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REVIEW

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Finding harmony in Marine Protected Area design guidelines

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Abstract
Widespread degradation of marine ecosystems and ecosystem services, coupled with national and global commitments to improve protection of the oceans, has led to a proliferation of efforts to designate new marine protected areas (MPAs) and MPA networks. A range of design features must be considered when designating MPAs, including MPA size and shape, level of protection, and the species and habitats protected, and evidence suggests these design elements can be crucial in determining MPA effectiveness. Over the past several decades, expansive literature has emerged providing recommendations for MPA design, and yet collectively these recommendations can be overwhelming and even contradictory for MPA planners. To address this barrier, we reviewed and synthesized 307 unique MPA design recommendations across 56 peer-reviewed and gray literature publications. We created a new set of 24 condensed design guidelines grouped by conservation objectives: ecological spatial connectivity (e.g., genetic, larval, community); habitat representation; species or population persistence; mitigation of and complementarity to human activities; and permanence and adaptability. We then discuss examples of datasets, models, and tools that can be utilized to implement specific guidelines. Our review and novel synthesis can help decision-makers understand and apply MPA design recommendations to achieve desired conservation objectives.

KEYWORDS
conservation planning, design, guideline, marine protected area, marine reserve, no-take, ocean conservation, recommendation

1 | INTRODUCTION

Marine protected areas (MPAs) are a widely applied conservation tool developed primarily to achieve biological and ecological objectives (IUCN, 2018). Specific examples of conservation objectives include increased biodiversity and biomass within protected areas, and increased adult spillover and larval export leading to higher biomass outside of protected areas (Gaines et al., 2010). However, these benefits are dependent on the design of the MPA

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(Edgar et al., 2014; Gill et al., 2017; Grorud-Colvert et al., 2021). While well-enforced, fully protected MPAs appear to most consistently achieve conservation goals (Grorud-Colvert et al., 2021; Lester & Halpern, 2008), these features do not guarantee MPA success (Gill et al., 2017; Lester et al., 2009). Rather, MPA planning also requires careful consideration of the characteristics of the local marine ecosystem and specific conservation objectives to determine the best placement, size, and configuration of MPAs (Green et al., 2014; Grorud-Colvert et al., 2021). With so many considerations, the MPA planning process can result in a wide variety of MPA designs with varying levels of complexity. For example, MPAs can be a single protected area to restrict fishing (e.g., Papahānaumokuākea Marine National Monument; Kikiloi et al., 2017) or complex networks of smaller reserves (e.g., those in Belize [Cho, 2005]; California [Airamé et al., 2003; Saarman et al., 2013]). Conversely, MPA planning could result in a series of zones with different fishing and access restrictions applied to each (e.g., Great Barrier Reef, Australia; Great Barrier Reef Marine Park Authority [GBRMPA], 2004). There is no one size fits all approach to MPA design, but general rules of thumb and best-practice planning principles are useful to achieve long-term conservation objectives.

Recommendations for designing MPAs are scattered across an extensive and expanding body of literature, including theoretical expectations for designing MPAs for biodiversity protection (Botsford et al., 2003; Halpern & Warner, 2003; Roberts et al., 2001, 2003), considerations for incorporating multiple biological objectives (Gaines et al., 2010; Green et al., 2014; McLeod et al., 2009), and empirical evaluations of MPA effectiveness (Edgar et al., 2014; Gill et al., 2017; Lester et al., 2009). Most of these recommendations are focused, explicitly or implicitly, on protecting nearshore habitats, although more recent recommendations provide principles specific to offshore areas (Ceccarelli et al., 2021). Currently, there is no comprehensive review that synthesizes these diverse recommendations in a way that can streamline decision-making across a range of planning contexts. Given the global effort to protect 30% of the world's oceans by 2030 (United Nations Environment Programme, 2022) and the increasing need to design MPAs in a variety of different contexts, a review that summarizes MPA design recommendations without losing the nuances associated with particular habitats or places is an important and timely tool for ocean managers.

We present a comprehensive synthesis of MPA design recommendations from peer-reviewed and gray literature. Our efforts focused on documents that explicitly included recommendations for physical attributes (e.g., size, shape, location), as these are common features that dictate protected area planning. A unique feature of our approach is that we synthesize similar recommendations into single, condensed guidelines and categorize them by the conservation objectives they are meant to achieve, including spatial connectivity, habitat representation, species or population persistence, mitigation of and complementarity to human activities, and permanence and adaptability. While other review papers cite guidelines that have already been discussed in previous literature (Aceves-Bueno & Halpern, 2018) or suggest that a single MPA design (i.e., network of reserves of moderate size and variable spacing) can be applied across a variety of habitats and conservation goals (Halpern & Warner, 2003), we provide the context necessary for practitioners to make informed decisions to meet their specific conservation goals. Explicitly linking recommendations to conservation objectives makes it easier to use our synthesized guidelines in conservation planning processes. Importantly, the guidelines are general enough to be used in any planning context, but also capture nuanced information and other details necessary for specific conservation efforts in both nearshore and offshore environments.

