interdiction of invasive alien species and predators at a breeding colony, operating as a form of conservation trust fund. A bank may also have a contingency fund that would be used by a management authority to implement remedial actions both to address failed implementation by the bank owner or manager and stressors that are outside the control of the owner and manager, such as an oil spill that degrades a breeding colony [109].

A bycatch mitigation bank could adopt institutional and legal frameworks similar to those applied for wetlands and terrestrial banks. The governance body could include representatives across levels of government, from informal forms of self-governance and co-management frameworks, civil society and other stakeholders, similar to a Bank Review Team defined by USACE et al. [113] and USFWS [109] for wetlands and conservation banks, respectively. The bank would need an operational plan for business activities including to determine the cost for credits and an accounting system to track credits [108,109]. An enabling instrument could be a legal agreement between the bank owner and government management authority that contains all ecological and operational details [109,112]. The enabling instrument could define the structure for managing bank funds required for temporary or ongoing monitoring and management of offset projects. The instrument could define when a credit has reached maturity and is eligible for debiting, when the offset conservation activity has progressed to a stage where the level of risk of failure is deemed acceptable.

While there are currently no fisheries management frameworks with an offset program designed to achieve a bycatch-neutral or -negative objective, there are examples of bycatch offset activities being implemented. Some tuna canning companies that are members of the International Seafood Sustainability Foundation contribute US$1 per ton of albacore tuna purchased from pelagic longline fisheries. These contributions are then distributed by The Ocean Foundation through grants to support marine turtle conservation [114]. And, for example, a US California swordfish driftnet fishery association funded a Mexican environmental non-governmental organization's activities to protect a nesting site of the Pacific leatherback marine turtle [115]. There are also examples of fishers being paid to release threatened species, a type of Payments for Ecosystem Services scheme [92,93,116,117]. Broader, proposed applications of Payments for Ecosystem Services schemes would pay artisanal, small-scale fishers to avoid and minimize threatened bycatch [118], or tax fishers for bycatch [70,107]. But these examples of reward and penalty schemes are not being applied to offset bycatch.

4.1. Fisheries monitoring requirements

Bycatch offset programs require robust monitoring of the fishery that is offsetting its bycatch, and also when an offset program includes conservation activities designed to reduce bycatch in other fisheries. Monitoring could be achieved through conventional at-sea observers, fisheries electronic monitoring (EM) systems, or combination of the two approaches. Other fisheries monitoring approaches, including logbook programs, port sampling and fisher surveys, are unsuitable for an offset program because they produce inaccurate bycatch estimates [41,119].

When an offset program includes vessel-based bycatch levies, 100%

observer and/or EM coverage would enable robust estimates of individual vessel bycatch. A more cost-effective option is to use an EM audit model. All vessels are equipped with EM systems, and random samples of imagery and sensor data are reviewed to assess the accuracy of logbook data, which is self-reported by fishers. To incentivize accurate logbook reporting, penalties - such as full review of EM imagery, assigning an observer, or issuing a fine - can be applied when a vessel is found to have systematically recorded logbook data with low precision with EM data [119,120].

Alternatively, an estimated fleet-average bycatch rate could be applied to all vessels of that fleet to determine their cost for their offset bycatch fee. Individual vessels could receive a performance-based rebate if they prove, through independently verified and robust evidence, that their bycatch rate was lower than the estimated fleet average. This would reduce monitoring costs by placing the burden of proof on fishing entities [107].

Fleetwide bycatch offsets, depending on a given fishery-threatened bycatch species interaction, may require monitoring only a sample instead of all effort as is necessary with vessel-based bycatch levies. However, fleetwide offsets are less likely to elicit a strong economic incentive for improved bycatch mitigation performance by individual vessels [107], and can be inequitable as some vessels in a fleet may be responsible for a disproportionate share of bycatch [41,121].

4.2. Potential benefits and risks

Supplemental Material Table S1 summarizes potential ecological, socioeconomic and governance benefits and risks of bycatch mitigation offsets, and actions that increase the probability of achieving the benefits and avoiding the costs. Each potential benefit and cost included in Table S1 is categorized by offset approach.

