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Conceptual frameworks and key questions for assessing the contribution of marine protected areas to shark and ray conservation

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Article impact statement: Standardization of key terms and use of the portfolio risk concept describe how protected areas contribute to shark and ray conservation.

Abstract

Marine protected areas (MPAs) are key tools in addressing the global decline of sharks and rays, and marine parks and shark sanctuaries of various configurations have been established to conserve shark populations. However, assessments of their efficacy are compromised by inconsistent terminology, lack of standardized approaches to assess how MPAs contribute to shark and ray conservation, and ambiguity about how to integrate movement data in assessment processes. We devised a conceptual framework to standardize key terms (e.g., *protection*, *contribution*, *potential impact*, *risk*, *threat*) and used the concept of portfolio risk to identify key attributes of sharks and rays (assets), the threats they face (portfolio risk), and the specific role of MPAs in risk mitigation (insurance). Movement data can be integrated into the process by informing risk exposure and mitigation through MPAs. The framework is operationalized by posing 8 key questions that prompt practitioners to consider the assessment scope, MPA type and purpose, range of existing and potential threats, species biology and ecology, and management and operational contexts. Ultimately, MPA contributions to shark and ray conservation differ according to a complex set of human and natural factors and interactions that should be carefully considered in MPA design, implementation, and evaluation.

KEYWORDS
ecosystem management, fisheries, marine, MPA, protected areas, risk assessment

Marcos conceptuales y preguntas clave para evaluar la contribución de las áreas marinas protegidas a la conservación de tiburones y rayas

Resumen: Las áreas marinas protegidas (AMP) son herramientas importantes para manejar la declinación mundial de tiburones y rayas, por lo que se han establecido parques marinos y santuarios de diversas configuraciones para conservar las poblaciones de tiburones. Sin embargo, el análisis de su eficiencia está compuesto por una terminología inconstante, la falta de estrategias estandarizadas para evaluar cómo las AMP contribuyen a la conservación de tiburones y rayas, y una ambigüedad sobre cómo integrar la información sobre movimientos en los procesos de evaluación. Diseñamos un marco conceptual para estandarizar los términos más importantes (p. ej.: *protección*, *contribución*, *impacto potencial*, *amenaza*, *riesgo*) y usamos el concepto de riesgo de portafolio para identificar los atributos

Correction added on [18/02/2023], after first online publication: The author names Fergus John Molloy and Karin Leeann Gerhardt were corrected. The online version of this article has been corrected accordingly.

clave de los tiburones y las rayas (activos), las amenazas que enfrentan (riesgo de portafolio) y el papel específico que juegan las AMP en la mitigación del riesgo (seguro). La información sobre los movimientos puede integrarse al proceso al guiar la exposición y mitigación del riesgo con las AMP. El marco conceptual es operado con el planteamiento de ocho preguntas clave que invitan a los practicantes a considerar el enfoque de la evaluación, el tipo de AMP y su propósito, gama de amenazas existentes y potenciales, la biología y ecología de las especies, y los contextos operativos y de manejo. Finalmente, las contribuciones que tienen las AMP a la conservación de los tiburones y las rayas difieren de acuerdo con un conjunto complejo de factores naturales y humanos e interacciones que deberían considerarse cuidadosamente en el diseño, implementación y evaluación de la AMP.

PALABRAS CLAVE
AMP, áreas protegidas, evaluación de riesgo, gestión de ecosistemas, marino, pesquerías

【摘要】
海洋保护区(marine protected area, MPA)是解决全球鲨鱼和鳐鱼种群下降问题的关键工具, 目前已经建立了各种配置的海洋公园和鲨鱼保护区来保护鲨鱼种群。然而, 由于术语不统一、缺乏标准化方法来评估MPA对鲨鱼和鳐鱼的保护贡献, 以及对如何在评估过程中整合运动数据的认识不清晰, 对MPA保护成效的评估仍面临阻碍。我们设计了一个概念框架来标准化关键术语(如保护、贡献、潜在影响、风险、威胁), 并使用组合风险的概念来确定鲨鱼和鳐鱼的关键属性(资源)、它们面临的威胁(组合风险), 以及MPA在减缓风险方面的具体作用(保障)。运动数据通过提供风险暴露和基于MPA的风险减缓的信息, 从而被整合到这个过程中。该框架的实施基于提出的8个关键问题, 以推动保护实践者考虑评估范围、MPA类型和目的、现有及潜在威胁的范围、物种生物学和生态学, 以及管理和操作背景。最终, 基于一系列复杂的人类与自然因素及其相互作用, MPA对鲨鱼及鳐鱼的保护贡献可能有所不同, 因此, 在MPA设计、实施和评估中应仔细考虑这些因素。**【翻译:胡怡思;审校:聂永刚】**

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INTRODUCTION

Sharks and rays are among the most threatened marine taxa, with up to one-quarter of chondrichthyans threatened with extinction (Dulvy et al., 2014). Overfishing is driving declines, but pollution, habitat loss and degradation, and climate change all affect sharks and rays (Chin et al., 2010; Dulvy et al., 2014). Although shark and ray declines are usually framed as potential losses in biodiversity and ecosystem services, these declines also threaten social, cultural, and economic values. Sharks and rays are major components of large-scale commercial fisheries as targets and bycatch (Clarke et al., 2014) and are vital to some small-scale fisheries (Jaiteh et al., 2016). Sharks and rays also play an important role in ecotourism (Gallagher et al., 2015) and have important cultural values (e.g., Dell'Apa et al., 2014).

Many threatened sharks and rays occur in heavily fished areas, and several global hotspots are urgently in need of conservation (Dulvy et al., 2014, 2017; MacNeil et al., 2020). Many hotspots are in waters of developing nations that have relatively low conservation and management capacity (Dulvy et al., 2014; Pomeroy & Andrew, 2011). These challenges mean that conventional fisheries management approaches, such as stock assessments, centralized fisheries management, and formal monitoring, control, surveillance, and enforcement systems, may not be viable, especially for small-scale fisheries that are highly dispersed, diverse, and complex (Pomeroy & Andrew, 2011).

Marine protected areas (MPAs) are effective species conservation and fisheries management tools (Green et al., 2014), although outcomes for mobile and long-lived predators, such as sharks, are highly variable (Dwyer et al., 2020). Where MPAs prohibit extractive activities, such as fishing, they help maintain or enhance fish populations (Russ et al., 2015) and support ecosystem functioning. Coastal fisheries in developing nations may best be managed with MPAs because centralized management structures and locally driven needs can be accommodated (Jupiter et al., 2014). In addition to reducing exposure to fishing pressure (Doherty et al., 2017; Knip et al., 2012; White et al., 2017), MPAs may conserve sharks and rays by protecting aggregation sites and migration corridors, including for wide-ranging pelagic species (Boerder et al., 2019). Though animal movement is rarely considered when designing MPAs (Martín et al., 2020), very large MPAs that encompass vast ocean areas can conceivably protect even wide-ranging species (Singleton & Roberts, 2014). Thus, there are calls for more MPAs to be established to conserve threatened sharks and rays (Davidson & Dulvy, 2017).