Though the majority of implemented MPAs are partially protected (allowing some types of extractive activities)—intended to enhance fisheries benefits in the short term (Costello & Ballantine, 2015) or to balance conservation and resource use goals—many design recommendations are developed with fully protected MPAs (no extractive or destructive activities allowed; Grorud-Colvert et al., 2021) in mind. We chose to focus on fully protected MPAs because of their prominence in the literature, their primary objectives to achieve conservation benefits, and their potential to be applied across a variety of protection levels. Recommendations that seek to achieve only socioeconomic objectives are not considered in our review, although we do include recommendations focused on balancing biological and socioeconomic objectives. We also present examples of how these guidelines have been implemented in real-world conservation planning and identify datasets, models, and tools that provide decision-makers with a clear and realistic understanding of how to begin the MPA design process. As such, our research goal was to create actionable guidelines for decision-makers to make efficient and informed decisions to design and implement MPAs. We do not explicitly dictate the design criteria that should be applied to all MPAs, but rather provide guidelines to consider during MPA development.

2 | MPA DESIGN GUIDELINES

We compiled a total of 219 documents from 2000 to 2020 which discussed MPA design from peer-reviewed and gray literature. We used a Web of Science search (TS = ((“marine protected area*”) OR (“marine reserve*”)) AND (“guideline*”)) to provide a starting point for collecting relevant literature. This search resulted in a total of 112 documents. To ensure no important guidelines were overlooked, we expanded our literature pool to include documents referenced within searched papers as well as key documents of which we had previous knowledge (107 additional documents). Our approach was not intended to be a fully comprehensive and systematic literature review of all papers published on MPA design guidelines, but rather a comprehensive compilation of MPA design recommendations. To this end, we continued reviewing papers and adding recommendations to our database until we only found recommendations that were identical to those that we had already recorded.

We reviewed each document for recommendations for physical attributes (e.g., size, shape, location) of fully protected MPAs that met our inclusion criteria (e.g., recommendations for physical design attributes, used directly to inform the practical designation of MPA areas; see Supporting Information for details). We retained 57 documents that met these criteria and extracted each recommendation. Documents often contained multiple

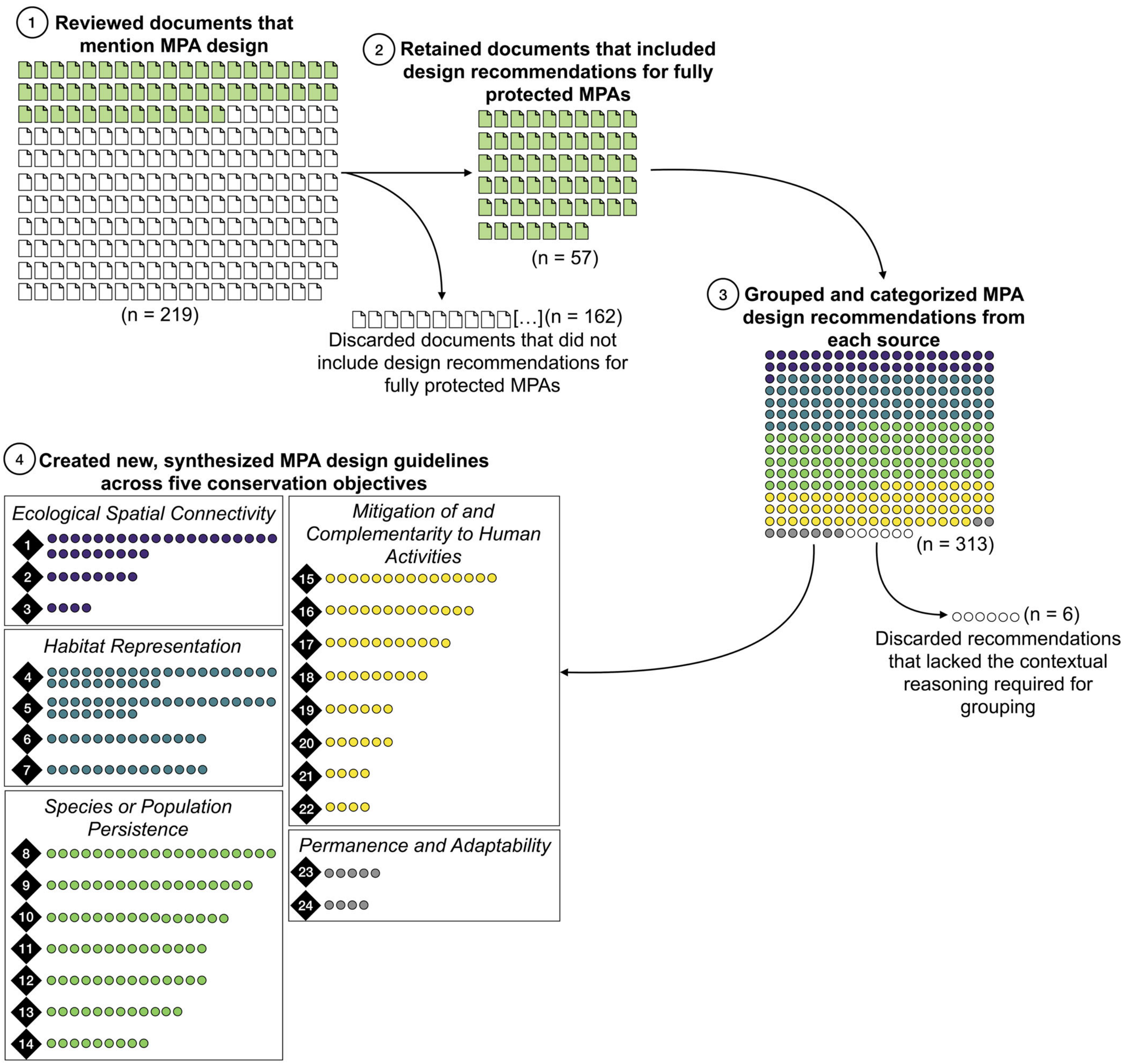

FIGURE 1 Documents that mention MPA design were reviewed for recommendations for fully protected MPAs. Recommendations were pulled from the literature and synthesized into a new set of MPA design guidelines across five conservation objectives.