Given the status quo where no fisheries globally are required to achieve no net loss of bycatch species threatened with extinction, mainstreaming offsets has the potential to achieve vast conservation gains. Bycatch offsets programs could be designed to contribute to achieving broad population- and species-wide, and landscape-level management objectives [122,123]. This could include maintaining a stock near target and above limit thresholds, and achieving objectives of species management, rebuilding and recovery plans. Offset activities could address the highest priority conservation objectives at broad spatial scales over the entire distributions of populations and species, across source and sink areas of their distribution, and across life history and ontogenetic stages. Bycatch offset programs can use a combination of on- and off-site and in- and out-of-kind conservation activities to achieve both local and broad objectives, discussed below.

As with other approaches that create economic incentives for the catch sector to mitigate bycatch, such as individual vessel bycatch quotas [41,70,124,125], requiring offsets for residual individual vessel-based bycatch, when integrated within a robust fisheries management framework, may strengthen fishers' resolve to avoid, minimize and remediate bycatch more effectively in order to reduce their offset costs. Thus, the offset acts as a 'double dividend' Pigovian tax, incentivizing prevention as well raising revenue for offsets [107]. Requiring offsets could also increase market demand for the innovation of more effective bycatch avoidance, minimization and remediation methods that are also more commercially viable, resulting in a net decrease in economic costs to the catch sector from bycatch [41,57].

Conversely, as with other approaches that create an economic penalty for bycatch, requiring offsets for residual bycatch could incentivize fishers to coerce observers, incentivize observer corruption, increase risks to observers' safety, and incentivize fishers to conceal bycatch from observers and EM systems [41]. Furthermore, problems well known in wetlands and terrestrial offsetting could occur by applying direct and compensatory mitigation offsets to fisheries bycatch (Table S1). These problems include lack of performance; temporal lags in offsetting losses; lack of equivalency between residual impacts and offsets; creation of a perverse incentive to not identify more effective bycatch avoidance, minimization and remediation solutions; and no biodiversity gains and hence ecological equivalency with bycatch losses when offset compensation is applied to activities that would have been conducted had the investment not been made (Table S1) [42,52,105,111,126].

Offset conservation activities may fail to achieve planned biodiversity gains for many reasons. Offset efforts through mitigating bycatch in other fisheries may fail because these complex social-ecological systems may lack adequately robust management frameworks and may lack the catch sector's buy-in and group norm to employ proposed changes [40]. Conservation activities at nesting colonies may fail if they do not have long-term investment and apply sustained engagement with local communities that results in their empowerment and improved welfare and change in human behaviors that threaten endangered species [127–129]. In some cases, there may be no suitable options available to offset a residual loss due to ecological or practicality constraints [130], or, discussed below, because some biodiversity losses from fisheries bycatch are irreversible.

Deviation from strict sequencing is an additional risk. Offsets have been characterized as a convenient and cost-saving mechanism for fishing and other seafood supply chain companies to avoid having to directly address their environmental performance, exporting their problems to the global south [131]. This is a risk if fisheries management authorities experience political coercion to reduce requirements for avoidance, minimization and remediation of adverse effects of bycatch due to the availability of an offset program. Strict legal and regulatory measures and robust and transparent surveillance and enforcement frameworks are needed to counter this risk (Table S1).

4.3. True and averted offset conservation interventions

Conservation actions that achieve 'true offsets' result from interventions that cause a gain in biodiversity. True offset activities could cause changes in factors that influence the density-dependent regulation of population growth. For example, increasing the carrying capacity of a population's habitat such as by enhancing the quality of a breeding colony, and expanding the area of existing or creating new breeding colonies, could increase absolute population size if breeding colony space or quality had been a density dependent factor limiting population growth. Or, establishing new breeding colonies could offset losses from the degradation or loss of existing colonies.

Other offset approaches avert future losses that were predicted to occur had the intervention not been implemented – they prevent a foregone loss in biodiversity [106]. While, under the Kyoto protocol, credit for carbon sequestration through "avoided deforestation" is not recognized due to concerns over proving that the habitat was truly under threat [132], averted foregone losses through bycatch offsets may be the equivalent of habitat preservation conducted as part of wetlands and conservation offset programs. Interventions to avert foregone losses include avoiding extrinsic factors that may play a role in regulating population growth, such as reducing or eliminating nesting colony predation by invasive alien species and mitigating bycatch mortality in other fisheries.