Concerns have been raised about the drivers of MPA establishment (Singleton & Roberts, 2014) and whether they meet their conservation objectives (Dulvy, 2013; Leenhardt et al., 2013; Rife et al., 2013) or are merely paper parks (Pieraccini et al., 2017). Telemetry studies provide opportunities to assess how MPAs may protect sharks and rays, but approaches typically use relatively simple comparisons, such as the time that tracked individuals spend inside versus outside of an MPA (e.g., da Silva et al., 2013; Doherty et al., 2017; Knip et al., 2012), or a species' potential range compared with MPA size (Green et al., 2014; White et al., 2017). Focusing on a species' spatial and temporal overlap with MPA boundaries is unlikely to adequately describe an MPA's contribution to shark and ray conservation because MPAs vary by type and purpose and sharks and rays have a wide range of life-history traits and strategies, population structures (Cortés, 2004; Wearmouth & Sims, 2008), and behaviors (Dwyer et al., 2020). Furthermore, an MPA's contribution to a species' conservation depends on it mitigating the wide spectrum of potential threats and its role among other management approaches.

We devised a framework to assess an MPA's contribution to shark and ray conservation; applied it to case studies; and demonstrated how telemetry data could be used within the framework. We also developed key questions to guide its application.

Approach

Our work emerged from concerns expressed by marine park managers about narratives regarding MPAs and shark and ray conservation. We reviewed the literature on environmental risk assessment and MPA evaluation that focuses on sharks and rays. Key terms and concepts were identified and presented at a workshop of marine park managers and researchers (Appendix S1). Workshop attendees provided input about key questions scientists and managers should address when seeking to understand an MPA's role in shark and ray conservation. Resulting terminology, concepts, and frameworks were revised with workshop attendees and others until consensus was reached.

Need for consistent terminology

Terminology used to describe MPAs and shark and ray conservation is wide ranging, especially descriptions of movement patterns and how these affect exposure to risks, such as fishing and habitat loss and MPA efficacy. Our literature review, workshop, and iterative discussions identified a set of commonly used key terms and their definitions relative to shark and ray movement and telemetry studies (Appendix S2). We defined an MPA as "a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, 2008). Chapman et al. (2015) clarified shark habitat- and movement-type terminology, but risk assessment and MPA effects terms are not well defined. We identified and defined the following terms: *asset*, *contribution*, *exposure*, *potential impact*, *protection*, *rebound potential*, *risk*, *sensitivity*, and *threat* (Table 1).

Some researchers use binary, value-associated terms, such as *complete* or *incomplete protection* or *adequate* or *inadequate protection* (e.g., White et al., 2017) to discuss *contribution*. Others simply state that MPAs provide protection without describing the extent or adequacy of the protection provided (e.g., Doherty et al., 2017; Knip et al., 2012). The former approach oversimplifies the complexity of the issues because arguably all MPAs can provide some benefit to the species, even if only indirectly. Thus, binary, value-associated descriptors may be inaccurate. The latter approach is perhaps more accurate, but ambiguity about protection extent does not help managers identify the best conservation options. Describing the level of protection an MPA provides can also imply that the MPA was designed to protect sharks and rays, which is not always true. For example, populations of some sharks in the Great Barrier Reef Marine Park may be recovering (Espinoza et al., 2014), but these MPAs were not specifically designed to protect sharks and rays.

We propose that *protection* be used to describe how an MPA protects specific parts of the population from specific risks and that *contribution* be used when discussing an MPA's role in a species' or population's overall conservation (Table 1). *Contribution* also recognizes that any adequately implemented MPA may contribute to shark and ray conservation through indirect benefits and highlights that MPAs often exist among a range of other management actions. We hope using these terms will improve clarity and consistency in discussions about MPA roles in shark and ray conservation.

FRAMEWORK FOR ASSESSING RISKS AND MPA CONSERVATION CONTRIBUTIONS

The complexity of components and interactions affecting an MPA's contribution to shark and ray conservation is analogous to that faced in financial risk assessment and asset management. The financial concept of portfolio risk describes the complex suite of risks in an asset portfolio over time (Connor et al., 2010). To mitigate portfolio risks, asset managers, for example, diversify and use insurance. We used these concepts to construct a framework for shark–MPA interactions and identified 4 key components (Figure 1): assessment context, asset portfolio, portfolio risk, and insurance and mitigation. Each component consists of several attributes that need to be considered to assess an MPA's contribution to shark and ray conservation.

Assessment context

The assessment context describes the scope and scale of the assessment, describing spatial scale (local, national, regional, global), temporal scale (current, future), and conservation context (individuals, populations, species). Being explicit about scope and scale means assessments are explained in the relevant context and are thus comparable and more precise (Chin et al., 2010).

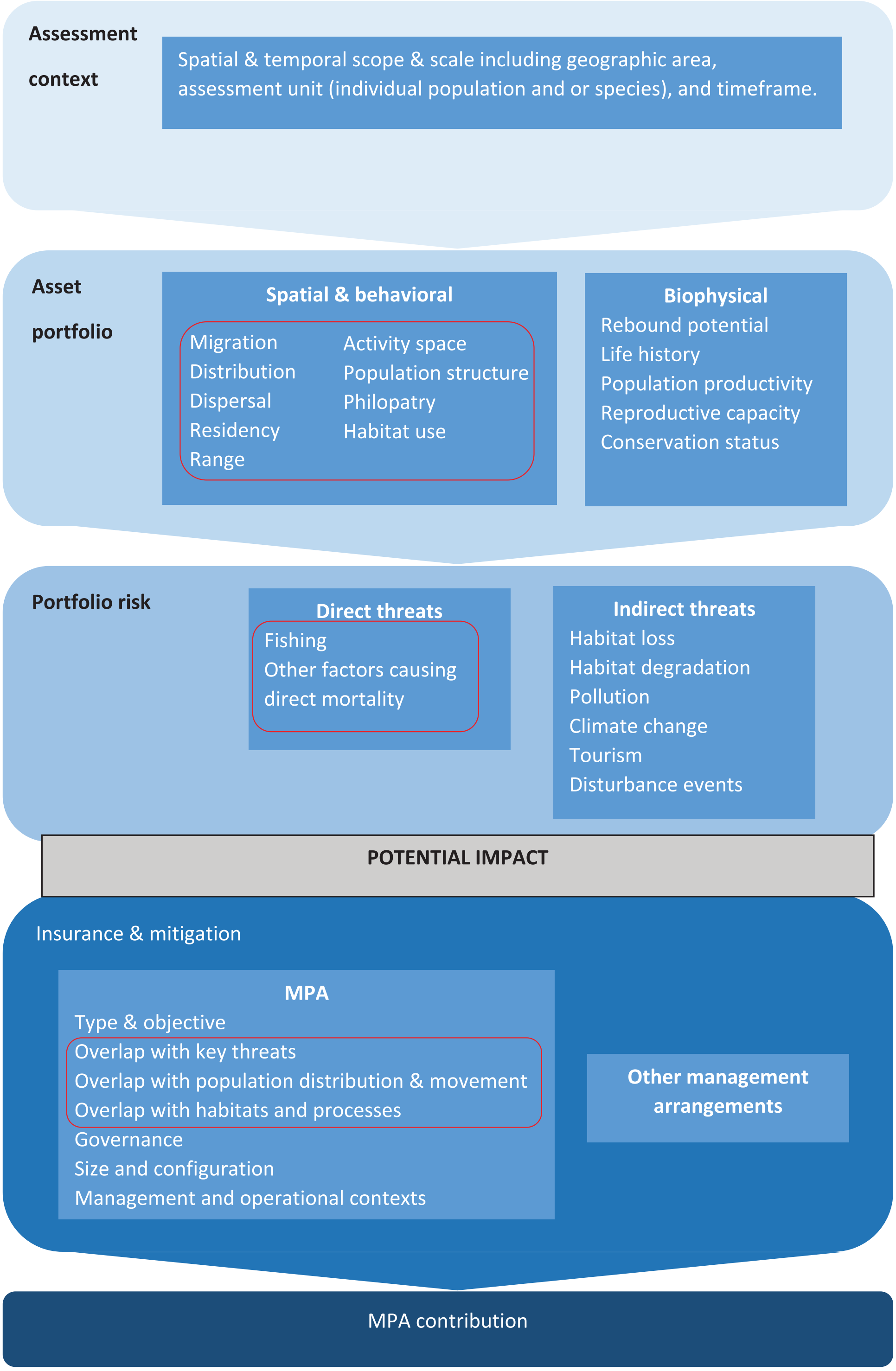

FIGURE 1 Components of steps in a framework for assessing the contribution of marine protected areas to shark and ray conservation (red boxes, telemetry data provide information to help define species attributes and exposure). When combined, these components and their interactions comprise the overall portfolio risk of a species or population