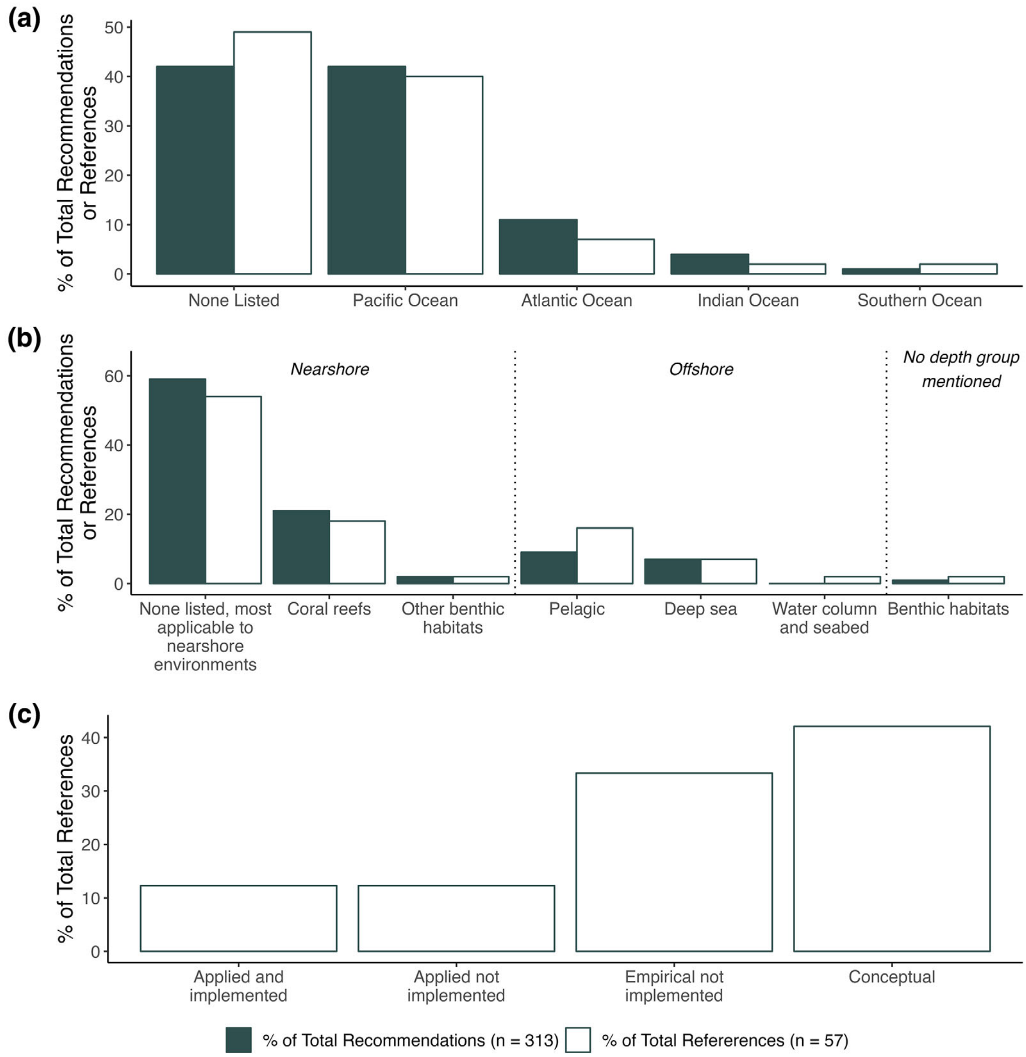

FIGURE 2 The percentage of documents (white bars) and MPA design recommendations (solid bars) by (a) ocean region (b) habitat they focused on, or (c) classification (documents only). Documents were classified as applied and implemented, applied but not implemented, empirical not implemented, or conceptual (see Supporting information for details of categories).

recommendations, yielding a total of 313 recommendations (Figure 1). Some of the documents were location-specific for areas such as the Great Barrier Reef, Mediterranean Sea, or Midatlantic Ridge ($n = 29$), whereas others presented general recommendations not intended for a specific location ($n = 28$; Table S1). The majority of documents that mentioned specific areas were focused on regions within the Pacific Ocean (Figure 2a), which is not only the largest ocean basin, but also contains the highest number and total area of established fully protected MPAs globally (Marine Conservation Institute, 2020). Some documents mentioned specific habitats for which the guidelines were developed (e.g., coral reefs); most documents that did not mention specific habitats had recommendations that were most relevant for nearshore areas (Figure 2b). Documents were also classified into four categories depending on whether they presented recommendations in a theoretical framework ("conceptual"—42% of reviewed documents, or "empirical not implemented"—33%; Supporting Information), or provided real-world applications of recommendations ("applied and implemented"—12%, or "applied not implemented"—12%; Supporting Information and Figure 2c).