Averted loss offsets result in a net loss. For example, a fishery with 100 adult Antipodean albatross (*Diomedia antipodensis*) residual mortalities offsets their bycatch by averting 200 adult Antipodean albatross mortalities by a different fishery. This is a substantial conservation benefit - 100 fewer mortalities occurred than if the residual bycatch and offset intervention had not occurred - but results in a net loss of 100 adults from the population. For some populations, averted offsets may enable maintaining a population near a target reference point to meet ecological and socioeconomic objectives, and may maintain anthropogenic mortalities at or below a threshold level above which a population decline is predicted to occur. However, for some threatened bycatch populations and species such as the Antipodean albatross population which is declining at 5% per year mainly due to fisheries bycatch [133], offset programs designed to meet population- or global species-level management objectives will require a combination of averted and true offsets.

Direct and compensatory fisheries bycatch offsets, both true and averted, would be achieved through conservation activities that, in theory, would not otherwise have been implemented [52,53,134]. Conservation activities could address priority direct and collateral threats to the threatened populations requiring offsets. Many fisheries have bycatch of numerous threatened species across multiple taxonomic groups, which would require complex offset programs.

The air-breathing bycatch species - marine reptiles, marine mammals and seabirds - are exposed to a broad range of anthropogenic threats across ontogenetic stages. As a result, a relatively broad range of conservation interventions to achieve both true and averted loss offsets are feasible. For example, in addition to avoiding, reducing and remediating mortality in commercial, subsistence and recreational fisheries, conservation actions to address threats to marine turtles include (Fig. 1) [135–141]:

- Avoid and minimize human hunting and egg collection;
- Control and eradicate invasive species at nesting and haul-out sites, including introduced predators and species that degrade nesting habitat;
- Implement climate change adaptation activities, including measures to counter reduced moisture content of nesting beaches and increased female-to-male ratios due to elevated temperatures, allow unobstructed landward migration of coastal habitats in response to relative sea-level rise, translocate turtle nests to sites that are less vulnerable to inundation and erosion due to relative sea-level rise, storm surges and increasingly intense storms;
- Avoid and minimize habitat degradation and loss and other adverse effects from coastal development, including obstacles such as coastal hardening for erosion control at critical habitat, and rehabilitate (partially return functions and structure of a previous pre-disturbance state) and restore (completely return to a previous state), but do not ecologically convert, degraded and lost critical habitats;
- Manage human disturbances at nesting beaches/breeding areas, haul-out sites and other coastal habitats;
- Conduct pathogen control, including for the virus that causes fibropapillomatosis tumor disease, such as through quarantine, vector control, stranding response, vaccination and translocation;
- Recover, rehabilitate and release stranded turtles (e.g., due to cold-stunning, fibropapillomatosis, boat strikes, shark predation injuries, being obstructed by coastal hardening structures and other development, decompression sickness);
- Control and remove pollution and contaminants at critical habitats;
- Manage light pollution;
- Mitigate boat strikes in critical habitat, such as within internesting habitat within migratory corridors and foraging hotspots, and near breeding colonies and haul-out sites;
- Mitigate the production and adverse impacts of marine debris. This includes plastics and other debris that are ingested by turtles, and abandoned, lost and discarded fishing gear that risk causing ghost fishing, habitat degradation, distribution and transfer of toxins and microplastics into marine food webs, and other adverse ecological impacts;
- Conduct head-starting through collection of eggs and hatchlings, protection until larger/older and release; and
- Rehabilitate and release injured wildlife.

Relative to the air-breathing bycatch species, coastal and estuarine fishes offer fewer options for bycatch offset conservation activities. For example, actions to address threats to elasmobranchs in coastal and nearshore habitats, other than avoiding, minimizing and remediating the effects of commercial, subsistence and recreational fisheries, include [9,142–150]:

- Avoid and minimize degradation and loss of critical habitats (e.g., spawning and nursery habitats, mating and foraging aggregation sites) and other adverse effects from coastal development;
- Rehabilitate and restore degraded and lost critical habitat;
- Recover prey species abundance through reduced anthropogenic mortality;
- Mitigate causes of human-induced climate change and implement climate change adaptation actions for ocean warming, deoxygenation, increased CO_2 concentration and acidification;
- Avoid and reduce mortalities from shark control and culling programs designed to address human-shark conflicts, to protect swimmers from shark attacks, to reduce shark depredation of catch and bait, and to reduce shark predation of threatened prey species;
- Avoid and reduce collection for display in aquaria;
- Restock areas with depleted or extirpated populations with captive-bred and translocated sharks;
- Mitigate the production and adverse impacts of marine debris, including derelict fishing gear, discussed above;
- Control and remove pollution;
- Avoid locating anthropogenic electromagnetic fields, such as generated by subsea cables and other infrastructure, in critical habitat, to avoid the potential impacts on orientation, movements and migration; and
- Recover and release stranded sharks - however, mortality rates of stranded sharks are extremely high, thus offering minimal potential.