Asset portfolio

The asset is the shark or ray individual or the population and its collective attributes. These include spatial and behavioral attributes (range, distribution, residency, migration and philopatry, activity space, population structuring, and habitat use) and biophysical attributes (life-history traits, biological productivity and rebound potential, abundance or rarity, and conservation

TABLE 1 Key terms and definitions for assessments of risk and how marine protected areas contribute to the conservation of sharks and rays

Key term	Definition
Asset	Natural resource that may require protection (e.g., sharks and rays, mobile marine species)
Contribution	An MPA's overall contribution to a species' or population's conservation; determining contribution requires consideration of the full spectrum of threats to the species or population and of existing conservation and management arrangements and measures and tools, which allows an MPA's potential conservation contribution to be placed in a realistic context
Exposure	Amount of interaction between an individual or population and a specific threat (i.e., the amount of overlap between a species' activity space and the footprint of a threat [e.g., fishing effort])
Potential impact	A threat's effect on individuals and populations; determined by the species' exposure and sensitivity to the threat (Chin et al., 2010); potential impacts of threats need to be understood to determine how an MPA reduces threat impact (see *protection* below); here, impact is related to risk, not to MPA effectiveness
Protection	Extent to which a management action addresses specific risks; MPAs provide direct benefits by reducing an individual, species, or populations' exposure to threats, such as fishing while individuals are in the MPA; MPAs provide indirect benefits by preserving ecological conditions and processes that support populations
Rebound potential	Measure of the ability of a species or population to recover from exploitation or environmental shocks
Risk	Probability and significance of an adverse event occurring that negatively affects an asset; often expressed as a categorical range (i.e., low to high) derived from the species' exposure to threats and the consequence or impact of the interaction
Sensitivity	Species' innate susceptibility to a specific threat; variables that contribute to species' susceptibility may include life-history traits, population structure, rebound potential, conservation status, distribution, rarity, and dependence on particular habitat type or location
Threat	Specific activity, process, or phenomenon, either naturally occurring or anthropogenic, that could affect individuals, species, and populations

status). Collectively, these attributes define a species' exposure and sensitivity to threats.

Sharks and rays have diverse movement and habitat use patterns that affect their exposure to threats and the potential benefit gained from an MPA. A large overlap between a species core activity space and a threat indicates high risk exposure, and MPA protection can be expressed as the amount of overlap between an MPA's boundaries and the species activity space. In many instances, threat exposure and MPA protection is inferred from telemetry data on species' ranges (e.g., Green et al., 2014; Jacoby et al., 2020; White et al., 2017), philopatry, dispersal and migration patterns (Chin et al., 2013; Doherty et al., 2017), and residency and activity space (e.g., Chin et al., 2016; da Silva et al., 2013; Martín et al., 2020).

Insights into MPA effectiveness can also be inferred from fisheries catch data that describe relative abundance between locations (Goetze & Fullwood, 2013; Jaiteh et al., 2016; Speed et al., 2018) and from population structure (Wearmouth & Sims, 2008). Because many sharks and rays have highly structured populations (Wearmouth & Sims, 2008), MPA assessments should consider which parts of a species' population are protected. Furthermore, an MPA's protection against specific threats may be increased if it protects critical processes (e.g., mating) or habitats with a disproportionate influence on fitness and survival (e.g., nursery grounds) (Chin et al., 2016; Knip et al., 2012).

Chondrichthyans have a wide range of life-history and demographic traits (Cortés, 2004), which affect their sensitivity to threats. Although sharks and rays are generally described as long lived, slow growing, and slow reproducing, they have different rebound potentials and some species are at lower risk than others (Simpfendorfer & Dulvy, 2017). Small, fast-growing species with high reproductive outputs can accommodate more fishing pressure (i.e., they have low sensitivity) (Tobin et al., 2010).

Life-history traits also indicate which size and sex classes drive population replenishment and thus should be prioritized for conservation. Large, slow-growing sharks may require protection of breeding adult females (McAuley et al., 2007; Prince, 2005). If an MPA does not protect these critical population components, its conservation contribution is reduced.

Some shark and ray species are at low conservation risk, whereas others are at high risk (Dulvy et al., 2014; Simpfendorfer & Dulvy, 2017). Thus, an MPA's conservation contribution will vary according to the sharks and rays that occur within their boundaries. For example, an MPA that protects a slow-growing, critically endangered endemic ray will have a globally significant conservation contribution, whereas an MPA that protects a small fraction of a common, widely distributed shark will have a much lower relative conservation contribution.

Portfolio risk

Portfolio risk describes the suite of threats and their impacts on the individuals, population, and species being assessed and identifies the greatest threats. Typically, *risk* is defined as the likelihood of an entity encountering a specific threat and the consequence or impact resulting from the encounter. Describing portfolio risk includes assessing 3 types of information: all relevant threats to sharks and rays in the assessment area (e.g., types of fishing, habitat loss and degradation, environmental pressures, such as storms, climate change, pollution); exposure and sensitivity of sharks and rays to each identified threat; and potential impact of the interaction between exposure and sensitivity to each threat (i.e., how much mortality this interaction is likely to cause in the asset). The higher the potential mortality, the higher the risk.

Once the key risks are identified, the potential effects of management interventions (i.e., insurance), such as MPAs, can be examined. A discussion or analysis of an MPA's effectiveness should include some consideration of the entire set of threats facing the species and the level of potential impact from those threats.

Insurance and mitigation

MPAs occur in a wide range of social–ecological contexts that affect how marine resources are used and valued and management contexts (e.g., governance, trust, legitimacy, and capacity) that describe the factors influencing MPA implementation and outcomes (MacKeracher et al., 2019). MPA designs and objectives also differ. The International Union for the Conservation of Nature (IUCN) protected area categories provide an international standard that defines different MPAs. For an area to meet IUCN criteria for an MPA, conservation must be its overarching purpose (Day et al., 2012). However, many MPAs allow extractive activities; thus, different types of MPAs afford different levels of protection to sharks and rays from fishing (Day, 2017; Frisch & Rizzari, 2019). Although totally closed zones or prohibited entry zones can produce strong conservation effects (Frisch & Rizzari, 2019), there is evidence that partial protection from fishing can also produce conservation benefits (Hall et al., 2021). Marine managed areas (MMAs) also exist, and, although they may not be established primarily for conservation objectives (Day, 2017), they can provide significant protection from fishing (Jupiter et al., 2014). So, MPAs range from large, multiple-use parks with conservation objectives and multi-institutional governance (Day & Dobbs, 2013; Hall et al., 2021) to small, locally managed MMAs established to improve food security (Jupiter et al., 2014); thus, MPA contributions may likewise vary.