We grouped recommendations that mentioned similar physical design attributes and ecological reasoning (e.g., spacing recommendations for larval connectivity; Ceccarelli et al., 2018; Gaines et al., 2010; McLeod et al., 2009) and created new, condensed guidelines that captured the range of information presented by each of the unique recommendations in the group. Some compiled recommendations contradicted one another. Contradictory recommendations that provided the context required to defend the recommendation—and to decide between contradicting recommendations—were retained as distinct guidelines. For example, one condensed guideline reads "create several, small MPAs to directly benefit fishers equally through juvenile and adult spillover", whereas another reads "create larger, fewer MPAs with simple shapes and boundaries to streamline management and enforcement and increase compliance". While contradictory, these guidelines map clearly onto different potential management objectives, with one intended to achieve fisheries benefits and the other focused on improving compliance and enforcement. Other recommendations did not provide the context required to create a clear guideline ($n = 4$, e.g., larger reserves increase fisheries benefits [Boerder et al., 2019]; larger reserves limit fisheries spillover [Gaines et al., 2010]). These recommendations were not included in the final guidelines (see Supporting information). Recommendations that were too specific to provide general guidance ($n = 2$, e.g., use MPA shapes that maximize recruitment export for coral reefs in Northwest Australia; Underwood et al., 2013) were also not included.

In total, 307 recommendations from 56 documents were recategorized into 24 condensed MPA design guidelines (Figure 1 and Table 1). We then grouped guidelines into broader categories based on the conservation objectives that could be achieved via implementation of these guidelines (Tables S2 and S3). Conservation objectives included ecological spatial connectivity (e.g., genetic, population, community; Carr et al., 2017; three guidelines), habitat representation (Roberts et al., 2003; four guidelines), species or population persistence (McLeod et al., 2009, Wilson et al., 2020; seven guidelines), mitigation of and complementarity to human activities (Munguia-Vega et al., 2018; eight guidelines), and permanence and adaptability (Green et al., 2014; Tittensor et al., 2019; two guidelines). By linking guidelines to specific MPA design objectives, practitioners can determine which design guidelines might be best suited to meet their conservation objectives. We provide an example of linking theoretical marine spatial planning objectives to the design guidelines synthesized here in the Table S4.

2.1 | Ecological spatial connectivity

Ecological spatial connectivity encapsulates the movement of a variety of ecological components (e.g., genes, organisms, populations, species, nutrients, energy) among spatially discrete ecosystems or habitat patches (Carr et al., 2017). Maintaining ecological spatial connectivity in an MPA context, either within a single area or among multiple areas, is considered important to maintain ecosystem function and foster resilience (Carr et al., 2017). We categorized the guidelines into population, ecosystem, genetic, and community connectivity, as defined by Carr et al. (2017). Most recommendations that facilitate ecological spatial connectivity focused on population connectivity (linkages of spatially discrete populations of a single species; $n = 29$), by incorporating knowledge of ocean currents, larval dispersal, and adult movement when developing MPA networks (Table 1). Additional recommendations focused on ecosystem connectivity ($n = 8$), by prioritizing the protection of areas with strong linkages of species, chemicals, and materials to other ecosystems, and genetic connectivity ($n = 4$), by protecting areas that facilitate gene flow and genetic diversity among distinct populations. Community connectivity, defined as the substantial movement of several species among habitats thereby altering species composition or ecological structure (Carr et al., 2017), was not specifically mentioned in the recommendations we reviewed. However, it could be achieved by implementing guidelines that prioritize the population, ecosystem, and genetic connectivity of multiple species.

While maintaining connectivity is often a general consideration in MPA network planning, few marine spatial planning efforts have included comprehensive analyses of ecological spatial connectivity across multiple scales and species. One of the few examples that included ecological spatial connectivity in marine spatial planning is the MPA network designed by regional stakeholder groups in California, USA to meet conservation requirements stated in the Marine Life Protection Act (Gleason et al., 2013). The conservation plan prioritized enhancing ecological connectivity by ensuring regular spacing among MPAs within the network, while also meeting several other MPA design criteria (Gleason et al., 2013). The dearth of papers including comprehensive connectivity analyses in MPA planning may be due to the considerable data and technical skills required to produce suitable connectivity models and matrices (Balbar & Metaxas, 2019).

2.2 | Habitat representation

Habitat representation refers to the protection of a portion of each major habitat type within a planning region to protect the range of species associated with each habitat (Roberts et al., 2003). The majority of MPA design recommendations that mentioned habitat representation indicated that between 10% and 50% of the area of each major habitat should be included in protected areas ($n = 30$). The percentage chosen for each habitat is likely to change on a case-by-case basis depending on species and habitat vulnerability, uniqueness, and threat level, but including at least some proportion of each environment can improve the probability that all biodiversity is

TABLE 1 MPA design guidelines synthesized from multiple contributing recommendations and further categorized by conservation objectives.