Oceanic fishes, whose main anthropogenic threat is from fishing mortality, offer an even more limited range of offset conservation actions, which may be limited to averted loss offsets. For example, commercial fisheries are the main threat to pelagic elasmobranchs, followed by effects of human-induced climate change and contaminant accumulation [9,16,151–153]. However, some sharks that are susceptible to capture in pelagic fisheries have distributions that include coastal habitats [154,155], where the additional threats discussed above for coastal elasmobranchs are additional sources of anthropogenic mortality.

Some offset approaches have no direct nexus to conservation gains (Table S1). For example, a fishing industry entity could potentially meet offset requirements by making in-kind contributions, such as making fishing vessels available for bycatch mitigation research or contributing fishers' knowledge to management activities [44]. Or, similarly, the entity could offset bycatch by conducting or paying for research or fisheries monitoring activities. These types of activities do not produce quantifiable biodiversity gains [42]. An activity that improves the robustness of information on bycatch, including the identification of informative predictors of bycatch risk, such as through increased observer coverage and research, or that develops more effective bycatch mitigation methods, may indirectly lead to biodiversity gains. But it is highly uncertain that these types of interventions will cause biodiversity gains, and it is also challenging to demonstrate causation. There is a high risk that the action will not result in a conservation gain and contribute to offsetting residual losses, supporting arguments that these types of activities should not be considered as offsets [42,156]. Alternatively, bycatch offsets programs could require a combination of conservation actions that include both offsets that result in direct conservation gains that are at least equivalent to the residual bycatch losses, and indirect forms of offsets that improve information and bycatch mitigation innovation but with relatively high uncertainty of an eventual biodiversity gain.

Furthermore, bycatch offsets by industrial fisheries and of developed countries that implement conservation interventions that cause socioeconomic costs to artisanal fishing communities of developing countries may be socioeconomically inequitable (Table S1). For example, an industrial fishery that offsets residual silky shark bycatch by implementing or paying for activities that reduce targeted silky shark catch by coastal fishing communities could reduce the local communities' food, nutrition and livelihood security [157,158], if the funding for the offset conservation activities is not employed to offset the socioeconomic costs to the coastal fishing communities. This raises concerns over social injustice of who bears the costs for the bycatch footprint of industrial seafood production. Similarly, allowing an industrial fishery to deviate from strict sequential marine turtle bycatch mitigation to offset avoidable turtle mortalities by paying for substantially lower economic cost conservation activities at nesting colonies in developing countries [115,159] raises equitability concerns. Bycatch offset programs could be designed to avoid an unjust distribution of burden on artisanal fisheries. Bycatch offset programs could require that affected human communities – both from residual bycatch impacts and from offset conservation activities – are at least no worse off, or are better off, following on- and off-site conservation offset activities [59,160].

Bycatch offset funding from industrial fisheries could be applied through Payments for Ecosystem Services schemes to reduce fishing mortality of threatened species in artisanal fisheries that otherwise could not afford the economic costs for bycatch avoidance, minimization and remediation interventions [107,118]. This could include paying for the initial outlay and ongoing maintenance and replacement of bycatch reduction devices that reduce catch rates of threatened bycatch species, and paying for artisanal fishers to release threatened catch (e.g., shortnose guitarfish Zapteryx brevirostirs in artisanal Brazilian bottomfish fisheries, [117]). The Payments for Ecosystem Services scheme could include offsetting any additional socioeconomic costs to the artisanal fishing community if the bycatch species were economically important target or incidental catch.

4.4. In-kind versus out-of-kind and on-site versus off-site offsets

Offset conservation activities could be either or both on-site and off-site, and either or both in-kind or out-of-kind. On-site offsets are conservation activities that occur within the part of the fishing grounds where threatened species bycatch occurred. In-kind offset activities involve mitigating bycatch of the same populations, age-classes, sex ratio. In some cases, bycatch offset programs can be designed to employ a combination of on- and off-site and in- and out-of-kind conservation activities to achieve both local and broad objectives.