Efficacy of MPAs also depends on compliance and enforcement (Rife et al., 2013); even well-resourced MPAs have enforcement challenges (e.g., Bergseth et al., 2017). Additionally, the spectrum of other management approaches implemented within MPAs and their contribution need to be considered when assessing MPA efficacy (e.g., Hughes et al., 2016). Thus, a discussion of MPA contribution to shark and ray conservation should consider all of these MPA attributes: social–ecological and management contexts; objectives and design; efficacy (especially the perceived level of MPA compliance and enforcement); and other management arrangements in place.

Applying the framework

Each component and attribute of the assessment framework (Figure 1) could be described using qualitative or semiquantitative approaches (e.g., Chin et al., 2010; Walker et al., 2021). The first component, assessment context, does not directly link to other framework components (Chin et al., 2010). Instead, it is an overarching component that clearly defines the scope and scale of the assessment.

The second component, asset portfolio, requires the assessor to identify the species of interest and examine its spatial, behavioral, and biophysical attributes and conservation state. These traits define the species' exposure and sensitivity. Where telemetry data can help describe spatial attributes and exposure to threats is also indicated. Many attributes cannot be informed by telemetry data; thus, considering only telemetry data provides an incomplete assessment of an MPA's contribution. The third component, portfolio risk, requires the assessor to examine all direct threats, such as fishing, and indirect threats, such as environmental disturbances, unsustainable tourism, pollution, climate change, and habitat loss and degradation to the species (Figure 1). This process should also consider selection effects that may alter impacts on different portions of the population (e.g., consequence of fishing juveniles vs. adult females). Assessing the asset's exposure (spatial and behavioral attributes) and sensitivity (biophysical attributes and conservation state) to each threat identifies the potential impact from each threat and thus the threats that pose the greatest risk.

Once portfolio risk is described, an MPA's potential to mitigate risks can be examined by explicitly describing the MPA's operational and management context, which includes considering its design attributes, such as its IUCN category, objectives, size, and configuration (single MPA or part of a network). Once the MPA is described, its potential to reduce exposure to specific threats (i.e., level of protection) can be determined by examining species attributes, including extent of activity space, residency, and proportion of the population that occurs in the MPA; size, sex, and maturity status of individuals in the MPA; and extent the MPA protects key life-history stages, reproductive processes, or habitats and processes that have a disproportionate effect on fitness and survival. The MPA's potential indirect benefits should also be included in the narrative. Finally, the assessor should explicitly consider operational and management contexts to explore how the MPA functions and thus the level of protection from risks identified in the portfolio risk. The MPA's contributions are thus explicitly described and can be placed in context of other management actions in the assessment area.

Key questions for assessing MPA contributions to shark and ray conservation

The conceptual framework (Figure 1) and case studies in Figure 2 illustrate the complexity of describing an MPA's potential to contribute to shark and ray conservation. To simplify, the complexities can be resolved into 8 key questions that when addressed integrate all the components and attributes. These

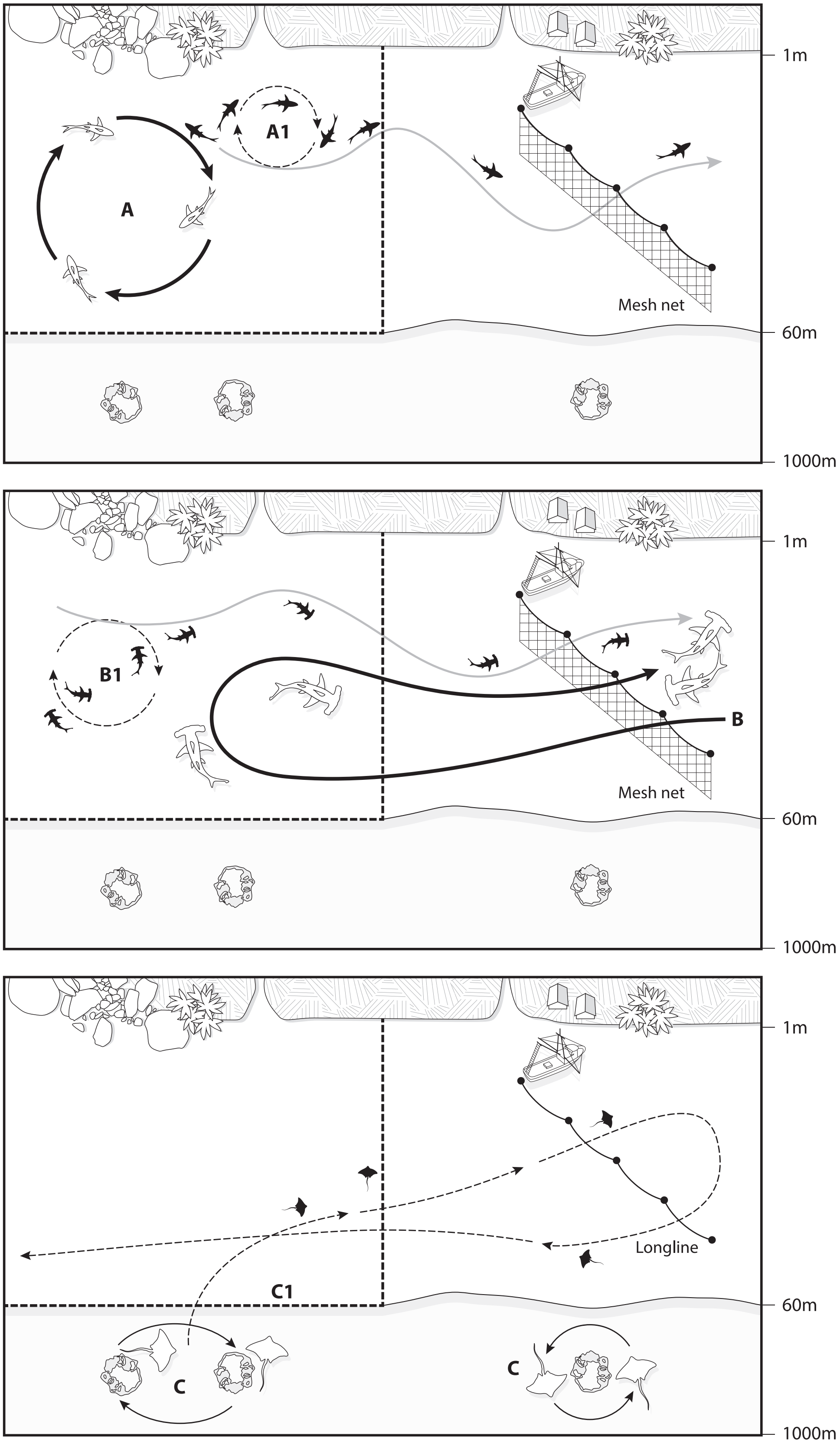

FIGURE 2 Case studies illustrating how population structure, life history, and movement can affect portfolio risk of sharks and rays and consequently how a marine protected area (MPA) contributes to protection (solid animals, juveniles; outlined animals, adults; solid dark arrows, movement of adults; dashed lines, movement of juveniles; solid gray line, dispersal of subadults). The area includes a productive coastal habitat and rocky foreshore that are within an established, well-enforced, no-take MPA (dashed line) that extends to the edge of the continental shelf. Impacts from habitat loss and degradation are minimal. The area outside the MPA is fished by vessels that are managed and monitored through adequately resourced fisheries management agencies

questions address all aspects of the framework and Table 2 provides specific guidance about the types of information needed to address each question and how to integrate this information into a management narrative or research study. Of particular note, telemetry data can be applied to address Question 2, which identifies how the species uses the area being assessed and the extent of protection an MPA might provide.