Conservation objective	Guidelines	Contributing recommendations, *n* (%)	Contributing sources, *n* (%)
Ecological spatial connectivity (e.g., genetic, population, ecosystem, etc.)	When designing MPA networks, use knowledge about hydrodynamics, larval dispersal, and adult movement to ensure population connectivity within and among individual reserves. As a rule of thumb, MPAs placed inshore should be placed closer together than those in the nearshore, which should be placed closer together than those in the offshore. (keyword: population connectivity)	29 (9.45)	17 (30.36)
	When placing MPAs, consider ecological linkages among protected and unprotected areas, including migration patterns, currents, and connectivity. Prioritize areas that have strong relationships with several other ecosystems. (keyword: ecosystem connectivity)	8 (2.61)	7 (12.5)
	When designing MPA networks, place MPAs in locations that will ensure gene flow among MPAs and maintain genetic diversity. If genetic diversity data are unavailable, but there are strong, consistent, and unidirectional currents, place MPAs upstream of other MPAs. (keyword: genetic connectivity)	4 (1.3)	4 (7.14)
Habitat representation	Represent between 10% and 50% of each major habitat within each bioregion, including different depths and environmental conditions. Larger percentages of protection should be used for areas projected to be affected by climate change, areas subject to more destructive activities, and areas with high fishing pressure.	30 (9.77)	17 (30.36)
	Have multiple (at least 3) replicate no-take MPAs within each bioregion, and include multiple (at least 3) representatives of each habitat within MPAs. Place replicates far enough apart so that not all will be affected by a single disturbance event (e.g. oil spill).	28 (9.12)	17 (30.36)
	Protect areas that are isolated, rare, or unique, either in hydromorphology or community assemblage.	14 (4.56)	12 (21.43)
	Protect diverse, biologically, and ecologically important areas.	14 (4.56)	12 (21.43)
Species or population persistence	Protect as much of key species' home ranges as possible, preferably using larger reserves. Pelagic and mobile species require larger reserves than nearshore species or species with smaller home ranges.	20 (6.51)	12 (21.43)
	Protect entire biological and ecological units, including the entire water column.	18 (5.86)	14 (25)
	Prioritize areas that will protect species that are ecologically, functionally, or commercially important, or vulnerable/endangered (e.g., large, migratory, at-risk species).	16 (5.21)	11 (19.64)
	When designing MPA networks, MPAs should be large enough or close enough to other MPAs to ensure that species are protected during all critical life stages.	14 (4.56)	13 (23.21)

TABLE 1 (Continued)

Conservation objective	Guidelines	Contributing recommendations, *n* (%)	Contributing sources, *n* (%)
	Individual MPAs should be large enough to ensure self-recruitment and minimum viable populations.	14 (4.56)	11 (19.64)
	Protect areas that represent a range of climate futures, including areas with high climate variability and resilience and climate refugia.	12 (3.91)	7 (12.5)
	MPAs should cover at least 30% of the management area to ensure viable populations.	9 (2.93)	9 (16.07)
Mitigation of and complementarity to human activities	Consider the anthropogenic threats to an area when determining MPA placement. Prioritize areas where the main threats can be mitigated by an MPA and avoid areas where the main threats cannot be mitigated by an MPA.	15 (4.89)	10 (17.86)
	Create larger, fewer MPAs with simple shapes and boundaries to streamline management and enforcement and increase compliance.	13 (4.23)	8 (14.29)
	Balance biological benefits of MPAs against socio-economic impacts, attempting to select areas that minimize impacts to local fishers while also achieving species and population protection.	11 (3.58)	8 (14.29)
	Place MPAs in areas that complement pre-existing managed areas, fishing grounds, and monitoring areas (e.g., placing MPAs in areas that are already protected by the local fishers, upstream of popular fishing sites, or adjoining existing nearshore MPAs).	9 (2.93)	6 (10.71)
	Create MPAs with simple, compact shapes (e.g., squares, circles) to reduce edge effects from increased fishing pressure along the edge of the reserve.	6 (1.95)	6 (10.71)
	Where impacts outside of an MPA may flow into the MPA (e.g., seabed disruption from mining or trawling creating sediment plumes), create a buffer zone around the MPA to limit such activities.	6 (1.95)	6 (10.71)
	Create several, small MPAs to directly benefit fishers equally through juvenile and adult spillover.	4 (1.3)	4 (7.14)
	Protect areas that are identified as priority areas for protection by the local community and are important for non-extractive industries (e.g., dive tourism sites).	4 (1.3)	3 (5.36)
Permanence and adaptability	Static MPAs should be permanent and prohibit all extractive activities.	5 (1.63)	4 (7.14)
	Static MPAs can be used in combination with dynamic MPAs (movable in space and time) to ensure that critical habitats are constantly protected while also allowing managers to proactively respond to changing ocean conditions.	4 (1.3)	4 (7.14)

Note: The columns for contributing recommendations and contributing sources indicate the number of recommendations or sources that were consolidated into each guideline grouping, with the percent of total recommendations ($n = 307$) and total number of unique sources ($n = 56$) in parentheses. The remaining six recommendations and one literature source that were not included in this table lacked the context necessary to be grouped. A master dataset with the results of the systematic review can be found in Table S2.

at least partially protected. Another common recommendation ($n = 28$) was to protect spatially distinct replicates of major habitats (i.e., replication) to avoid an entire habitat being severely affected by natural disasters (e.g., hurricanes) or point disturbances (e.g., oil spills).

Habitat representation was one of several key components used to redesign the Great Barrier Reef Marine Park in Australia. A Scientific Steering Committee developed a series of principles to use in the design of fully protected MPAs in the Marine Park (Fernandes et al., 2005). The principles included protecting ≥20% of at least three different reefs within a single bioregion and ensuring that all unique community types and environments were included in fully protected areas (Fernandes et al., 2005). These efforts resulted in more than 22% of the Great Barrier Reef Marine Park being classified as fully protected with the successful protection of distinct bioregions, communities, and environments (Fernandes et al., 2005).