In some cases, off-site and out-of-kind offset conservation activities may best meet broad population- and species-level management objectives. For example, establishing new breeding colonies at higher elevations is the highest priority for the global species conservation of Laysan (Phoebastria immutabilis) and black-footed albatrosses (P. nigripes) [161,162]. Existing colonies, located at low elevations along atoll coastlines, are threatened by relative sea-level rise and storm surges resulting from outcomes of human-induced climate change [163]. For these species, conservation actions implemented to offset residual bycatch could include off-site conservation activities that create new breeding colonies [164]. Or, for example, a fishery that captures a population of a bycatch species with a low conservation threat could provide an out-of-kind offset for its residual bycatch by mitigating priority threats to a critically endangered population of that species, possibly in combination with in-kind conservation activities to ensure that the population subject to bycatch retains its least concern conservation status.

However, just as wetlands and other ecosystems have site-specific ecological attributes (e.g., store surface water) and services (e.g., reduce flood damage) that cannot be offset through off-site conservation activities [108,113,165], there are also localized effects of fisheries bycatch. For example, bycatch offsets that are based on increased local population biomass of a coastal shark species at one site does not offset local community-level effects and socioeconomic costs of reduced local abundance of that population at another site where, for instance, a coastal shark fishing community's food, nutrition and livelihood security may be at risk [157,166].

4.5. Equivalency between residual bycatch losses and offset gains

An issue for all 'polluter pays' mechanisms, measurable evidence-informed metrics are needed to determine whether ecological and socioeconomic equivalence is achieved between residual losses and offset gains. Bycatch offset programs need to define compensation ratios (also referred to as multipliers) and standardized procedures to assess the equivalency between residual bycatch losses and gains from in-kind and out-of-kind offsets. Employing independent validation of the implementation of conservation activities and of the measurement of metrics to estimate offset gains is as important as independent fisheries monitoring through observers and EM systems.

Assessment methods are needed to define a unit of measurement or 'currency' for residual bycatch losses and for offsets gains that account for uncertainty and any temporal lag between the impact and when the offset gain is fully effective [51,111,132,156,167]. When in-kind offsets are applied, the same standardized assessment approach should be applied for the valuation of both residual bycatch impacts and offsets [109]. Offset program equivalency assessment should account for predicted long-term responses to conservation activities, including whether the gains are contingent upon ongoing management interventions. Some offset conservation activities, such as area-based management tools and management of threats at critical habitat, including predator control and managing invasive plants at nesting colonies, may need to be managed in perpetuity in order to sustain the conservation gain [109]. Preservation of critical habitat in perpetuity may be a priority bycatch offset conservation action to implement threatened species management and recovery plans [109].

To provide operationally-feasible, systematic, practical, inexpensive and rapid approaches to determine equivalence, biodiversity assessment methods have relied on metrics that are proxies for a broad range of targeted ecological attributes [52,132,167,168]. Offset programs have mainly used relatively simplistic metrics based on attributes for habitat area and indicators for habitat quality or functions ('weighted area'), which do not robustly nor comprehensively measure losses and gains across targeted biodiversity attributes [126,167,169]. However, equivalency assessment methods for fisheries bycatch offset programs might be able to employ metrics that more robustly assess impacts and benefits of affected populations and species. Table 2 identifies metrics that could be systematically accounted for by equivalency assessments for fisheries bycatch offset programs.

Most biodiversity offset assessment approaches are not designed to estimate net change in socioeconomic values, including ecosystem services [126,132]. However, a bycatch assessment program's equivalency assessment method could define the socioeconomic impacts of residual bycatch and offset activities. For example, assessments could estimate socioeconomic costs to coastal fishing communities, public willingness-to-pay or willingness-to-accept, and tourism values of bycatch losses and offset gains [107,176,177].