CASE STUDIES

To demonstrate how the framework (Figure 1) and the questions (Table 2) are applied, we examined 3 case studies that incorporate actual examples from 3 different types of sharks and rays. Figure 2 shows real-world scenarios for 3 species with different life histories, movement patterns, population structures, and conservation and management contexts.

Case A

The asset portfolio in case A is the blacktip reef shark (*Carcharhinus melanopterus*), a common, relatively small but slow-growing coastal shark that has breeding populations of resident females with small activity spaces in Australia's Great Barrier Reef Marine Park (GBRMP) (e.g., Chin et al., 2016). Juveniles (A1) are resident and remain in the coastal habitat until they begin to mature, at which time they disperse along the coast (e.g., Chin et al., 2013).

The portfolio risk for this case includes limited line fishing and habitat loss and degradation. The MPA protects breeding adult females from net fishing; however, dispersing juveniles are exposed to net fisheries in adjacent MPA zones, and some juveniles are captured and retained in the fishery. However, the life history of these species suggests that preserving the biomass of adult breeding females is most important and that if enough juveniles avoid capture, the conservation outcome should be favorable (Prince, 2005).

By protecting the breeding adult females, the MPA is likely to make a significant direct contribution to conserving this species at a local scale (insurance and mitigation). However, because the species is widespread, the MPA's long-term contribution to the regional population is speculative.

Case B

The asset portfolio in case B is hammerhead sharks (*Sphyrna* spp.), which are large, relatively slow-growing, highly mobile species that show strong evidence of stock structuring in northern Australia (Chin et al., 2017). Large adult females appear to make seasonal migrations to coastal habitats to give birth in nursery grounds (Chin et al., 2017). The neonates and juveniles in case B1 are highly resident in discrete areas along the coast but disperse as they mature.

The portfolio risk for this case includes net and line fisheries as well as habitat loss and degradation. In the GBRMP, coastal no-take and conservation-park zones prohibit net fishing and thus protect neonates and juveniles. However, large breeding adults including pregnant females are exposed to net fisheries as they move between these zones and adjacent waters, and some are captured and retained. Some dispersing juveniles are also harvested.

The MPA's direct contribution to hammerhead conservation is reduced as the most important portion of the population, breeding females, are taken in adjacent fisheries. Additionally, fishing maturing juveniles exacerbates the risk. Consequently, fisheries management tools, such as seasonal restrictions of no-take provisions, may be a better option for species conservation, and MPA contributions to protecting neonates, juveniles, and nursery grounds should be recognized in the fisheries management approach (insurance and mitigation).

Case C

The asset portfolio in case C is a hypothetical case of a relatively rare, large, very slow-growing skate that aggregates around seamounts in deep water on the continental slope. Adults are highly resident at these seamounts but may migrate to shallower waters on the continental slope to lay eggs (e.g., Hoff, 2016). Upon hatching, the neonates migrate up the slope to the continental shelf where neonates and juveniles remain and intermingle, moving extensivley throughout the area as they maturec (Case C1).

The portfolio risk for this case includes deep water and shelf fisheries. The species' movements expose juveniles to longline fisheries; however, due to gear selection effects (e.g., they are rarely hooked due to their mouth size and feeding behavior), they are not captured and fisheries impact is negligible. Upon maturing, the juveniles move back into deeper waters. In this scenario, protection of all size classes is a priority due to the species' rarity and slow growth. However, there are no deep-water fisheries present and the animals are not captured in the existing longline fishery. Consequently, the MPA is not directly relevant to the species' protection in this case (insurance and mitigation).

These case studies illustrate the complexity of interactions between a species' biology, population structure, and movement patterns, and how they affect portfolio risk and an MPA's potential conservation contribution. However, other factors could also be considered. For example, species may be exposed to multiple threats from different fisheries, environmental disruption, climate change, pollution, habitat loss, and disturbance (Chin et al., 2010; Dulvy et al., 2014). Additionally, the MPA may provide indirect benefits, such as increasing prey abundance, that benefit the growth and survival of neonates and juveniles (Figure 2, cases A1 and B1). The implications of scope and scale also need to be considered. For example, although the hypothetical MPA is presently not relevant to protection of the skate (Figure 2, cases C and C1), this species could be rapidly depleted should fisheries move into deeper water in the future (Simpfendorfer & Kyne, 2009); consequently, precautionary management may be required. Finally, these case study

TABLE 2 Eight key questions when assessing the contribution of a marine protected area (MPA) to shark and ray conservation

Question	How to answer the question	Relevance and application
Question 1: What is the scope of the study?	Clearly define the spatial scale of the assessment: is the assessment describing the MPA's conservation contribution at a local scale, regional scale, global scale, or at multiple scales? The scale selected may depend on the intended audience of the study. Clearly define the temporal scale of the study: is the study examining past and present trends, or is it predicting how an MPA's effects may change under future conditions? Interpretation should also distinguish between individuals, populations, and the entire species. Some studies focus on movements and behaviors of individuals that are then extrapolated to the conservation of the population. This distinction should be made clear, and the results of the study discussed in terms of the population at an appropriate scale (e.g., Chin et al., 2016–208-209). This information should be included in the introduction section describing the study's aims, in the methods section describing the analyses, and in the discussion section describing the study's ramifications and limitations.	Describes the assessment context (Figure 1). This is essential to help ensure the appropriate data are used and the findings are interpreted at the appropriate spatial and temporal scales. For example, the study could focus on a particular location and its surrounding MPAs (e.g., Goetze & Fullwood, 2013), a single location within a broader MPA network (e.g., Chin et al. 2016; Knip et al., 2012), or over a large area encompassing an entire MPA network (e.g., White et al., 2017). Being explicit about the temporal scale also clearly describes whether the study is examining the present-day contribution (e.g., Goetze & Fullwood 2013) or informing the design of future MPAs (e.g., Doherty et al., 2017).
Question 2: What is the species' movement pattern and population structure?	Summarize what is known about the species' movement and behavior (Figure 1), including residency, habitat use, philopatry, and migration and whether particular habitats or locations are especially important to its conservation. Describe the species' range and distribution (e.g., local resident vs. highly migratory) and define population structure. Movement patterns should also be described separately for sexes and life stages. For example, this information could illustrate that an MPA makes a high conservation contribution to a species that has breeding adult females that are highly resident with small home ranges within the MPA (Figure 2, case A), but makes a lower contribution to a second species where adult females are wide ranging and experience mortality from fishing gear set outside the MPA (Figure 2, case B). The species' life history, conservation context, and population structure could be discussed in the introduction section and revisited in the discussion when analyzing the MPAs contribution to its overall protection.	Describes part of the asset and portfolio risk, specifically the spatial and behavioral aspects that affect its exposure and sensitivity to threats (e.g., distribution, habitat specificity, and dependencies), and the potential benefit received from an MPA. This information is often derived from telemetry data, but may also come from tag, mark, and recapture data and other data types that indicate population structure and movement and connectivity (e.g., parasites, genetics).
Question 3: What are the life-history and population characteristics of the species?	Describe information about growth rate (or use size as a proxy indicator of growth), age at maturity, reproductive output (number of pups, reproductive periodicity), relative abundance, distribution, and conservation status. Information about sex segregation and population structuring should be included. The species' life history, conservation context, and population structure could be discussed in the introduction section and revisited in the discussion when analyzing the MPAs contribution to its overall protection.	Describes parts of the asset portfolio, specifically the biophysical attributes concerning rebound potential and conservation context (Figure 1). Identifying the species' conservation status can help place an MPA's contribution in the appropriate context (e.g., an MPA's global significance may be much greater if it makes a large contribution to the protection of a critically endangered species). Exploring the species population characteristics helps determine how an MPA may contribute to its conservation. For example, a rare, slow- growing species with a restricted range may gain much more benefit from an MPA than a fast-growing, widely distributed species.