2.3 | Species or population persistence

Protecting focal species and populations is often a priority goal for MPAs and can be achieved through a variety of approaches that depend on the amount of data available and the life history characteristics of the species or population. Most recommendations that focus on species or population persistence discuss conserving a species' entire home range ($n = 20$), and several others focus on protecting areas that are particularly vulnerable or ecologically important to focal populations ($n = 16$; e.g., nursery habitats, spawning aggregations; McLeod et al., 2009). Identifying the most important areas to protect can require expansive datasets (e.g., Gilman et al., 2020; McLeod et al., 2009; Underwood et al., 2013), but species and population persistence can also be achieved when data are limited. For example, protecting 30% of the management area is a proposed baseline for ensuring the persistence of local species and populations ($n = 9$), and protecting the entire water column (i.e., rather than only protecting the seafloor) can protect all species around a particular feature ($n = 18$; e.g., Ceccarelli et al., 2018; McLeod et al., 2009; Munguia-Vega et al., 2018).

A marine spatial plan in Bimini, Bahamas prioritized the persistence of local elasmobranch populations by using 4 years of animal tracking data from 99 individuals across 7 species (van Zinnicq Bergmann et al., 2022). From these data, researchers identified core use areas and quantified levels of seasonal and annual residency in Bimini for each species (van Zinnicq Bergmann et al., 2022). Results from the tracking study were used to inform a spatial prioritization framework that selected areas for protection in which core-use areas and vulnerable nursery habitats for lemon sharks (*Negaprion brevirostris*) overlapped (van Zinnicq Bergmann et al., 2022).

2.4 | Mitigation of and complementarity to human activities

Fully protected MPAs focus on eliminating all extractive and destructive activities (Grorud-Colvert et al., 2021). Therefore, many recommendations give guidance on how to best site MPAs to protect biodiversity given the existing human activities in the local area. One common recommendation suggests protecting areas where threats can be mitigated by MPAs and avoiding protecting areas where threats cannot be mitigated by MPAs (e.g., Munguia-Vega et al., 2018; $n = 15$). For example, areas of refuge from climate change are considered worthwhile to protect (Green et al., 2014), while areas with high land-based pollution and high vessel traffic are unlikely to yield conservation benefits if protected (Halpern & Warner, 2003). Another important consideration when designing MPAs is how to balance the biological benefits of a proposed MPA against their economic impacts ($n = 11$). Protecting areas that minimize negative or maximize positive impacts to existing ocean users (e.g., fisheries, the tourism industry) while also providing conservation benefits is more likely to be supported and enforced by the local community and meet future ecological objectives (Hamel et al., 2013; Mangubhai et al., 2015).

Minimizing the economic impact that an MPA would impose on local fishers, while still achieving conservation goals, was a key component of the MPA design process around the island of Montserrat in the Caribbean (Flower et al., 2020). Marine spatial planning efforts sought to maintain and enhance the biomass of fishery species, protect systemwide biodiversity, and conserve live coral and reef ecosystems to achieve ecological objectives while also maintaining the livelihoods of local ocean users (Flower et al., 2020). Stakeholder survey and GPS-derived fishing activity data were used to quantify areas that would most negatively impact current fishing activity. The proposed MPA was then designed to protect 30% of each habitat within Montserrat's territorial waters and 50% of total coral and fish species richness to achieve stated ecological and biological goals, while also avoiding areas important to the local fishery (Flower et al., 2020).

2.5 | Permanence and adaptability

Several guidelines suggested that MPAs should be permanent in both space and time to allow time for recovery and promote long-term conservation benefits (Green et al., 2014; $n = 5$). Rotating, seasonal, and other dynamic fisheries closures are beyond the scope of this article, but have been found to successfully protect species with predictable migration routes or spawning behaviors (Dunn et al., 2016; Ortuño Crespo et al., 2020). As climate change continues to impact our oceans, the conservation benefits of established MPAs should be regularly re-evaluated and adapted to most effectively protect vulnerable species and habitats (Wilson et al., 2020). If used in combination with static MPAs, dynamic MPAs that adapt to changing ocean conditions can ensure the protection of vulnerable habitats against climate change ($n = 4$; Ortuño Crespo et al., 2020; Tittensor et al., 2019). Alternatively, developing static MPAs that account for future environmental changes may provide similar benefits to dynamic MPAs developed to mitigate climate change.

Protecting areas of climate refugia can provide some assurance that permanently protected areas will meet conservation objectives in the future despite changing ocean conditions. For example, Brito-Morales et al. (2022) used climate change data across the full range of ocean depths to identify areas in the high seas that are least exposed and least likely to change with ocean warming across all depth zones. However, while designing MPAs with climate futures in mind can help to ensure the protection of species or habitats in the future, permanent MPAs designed based on current conditions are still likely to provide future conservation benefits (Rassweiler et al., 2020).

3 | CONSIDERATIONS FOR IMPLEMENTING MPA GUIDELINES

3.1 | Finding clarity in contradictions

The growing body of literature that provides recommendations for MPA design encompasses numerous habitats across all of the world's major oceans, resulting in a long list of sometimes contradictory recommendations. Deciding which recommendations are the most appropriate for designing an MPA in a particular context can be overwhelming and confusing. By synthesizing these recommendations into fewer design guidelines that are explicitly linked to conservation objectives, our novel approach supports managers in making informed decisions in the MPA design process.