The population-specific valuation of residual bycatch impacts and offset gains should account for the effect of species-specific sex and age on the contribution to long-term population viability, which considers the sensitivity of a population, or sub-population/colony, to mortality levels [172–175]. The valuation should also account for the relative reproductive value of species-specific sex and age - the capacity for future reproductive contribution to the population. Relative reproductive value is widely used in assessing the viability of wildlife populations exposed to anthropogenic impacts in data-limited settings [170,171]. For example, marine turtles, like other long-lived species, have high adult survivorship and high rates of hatchling and juvenile mortality [178]. Marine turtle population dynamics are far more sensitive to changes in reproductive output (number of clutches laid per season, number of skipped breeding seasons) than to mortality of immatures and to a lesser extent of adults (especially adult males) [179–181]. These types of considerations led Crouse et al. [182] to estimate that 588 loggerhead hatchlings had an equivalent relative reproductive value of 1

Table 2
Metrics for equivalency assessments of fisheries bycatch offset programs to determine whether ecological and socioeconomic equivalence is achieved between residual bycatch losses from fishing mortalities and sublethal effects of fishing and gains from offset conservation activities after applying defined compensation ratios.

Metric	Equivalency assessment aspects
Valuation of residual bycatch fishing mortalities and sublethal effects	
Total population-specific (direct and collateral) magnitude of bycatch fishing mortality and sublethal effects	Observed mortalities: Catch, by species, age-class and sex, observed to have died from the interaction, based on the: (1) condition upon haulback, (2) fate of catch retrieved alive (retained versus released), and (3) condition upon release of non-retained live catch
	Predicted post-release mortalities: Probability of post-release mortality of live released catch, by species, age-class and sex, based on informative predictors such as handling and release methods, duration of air exposure, environmental conditions, condition at release, body size, and amount and anatomical position of gear remaining attached [87,89,91]
	Predicted magnitudes, by species, age-class and sex, of pre-catch, ghost fishing and collateral mortalities [84]
	Predicted adverse sublethal effects: Effects on fitness, growth and reproduction of injuries and stress from fisheries interactions [82,84]
Uncertainty	Estimated uncertainty of each estimated component of residual bycatch mortality and sublethal effects
Relative reproductive value of residual bycatch removals	Relative reproductive value of species-specific sex and age - the capacity for future reproductive contribution to the population [170,171]
Impact of residual bycatch removals on long-term population viability	Account for the effect of species-specific sex and age on the contribution to long-term population viability – the sensitivity of a population, or sub-population/colony, to mortality levels [172–175]
Effects on population- and species-level objectives	Effect of the residual bycatch on meeting broad objectives of population- and species-level management and recovery plans
Site-specific impacts	Site-specific ecological and socioeconomic losses due to fishing mortality removals and sublethal effects
Metric	Equivalency assessment aspects
Valuation of offset activities	
Qualifying interventions	Conservation activities that qualify for offsets, including to implement population or species management and rebuilding/recovery plans
Population-specific initial and ongoing abundance response	Population-specific magnitude of individuals that are conserved due to a conservation intervention, or for a conservation action that will be implemented long-term or in-perpetuity (e.g., predator control at a nesting colony, establishment of a no-take MPA in a shark pupping ground), the initial conservation gain and annual averted loss thereafter
Uncertainty	Estimated certainty of the response to the offset conservation activity, including an estimate of the long-term performance of an intervention if relevant
Relative reproductive value of conservation gains	See above, relative reproductive value of residual bycatch removals
Impact of offset activity on long-term population viability	See above, impact of residual bycatch removals on long-term population viability
Temporal lag	The amount of time between residual bycatch losses and equivalent offset gains
Effects on population- and species-level objectives	Contribution of the offset conservation gains towards meeting broad objectives of population- and species-level management and recovery plans
Site-specific gains	Whether conservation gains are on- or off-site, and site-specific ecological and socioeconomic gains due to offset activities

adult, and Chaloupka [183] to estimate that 1 adult female green turtle that nests in the Great Barrier Reef region is equivalent to 588 pelagic juvenile green turtles that are exposed to pelagic longline fisheries, or to 1330 eggs/hatchlings.