(Continues)

TABLE 2 (Continued)

Question	How to answer the question	Relevance and application
Question 4: What are the key threats to the species?	Identify the key threats that the species has highest exposure and sensitivity to and thus have the highest impact. This involves describing movement and behavior patterns, comparing these with where threats are occurring, and using information on the species biophysical attributes to predict the impact severity from this overlap. Information should include evidence of known direct (e.g., fishing) and indirect (habitat loss, disturbance) threats (Figure 1) and statements of how well these impacts are quantified and understood. Selection effects (Figure 1, Figure 2) should be clearly identified (i.e., whether threats mainly occur in specific sexes and size classes of the population). There should be clear distinction between threats and impacts (Table 1). For example, selectivity effects may mean that even if a species encounters fishing gear (threat), the impact may be minimal if capture or retention rates are low or postrelease survival is high (e.g., C1 in Figure 2). This narrative should be included in the introduction or background section of articles and reports when describing the local situation (e.g., fishing activities) and in the discussion when describing how an MPA may reduce risks.	Identification of threats informs portfolio risk, an essential step because the key risks and impacts need to first be identified to understand how MPAs may contribute to mitigating these risks.
Question 5: How do species and population characteristics and movement patterns in combination with key threats contribute to portfolio risk?	Discuss the conservation significance of the threats and impacts a species encounters within the portfolio of risk and how the population is likely to be affected by these threats, and predict which portions of the population most need protection (long-lived, slow growing species are more likely to need protection for adult females). This narrative should be included in the discussion, specifically in describing whether an MPA addresses the key threats or protects key elements of a population, and thus assessing it's contribution to the species' conservation	Identifies the highest priority conservation issues, and highlights the drivers behind these issues. Identifying why the asset is at risk can help understand how an MPA may (or may not) protect the asset.
Question 6: What are the characteristics of the MPA?	Clearly identify the MPA objectives (e.g., conservation, habitat protection, tourism, enhancing fisheries), including what type of MPA it is according to the International Union for the Conservation of Nature (IUCN) classification (Figure 1). Describe how long it has been established. Describe the MPA's size, the habitat types it protects, and the activities it manages. Does it protect key habitats and biological processes? Clarify whether it is a stand-alone MPA, part of an MPA network, or a very large MPA. A key factor will be whether the MPA allows extractive activities such as fishing. Assess the MPA's overlap with key threats and key habitats and biological processes (e.g., nursery grounds, mating areas). Information about the MPA's objectives and design could be included in the methods section and revisited in discussion about its efficacy.	An MPA's contribution to species' protection depends on the restrictions it places on activities. Some MPAs allow certain types of fishing, whereas others are strictly no take. Thus, the MPA needs to be clearly described according to its IUCN category (Figure 1). Discussion of an MPA's effectiveness must also explicitly consider its design and intent. For example, if an MPA was designed for habitat protection or to protect cultural values, it is incongruous to assess its efficacy based on its contribution to shark and ray conservation. An MPA's conservation effects depend in part on the extent of overlap between the MPA and the threats and impacts, as well habitats where key biological processes for species are occurring.

(Continues)

TABLE 2 (Continued)

Question	How to answer the question	Relevance and application
Question 7: What is the operational context of the MPA?	Briefly describe the social, cultural, economic, and political context of the MPA, including the main social, cultural, and economic pressures behind the MPA's establishment and operation. Briefly describe the social, cultural, and economic values for the species involved, and the drivers behind the pressures causing impacts (Figure 1). Describe the governance structure: is it a locally managed MPA established by community action, a government MPA, or driven by a nongovernmental organization with comanagement arrangements (Figure 1)? Indicate how the MPA is managed (who is managing it, are resources for management sufficient). Provide information about the MPAs legitimacy with users, stakeholders, and communities. Also indicate the level of compliance and enforcement. Identify any relevant issues that affect the MPA's implementation (e.g., noncompliance, inconsistent funding, community disagreements or disputes, displacement, lack of political will).	This information describes how an MPA is being implemented and thus determines whether an MPA's contribution is only theoretical (indicating that new research and conservation efforts may need to be developed) or is tangible (indicating that existing efforts need to be maintained, enhanced, or both). This narrative could be placed in the methods section describing the study site and should be revisited in the discussion regarding the actual contribution of the MPA to species' conservation and about future research and conservation needs.
Question 8: What other management arrangements are in place?	Briefly describe the wider management context (Figure 1). Are species in question managed through fisheries management plans or conservation plans? Briefly describe the existing management arrangements that may affect the key direct pressures and impacts identified in Question 4. If fishing is a key pressure, are there closed seasons, catch limits (size or sex restrictions, bag limits), no-take species, or restrictions on types of fishing gear. Briefly describe the existing management arrangements that may affect the key indirect pressures and impacts identified in Question 4. For example, if habitat destruction is a key impact, describe whether there is management for habitat protection, pollution reduction, and so forth.	To assess and MPAs role in species conservation, its contributions must be considered alongside existing management tools. For example, an MPA's contribution could be large if it was the only management in place, but could be reduced if it protects species that are already effectively protected through other means. Conversely, conclusions regarding an MPA's social and economic impacts should not be isolated from other management arrangements affecting the same species (Hughes et al., 2016). These considerations should be explored in the discussion to place the MPA's contributions into the wider context of actions both directly and indirectly managing the species.

designated that compliance and management of the MPA and the adjacent fishery were sound. This may not be the case (e.g., Campbell et al., 2012). If MPA compliance is low, the MPA's conservation contribution may be diminished (Campbell et al., 2012; Rife et al., 2013).

Accommodating data paucity and uncertainty

In an ideal scenario, sufficient data would be available to address all 8 questions and populate the framework. In reality, information is likely patchy and incomplete. Where data on species movement and behavioral and biophysical attributes are limited, proxy data from conspecifics or closely related species should be used. The life-history traits, population structures, and generalized movement behaviors of many sharks and rays are well documented, and these traits can be applied in risk assessments (Chin et al., 2010; Tobin et al., 2010). The IUCN Red List is also widely used as a proxy for species vulnerability (e.g., Dulvy et al., 2014; Hylton et al., 2017). Species vulnerability, threats, and management efficacy can also be ranked using descriptive categories and integrated into risk assessment frameworks (e.g., Chin et al., 2010). Using descriptive categories enables assessors to accommodate patchy and incomplete data and to be explicit about uncertainty. Additionally, preliminary assessments of a species' current condition and historical trends and threats can be inferred from historical data and stakeholder interviews (Ward-Paige, 2017) and structured expert elicitation

(Hemming et al., 2018). Nevertheless, managers are still often required to make decisions based on the best available information, and where unacceptable shark and ray conservation risks exist, uncertainty is not a reason to delay assessments to guide management actions as echoed by the precautionary principle of the United Nations Fish Stocks Agreement (1995).