Some of the most common contradictions among the recommendations we reviewed can be explained by the unique sets of challenges associated with protecting nearshore areas compared with offshore areas. While Ceccarelli et al. (2021) recently synthesized MPA design guidelines for offshore environments, most published MPA design recommendations are either focused on a specific nearshore region (e.g., Great Barrier Reef, Coral Triangle) or are most applicable to nearshore environments, where most conservation efforts are directed. The fundamental differences in the species, habitats, and size of areas being considered for protection in nearshore versus offshore habitats result in differences between guidelines targeted specifically for these environments. For example, Ceccarelli et al. (2018) suggest spacing MPAs 500 m to 5 km apart in inshore environments, 5–20 km apart in nearshore environments, and 20–200 km apart offshore. Additional sources provide recommendations for nearshore areas, such as 1–20 km (Green et al., 2014) and 15–20 km (McLeod et al., 2009). The discrepancies among these recommendations reflect the differences in the range of adult movement and larval dispersal distances for the species intended to be protected nearshore compared with offshore. This example demonstrates the difficulty of providing a single, general recommendation and indicates that reserve spacing, among other guidelines, will have to be tailored to the location and associated species of interest.

There were also contradictions among design recommendations given existing human activities and considerations for effective MPA management. A small number of recommendations ($n = 4$) suggest several, smaller reserves to provide benefits to fisheries while achieving ecological objectives. However, for a small MPA to provide substantial fisheries benefits, the MPAs must be large enough to encompass a significant proportion of the home range of a fishery's target species and be well enforced. In contrast, more recommendations ($n = 11$) suggest fewer, larger MPAs because they are generally easier to manage and enforce. We attempt to clarify such contradictions in our condensed guidelines so that managers can make the best decision for their specific conservation objectives and local context. As such, future research efforts that focus on the effectiveness of specific MPA design recommendations are important to help resolve some of the apparent contradictions we noticed within the literature.

3.2 | Information requirements

Nearly all MPA design guidelines require some form of data to inform the decision-making process. Local data, knowledge, and leadership are vital for designing effective MPA networks and suitable sources of locally collected data include social surveys (e.g., Johnson et al., 2020), ecological surveys (e.g., Flower et al., 2020), and tracking data (e.g., van Zinnicq Bergmann et al., 2022). Traditional ecological knowledge and other sources of ecological information held by individuals can be gathered using surveys, with mapping tools such as SeaSketch (2022) used to create spatial information. Such information can be used to identify suitable areas for protection and areas to avoid placing MPAs, such as economically or culturally important fishing grounds (e.g., Flower et al., 2020; Klein et al., 2008). Where local data are limited and resources for data collection are not available, global datasets can help fill critical gaps.

Habitat data are required for designing a representative network of MPAs. For nearshore, shallow waters, there are freely available, high-resolution regional and global maps of coral reefs (Allen Coral Atlas, 2022; United Nations Environment Programme World Conservation Monitoring Program [UNEP-WCMC] et al., 2021), mangroves (Spalding et al., 2010), seagrasses (UNEP-WCMC & Short FT, 2021), and saltmarshes (Mcowen et al., 2017). Identifying habitats in deeper, offshore waters is more challenging due to sparse survey efforts over the vast majority of the ocean. However, the global map of seafloor geomorphic features (Harris et al., 2014) includes key habitats that can be used as proxies for biodiversity (e.g., shelves, abysses, canyons, seamounts) and guidelines for how much of each feature to protect have already been developed (Ceccarelli et al., 2021).

Ecological data on species distributions and important ecological areas are another form of information that are frequently used in MPA planning (Elith & Leathwick, 2009; Rodrigues & Brooks, 2007). Aquamaps (Kaschner et al., 2019) provide global range maps for over 33,000 marine species and are frequently used in global MPA planning exercises (e.g., Jones et al., 2020; Sala et al., 2021). However, these data do not provide any information on the relative abundance of a species in an area or the relative ecological importance of areas for a species (e.g., areas used for breeding, feeding, and mating). Finer scale data on species area usage and connectivity can be found for a selection of species in the Migratory Connectivity in the Ocean portal (MiCO), 2022. Tracking data, such as that available via the Ocean Tracking Network (Ocean Tracking Network, 2022), which houses telemetry data for 311 species, can also be used to map connectivity and ecologically important habitats, but this requires specialized data analysis skills and knowledge of individual species' ecology. Existing databases on ecologically important areas such as the Key Biodiversity Areas (Edgar et al., 2008; Key Biodiversity Areas, 2022), Ecologically or Biologically Significant Marine Areas (Ecologically or Biologically Significant Marine Areas, 2009), and Important Bird and Biodiversity Areas (Donald et al., 2019) can also be used to guide placement of MPAs (Edgar et al., 2008; McGowan et al., 2018).

Finally, data related to climate projections are increasingly needed for MPA design (e.g., for species or population persistence guidelines) and integrating climate change into MPA design is at the forefront of current research efforts (Tittensor et al., 2019; Wilson et al., 2020). For example, methods to identify climate refugia and areas that may acclimate to changing ocean conditions are now available for both coral reef (Beyer et al., 2018; Chollett et al., 2014; Dixon et al., 2022) and open ocean habitats (Brito-Morales et al., 2022; Levin et al., 2020). Coral reef ecosystems are particularly susceptible to climate change and tools that provide a global perspective on both historical and future stress levels for corals are increasingly important to consider in MPA planning (Dixon et al., 2022). Alternatively, climate model data are applicable to all marine habitats and can be accessed via numerous web services, such as the Earth System Grid Federation (Earth System Grid Federation, 2022; Williams et al., 2016). However, using these data requires considerable computational skills and computing power. Using preprocessed ocean data, such as those available via Bio-Oracle (Assis et al., 2018; Tyberghein et al., 2012) or open-access data and code published with peer-reviewed articles (e.g., temperature data at multiple ocean depths [Brito-Morales et al., 2022]; pH, oxygen content, and particulate organic carbon flux [Levin et al., 2020]) are approaches that are less resource-intensive.