4.6. *Irreversible losses*

Bycatch offset activities may not achieve equivalency because some manifestations of biodiversity are irreplaceable – they cannot be offset [53,105,184]. It is not possible to offset residual impacts that cause the extirpation of a population or global extinction of a species [52,109,126,130]. Some populations/stocks may not be able to recover from reductions in biomass from fishing [6,7,9,183]. Reduced population sizes and extirpations from fishing may cause protracted or irreparable regime shifts in the state of local communities and broad, regional ecosystems, in some cases through synergistic interactions with other anthropogenic and natural stressors. These shifts may occur abruptly in some systems when tipping points are exceeded [100,185–187]. For some species and fisheries, it may not be possible to offset intraspecific changes in genetic diversity from fisheries-induced evolution [18,188]. Fisheries that selectively remove individuals based on highly heritable physiological, morphological and behavioral traits that vary within affected populations can reduce the range of phenotypes for these traits within the population, reducing population fitness and resilience, and reducing evolutionary responses to changes in pressures [18,19]. In these cases where offset options are unavailable or the residual bycatch impact is irreplaceable and cannot be offset, under a no-net loss policy, strict sequencing would require activities that achieve full avoidance. However, the existence of a fisheries bycatch offset program might cause regulators to deviate from strict sequencing ([108]; Table S1).

5. Conclusions

This study defined potential benefits and limitations of applying a sequential mitigation hierarchy to manage adverse ecological and socioeconomic impacts of fisheries bycatch, and approaches to maximize the likelihood of achieving the benefits and minimizing risks. Robust, evidence-informed metrics are needed to determine equivalency, such as in relative reproductive value and long-term population viability, between residual bycatch losses and gains from in-kind versus out-of-kind, and on-site versus offsite offsets. Application of a sequential mitigation hierarchy promises to improve the evaluation of alternative bycatch management strategies, increasing the certainty of meeting objectives of bycatch management.

Mainstreaming offsets has the potential to achieve vast conservation gains given the status quo where globally no fisheries are required to achieve no net loss of bycatch species threatened with extinction. Bycatch offsets systems can be applied now in fisheries with bycatch management frameworks that range from rudimentary to robust. At a minimum, however, effective bycatch offset programs require enabling conditions and management systems that are sufficiently robust to avoid the numerous potential pitfalls summarized in Table S1, including to ensure strict adherence to a sequential bycatch mitigation hierarchy. Offsets are intended to be the final tier of a sequential bycatch mitigation hierarchy - a last resort if threatened bycatch cannot first be avoided, minimized and remediated. If strict sequencing is followed, then offsets do not present a way for seafood companies to buy their way out of bycatch management requirements and export their problem to the global south. Fisheries with one or more rudimentary management component of bycatch monitoring, control, surveillance, enforcement and outcomes of enforcement actions would need to first make improvements to address these deficits. For example, observer coverage rates remain at very low levels in most marine capture fisheries and there are major deficits in evidence-informed policy to avoid, minimize and remediate threatened species bycatch at national and regional levels [41].

A sequential bycatch mitigation hierarchy remains absent from national fisheries legal and policy frameworks, international guidelines on managing bycatch and binding measures of regional fisheries management organizations [32,45,189]. The concept is also absent from major seafood buyers' sustainable sourcing policies, catch sector voluntary codes of practice, and environmental sustainability standards of fisheries certification programs, such as the Marine Stewardship Council [55,56]. Given this current lack of regulatory and market-based incentives for the catch sector and other seafood supply chain entities to offset their residual bycatch, a voluntary industry approach may initially be appropriate [60]. Bycatch offset pilot projects could be an effective initial step to provide practical experience, and to demonstrate efficacy [132] as well as economic viability.

A component of the pilots could assess economic viability by determining whether there is a net economic cost or benefit, including by assessing whether the bycatch offset pilot resulted in changes in seafood product value through the supply chain, and affected market access. The economic assessment would also account for any initial outlay costs, for example, to improve the fisheries monitoring system to enable reliable estimates of individual vessel-based bycatch. This would enable answering whether companies obtain a price premium, access new markets, and have higher certainty of retaining existing markets, for seafood products sourced from bycatch-neutral fisheries, and whether the economic value of these benefits outweigh the costs of offset activities. Pilots could also be designed to answer whether a bycatch offset program can provide economic benefits to small scale, artisanal fisheries with relatively low value target catch, after accounting for the costs for likely needed major improvements in monitoring. Findings from bycatch offset pilots might catalyze the political will needed to achieve the broad changes in legal frameworks, voluntary seafood sourcing policies of major seafood buyers, and certification schemes for sustainable fisheries necessary to mainstream a sequential bycatch mitigation hierarchy, including bycatch offsets [190].

Data Availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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Author statement

All authors contributed to conceptualization and to writing, reviewing and editing the original and revised versions of the manuscript. Gilman lead project management.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105522.

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