Summarizing MPA contributions to shark and ray conservation

Existing research indicates that MPAs likely contribute to shark and ray conservation. In some cases, an MPA could be the most effective management option where fisheries management capacity is limited or where multiple conservation outcomes are sought. In nations in the Global South with limited management capacity and extreme logistical challenges, locally managed marine area MPAs may be key management tools (Jupiter et al., 2014). However, a fundamental challenge facing natural resource managers remains: understanding the significance of an MPA's contributions to the target species' conservation and its usefulness among other management tools. Addressing the questions identified here will provide responsible interpretations of data within a defined context and assessments that are more explicit and complete. As new information becomes available, it can be used to refine management through the adaptive management cycle. Consequently, we encourage authors and assessors to address the key questions as best as possible given the information they have available and propose that as long as uncertainty is explicit, addressing even some of these questions will improve the quality of the interpretations that managers can use to inform decisions for the conservation and management of sharks and rays.

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REFERENCES

Bergseth, B. J., Williamson, D. H., Russ, G. R., Sutton, S. G., & Cinner, J. E. (2017). A social–ecological approach to assessing and managing poaching by recreational fishers. *Frontiers in Ecology and the Environment*, *15*, 67–73.

Boerder, K., Schiller, L., & Worm, B. (2019). Not all who wander are lost: Improving spatial protection for large pelagic fishes. *Marine Policy*, *105*, 80–90.

Campbell, S. J., Hoey, A. S., Maynard, J., Kartawijaya, T., Cinner, J., Graham, N. A. J., & Baird, A. H. (2012). Weak compliance undermines the success of no-take zones in a large government-controlled marine protected area. *PLoS ONE*, *7*, e50074.

Chapman, D. D., Feldheim, K. A., Papastamatiou, Y. P., & Hueter, R. E. (2015). There and back again: A review of residency and return migrations in sharks, with implications for population structure and management. *Annual Review of Marine Science*, *7*, 547–570.

Chin, A., Heupel, M. R., Simpfendorfer, C. A., & Tobin, A. J. (2013). Ontogenetic movements of juvenile blacktip reef sharks: Evidence of dispersal and connectivity between coastal habitats and coral reefs. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *23*, 468–474.

Chin, A., Heupel, M. R., Simpfendorfer, C. A., & Tobin, A. J. (2016). Population organisation in reef sharks: New variations in coastal habitat use by mobile marine predators. *Marine Ecology Progress Series*, *544*, 197–211.

Chin, A., Kyne, P. M., Walker, T. I., & McAuley, R. B. (2010). An integrated risk assessment for climate change: Analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change Biology*, *16*, 1936–1953.

Chin, A., Simpfendorfer, C. A., White, W. T., Johnson, G. J., McAuley, R. B., & Heupel, M. R. (2017). Crossing lines: A multidisciplinary framework for assessing connectivity of hammerhead sharks across jurisdictional boundaries. *Scientific Reports*, *7*, 46061.

Clarke, S., Sato, M., Small, C., Sullivan, B., Inoue, Y., & Ochi, D. (2014). *Bycatch in longline fisheries for tuna and tuna-like species: A global review of status and mitigation measures. Fisheries and aquaculture technical paper 588*. Food and Agriculture Organization.

Connor, G., Goldberg, L. R., & Korajczyk, R. A. (2010). *Portfolio risk analysis*. Princeton University Press.

Cortés, E. (2004). Life history patters, demography and population dynamics. Pages 449–470 In J. C. Carrier, J. A. Musick, & M. Heithuas, editors. *Biology of sharks and their relatives*. CRC Press.

da Silva, C., Kerwath, S. E., Attwood, C. G., Thorstad, E. B., Cowley, P. D., Økland, F., Wilke, C. G., & Næsje, T. F. (2013). Quantifying the degree of protection afforded by a no-take marine reserve on an exploited shark. *African Journal of Marine Science*, *35*, 57–66.

Davidson, L. N. K., & Dulvy, N. K. (2017). Global marine protected areas to prevent extinctions. *Nature Ecology & Evolution*, *1*, 0040.

Day, J. C. (2017). When is fishing allowed in an MPA? *MPA News*, *18*(8), 5–6.

Day, J. C., & Dobbs, K. (2013). Effective governance of a large and complex cross-jurisdictional marine protected area: Australia's Great Barrier Reef. *Marine Policy*, *41*, 14–24.

Dell'Apa, A., Chad Smith, M., & Kaneshiro-Pineiro, M. (2014). The influence of culture on the international management of shark finning. *Environmental Management*, *54*, 151–161.

Doherty, P. D., Baxter, J. M., Godley, B. J., Graham, R. T., Hall, G., Hall, J., Hawkes, L. A., Henderson, S. M., Johnson, L., Speedie, C., & Witt, M. J. (2017). Testing the boundaries: Seasonal residency and inter-annual site fidelity of basking sharks in a proposed Marine Protected Area. *Biological Conservation*, *209*, 68–75.

Dudley, N. (2008). *Guidelines for applying protected area management categories*. IUCN.

Dulvy, N. K. (2013). Super-sized MPAs and the marginalization of species conservation. *Aquatic Conservation-Marine and Freshwater Ecosystems*, *23*, 357–362.

Dulvy, N. K., Fowler, S. L., Musick, J. A., Cavanagh, R. D., Kyne, P. M., Harrison, L. R., Carlson, J. K., Davidson, L. N., Fordham, S. V., Francis, M. P., Pollock, C. M., Simpfendorfer, C. A., Burgess, G. H., Carpenter, K. E., Compagno, L. J., Ebert, D. A., Gibson, C., Heupel, M. R., Livingstone, S. R., … White, W. T. (2014). Extinction risk and conservation of the world's sharks and rays. *eLife*, *3*, e00590.

Dulvy, N. K., Simpfendorfer, C. A., Davidson, L. N. K., Fordham, S. V., Bräutigam, A., Sant, G., & Welch, D. J. (2017). Challenges and priorities in shark and ray conservation. *Current Biology*, *27*, R565–R572.

Dwyer, R. G., Krueck, N. C., Udyawer, V., Heupel, M. R., Chapman, D., Pratt, H. L., Garla, R., & Simpfendorfer, C. A. (2020). Individual and population benefits of marine reserves for reef sharks. *Current Biology*, *30*, 480–489. e485.

Day, J.C., Dudley, N., Hockings, M., Holmes, G., Laffoley, D., Stolton, S., & Wells, S.M. (2012). *Guidelines for applying the IUCN protected area management categories to marine protected areas*. IUCN.

Espinoza, M., Cappo, M., Heupel, M. R., Tobin, A. J., & Simpfendorfer, C. A. (2014). Quantifying shark distribution patterns and Species-habitat associations: Implications of marine park zoning. *PLoS ONE*, *9*, e106 885.

Frisch, A. J., & Rizzari, J. R. (2019). Parks for sharks: Human exclusion areas outperform no-take marine reserves. *Frontiers in Ecology and the Environment*, *17*, 145–150.

Gallagher, A. J., Vianna, G. M. S., Papastamatiou, Y. P., Macdonald, C., Guttridge, T. L., & Hammerschlag, N. (2015). Biological effects, conservation potential, and research priorities of shark diving tourism. *Biological Conservation*, *184*, 365–379.

Goetze, J. S., & Fullwood, L. A. F. (2013). Fiji's largest marine reserve benefits reef sharks. *Coral Reefs*, *32*, 121–125.

Green, A. L., Fernandes, L., Almany, G., Abesamis, R., McLeod, E., Aliño, P. M., White, A. T., Salm, R., Tanzer, J., & Pressey, R. L. (2014). Designing marine reserves for fisheries management, biodiversity conservation, and climate change adaptation. *Coastal Management*, *42*, 143–159.