When identifying which data to use, the size of the planning area and the technical capability of the team conducting the planning are key considerations. Designing MPAs for relatively small areas will require higher resolution data than MPAs being proposed for larger areas. For example, a small MPA in a bay will require high-resolution habitat and stakeholder usage data to be effectively designed, whereas designing MPAs for a large offshore area may be possible using lower resolution, global datasets. Many datasets listed in this section can be downloaded and used as-is and are ideal when technical capacity or time is limited. When more locally relevant data are required and are not already available, consideration should be given to the amount of time and resources required to collect new data. Scientific survey data can be expensive and time consuming to collect, and citizen science data might be able to provide similar results at a lower cost. Similarly, mapping local or expert knowledge can be low cost and relatively high resolution while ensuring that stakeholder knowledge and values are explicitly incorporated into planning.

3.3 | Models and tools

The process of selecting areas for protection can be very complex, as it requires consideration of how to meet conservation objectives while maximizing benefits and minimizing impacts to stakeholders. Numerous decision support tools exist to aid marine spatial planning processes (reviewed in Depellegrin et al., 2021; Janßen et al., 2019; Pınarbaşı et al., 2017), which often include MPAs as well as ocean uses such as aquaculture, renewable energy, and shipping (Ehler & Douvere, 2009). Some tools can be tailored for use in any location (e.g., SeaSketch; Burnett, 2020), whereas others have been developed to cater to the needs of specific efforts (e.g., Europe; Depellegrin et al., 2021). These tools vary in their design, but at a minimum allow users to visualize data and have functionalities that include impact assessment, conflict and economic analysis, tradeoff analysis, and participatory planning (Depellegrin et al., 2021; Janßen et al., 2019).

A subset of these decision support tools, called spatial conservation prioritization tools, use different optimization approaches to identify areas for conservation and incorporate some of the guidelines we have summarized, such as habitat representation, connectivity, and minimizing socioeconomic impacts (Wilson et al., 2009). Marxan (Ball et al., 2009) and the R package *prioritizr* (Hanson et al., 2022) both identify priority conservation areas based on user data and conservation targets (e.g., protecting 30% of all habitats), while also minimizing "costs" (e.g., financial cost, opportunity cost, other measures of impact). In contrast, Zonation is another widely used prioritization software that does not output a single map of priority areas, but rather can provide a ranking of all cells within the area, enabling the user to see the relative importance of areas for meeting conservation goals (Moilanen et al., 2009).

4 | THE PATH FORWARD FOR MPA DESIGN

Less than half of implemented MPAs are fully or highly protected (Marine Conservation Institute, 2020) and it is likely that partially protected MPAs will continue to play an important role in meeting ocean protection commitments. While partially protected areas often have reduced conservation benefits compared with fully protected areas (Campbell et al., 2018; Turnbull et al., 2021), they can provide a more equitable approach while still achieving positive biodiversity outcomes (Andradi-Brown et al., 2023). All of the MPA design guidelines presented here can be applied across protection levels, but additional guidelines (e.g., which specific activities to prohibit or restrict) are required for the development of partially protected MPAs. While guidelines for partially protected areas are outside the scope of this research, the guidelines we provide can serve as a foundation of knowledge across an array of planning contexts. For example, ensuring the protection of some or all of a key species' home range is a vital guideline to consider if species or population persistence is a key conservation goal, regardless of if the MPA is partially or fully protected.

Clear guidelines have played a vital role in the successful design and implementation of MPA networks in California and the Great Barrier Reef ($n = 3$ and $n = 2$ of the documents we reviewed, respectively), but these cases are the minority, as only 7 (12.3%) of the documents we reviewed discussed recommendations that were used in MPAs that had been implemented. The majority (42.1%) of documents discussed recommendations in a conceptual framework only (Figure 2c). Continued efforts to synthesize and contextualize MPA design recommendations, including their success in creating effective MPAs, will be vital to building adaptable tools.

As more MPAs are developed, the breadth of MPA design recommendations will continue to grow. While it is difficult to create MPA design guidelines that have both general and local relevance, the future of MPA planning will need to include tools that allow decision-makers to meet a range of objectives, spanning from global to local scales. We have collated and synthesized existing design guidelines at the broad scale, but included relevant information for application in nearshore and offshore environments. We provide a novel synthesis of guidelines focused on achieving ecological objectives, and a comparable synthesis of guidelines addressing social, cultural, and economic objectives would also be valuable.

Advancements in technology and a push towards open-source data will allow decision-makers to have easier access to the regional and global datasets that are required to build effective MPAs in a future of changing ocean conditions. More importantly, however, technological advancements will allow decision-makers to more easily gather localized datasets to inform MPA design. With increased availability and improved technology, we also expect more capacity to develop robust monitoring and evaluation programs which are needed to determine the effectiveness of design criteria in meeting MPA objectives. As a result, we may see a shift in the literature away from the theoretical MPA design recommendations that dominated our literature search and towards recommendations that have been successfully implemented in existing MPAs. With multiple tools in hand, we can move one step closer to streamlining future successful marine conservation efforts.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data are available in the Supporting information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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