Hall, A. E., Cameron, D. S., & Kingsford, M. J. (2021). Partially protected areas as a management tool on inshore reefs. *Reviews in Fish Biology and Fisheries*, *31*, 631–651.

Hemming, V., Burgman, M. A., Hanea, A. M., McBride, M. F., & Wintle, B. C. (2018). A practical guide to structured expert elicitation using the IDEA protocol. *Methods in Ecology and Evolution*, *9*, 169–180.

Hoff, G. R. (2016). Identification of multiple nursery habitats of skates in the eastern Bering Sea. *Journal of Fish Biology*, *88*, 1746–1757.

Hughes, T. P., Cameron, D. S., Chin, A., Connolly, S. R., Day, J. C., Jones, G. P., McCook, L., McGinnity, P., Mumby, P. J., Pears, R. J., Pressey, R. L., Russ, G. R., Tanzer, J., Tobin, A., & Young, M. A. (2016). A critique of claims for negative impacts of Marine Protected Areas on fisheries. *Ecological Applications*, *26*, 637–641.

Hylton, S., White, W. T., & Chin, A. (2017). The sharks and rays of the Solomon Islands: A synthesis of their biological diversity, values and conservation status. *Pacific Conservation Biology*, *23*, 324–334.

Jacoby, D. M. P., Ferretti, F., Freeman, R., Carlisle, A. B., Chapple, T. K., Curnick, D. J., Dale, J. J., Schallert, R. J., Tickler, D., & Block, B. A. (2020). Shark movement strategies influence poaching risk and can guide enforcement decisions in a large, remote marine protected area. *Journal of Applied Ecology*, *57*, 1782–1792.

Jaiteh, V. F., Lindfield, S. J., Mangubhai, S., Warren, C., Fitzpatrick, B., & Loneragan, N. (2016). Higher abundance of marine predators and changes in fishers' behavior following spatial protection within the world's biggest shark fishery. *Frontiers in Marine Science*, *3*, 43.

Jupiter, S. D., Cohen, P. J., Weeks, R., Tawake, A., & Govan, H. (2014). Locally-managed marine areas: Multiple objectives and diverse strategies. *Pacific Conservation Biology*, *20*, 165–179.

Knip, D. M., Heupel, M. R., & Simpfendorfer, C. A. (2012). Evaluating marine protected areas for the conservation of tropical coastal sharks. *Biological Conservation*, *148*, 200–209.

Leenhardt, P., Cazalet, B., Salvat, B., Claudet, J., & Feral, F. (2013). The rise of large-scale marine protected areas: Conservation or geopolitics? *Ocean & Coastal Management*, *85*, 112–118.

MacKeracher, T., Diedrich, A., & Simpfendorfer, C. A. (2019). Sharks, rays and marine protected areas: A critical evaluation of current perspectives. *Fish and Fisheries*, *20*, 255–267.

MacNeil, M. A., Chapman, D. D., Heupel, M., Simpfendorfer, C. A., Heithaus, M., Meekan, M., Harvey, E., Goetze, J., Kiszka, J., Bond, M. E., Currey-Randall, L. M., Speed, C. W., Sherman, C. S., Rees, M. J., Udyawer, V., Flowers, K. I., Clementi, G., Valentin-Albanese, J., Gorham, T., … Cinner, J. E. (2020). Global status and conservation potential of reef sharks. *Nature*, *583*, 801–806.

Martín, G., Espinoza, M., Heupel, M., & Simpfendorfer, C. A. (2020). Estimating marine protected area network benefits for reef sharks. *Journal of Applied Ecology*, *57*, 1969–1980.

McAuley, R. B., Simpfendorfer, C. A., Hyndes, G. A., & Lenanton, R. C. J. (2007). Distribution and reproductive biology of the sandbar shark, *Carcharhinus plumbeus* (Nardo), in Western Australian waters. *Marine and Freshwater Research*, *58*, 116–126.

Pieraccini, M., Coppa, S., & De Lucia, G. A. (2017). Beyond marine paper parks? Regulation theory to assess and address environmental non-compliance. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *27*, 177–196.

Pomeroy, R. S., & Andrew, N. (2011). *Small-scale fisheries management: Frameworks and approaches for the developing world*. CABI.

Prince, J. D. (2005). Gauntlet fisheries for elasmobranchs - The secret of sustainable shark fisheries. *e-journal of Northwest Atlantic Fishery Science*, *35*, 407–416.

Rife, A. N., Erisman, B., Sanchez, A., & Aburto-Oropeza, O. (2013). When good intentions are not enough … Insights on networks of "paper park" marine protected areas. *Conservation Letters*, *6*, 200–212.

Russ, G. R., Miller, K. I., Rizzari, J. R., & Alcala, A. C. (2015). Long-term no-take marine reserve and benthic habitat effects on coral reef fishes. *Marine Ecology Progress Series*, *529*, 233–248.

Simpfendorfer, C. A., & Dulvy, N. K. (2017). Bright spots of sustainable shark fishing. *Current Biology*, *27*, R97–R98.

Simpfendorfer, C. A., & Kyne, P. M. (2009). Limited potential to recover from overfishing raises concerns for deep-sea sharks, rays and chimaeras. *Environmental Conservation*, *36*, 97–103.

Singleton, R. L., & Roberts, C. M. (2014). The contribution of very large marine protected areas to marine conservation: Giant leaps or smoke and mirrors? *Marine Pollution Bulletin*, *87*, 7–10.

Speed, C. W., Cappo, M., & Meekan, M. G. (2018). Evidence for rapid recovery of shark populations within a coral reef marine protected area. *Biological Conservation*, *220*, 308–319.

Tobin, A. J., Simpfendorfer, C. A., Mapleston, A., Currey-Randall, L. M., Harry, A. V., Welch, D. J., Ballagh, A. C., Chin, A., Szczenski, N., Schlaff, A. M., White, J., & Moore, B. R. (2010). *A quantitative ecological risk assessment of sharks and finfish of Great Barrier Reef World Heritage Area inshore waters: A tool for fisheries and marine park managers: Identifying species at risk and potential mitigation strategies*. Marine and Tropical Sciences Research Facility.

United Nations (1995). *Agreement for the implementation of the provisions of the United Nations Convention of the Law of the Sea on 10 December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks*. United Nations.

Walker, T. I., Day, R. W., Awruch, C. A., Bell, J. D., Braccini, J. M., Dapp, D. R., Finotto, L., Frick, L. H., Garcés-García, K. C., Guida, L., Huveneers, C., Martins, C. L., Rochowski, B. E. A., Tovar-Ávila, J., Trinnie, F. I., & Reina, R. D. (2021). Ecological vulnerability of the chondrichthyan fauna of southern Australia to the stressors of climate change, fishing and other anthropogenic hazards. *Fish and Fisheries*, *22*, 1105–1135.

Ward-Paige, C. A. (2017). A global overview of shark sanctuary regulations and their impact on shark fisheries. *Marine Policy*, *82*, 87–97.

Wearmouth, V. J., & Sims, D. W. (2008). Sexual segregation in marine fish, reptiles, birds and mammals: Behaviour patterns, mechanisms and conservation implications. Pages 107–170 In D. W. Sims, editor. *Advances in marine biology*. Elsevier Academic Press.

White, T. D., Carlisle, A. B., Kroodsma, D. A., Block, B. A., Casagrandi, R., De Leo, G. A., Gatto, M., Micheli, F., & McCauley, D. J. (2017). Assessing the effectiveness of a large marine protected area for reef shark conservation. *Biological Conservation*, *207*, 64–71.

SUPPORTING INFORMATION

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