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A Scientific Synthesis of Marine Protected Areas in the United States: Status and Recommendations

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Marine protected areas (MPAs) are a key tool for achieving goals for biodiversity conservation and human well-being, including improving climate resilience and equitable access to nature. At a national level, they are central components in the U.S. commitment to conserve at least 30% of U.S. waters by 2030. By definition, the primary goal of an MPA is the long-term conservation of nature; however, not all MPAs provide the same ecological and social benefits. A U.S. system of MPAs that is equitable, well-managed, representative and connected, and includes areas at a level of protection that can deliver desired outcomes is best positioned to support national goals. We used a new MPA framework, The MPA Guide, to assess the level of protection and stage of establishment of the 50 largest U.S. MPAs, which make up 99.7% of the total U.S. MPA area (3.19 million km^2). Over 96% of this area, including 99% of that which is fully or highly protected against extractive or destructive human activities, is in the central Pacific ocean. Total MPA area in other regions is sparse – only 1.9% of the U.S. ocean excluding the central Pacific is protected in any kind of MPA (120,976 km^2). Over three quarters of the non-central Pacific MPA area is lightly or minimally protected against extractive or destructive human activities. These results highlight an urgent need to improve the quality, quantity, and representativeness of MPA protection in U.S. waters to bring benefits to human and marine communities. We identify and review the state of the science, including focal areas for achieving desired MPA outcomes and lessons learned from places where sound ecological and social design principles come together in MPAs that are set up to achieve national goals for equity, climate resilience, and biodiversity conservation. We recommend key opportunities for action specific to the U.S. context, including increasing funding, research, equity, and protection level for new and existing U.S. MPAs.

Keywords: marine protected area, biodiversity, ocean protection, conservation outcomes, The MPA Guide, area-based management

1 INTRODUCTION

The ocean is critically important to the planet and human well-being, which makes its sustainable management increasingly urgent. Marine biodiversity worldwide is under threat from human misuse and related impacts (Halpern et al., 2012; Allison and Bassett, 2015; McCauley et al., 2015), including in the United States (Fautin et al., 2010). Increased attention to widespread inequity and injustice have highlighted the interconnectedness of biodiversity, climate, and social justice crises and the immediacy of the threats facing marine systems and society (Bennett et al., 2021). These crises underscore the ocean's vast potential to provide vital ecosystem services on local, regional, and global scales (IPBES, 2019; Stuchtey et al., 2020). Sustaining these services requires reducing impacts from land-based activities (e.g., lowering greenhouse gas emissions and imposing controls on pollutants), as well as employing an effective suite of complementary tools to enable an inclusive, whole-ocean approach to marine resource management and governance (Laffoley et al., 2020; Winther et al., 2020).

Effective use of strategic management tools – both area-based and non-area-based – can protect and restore ocean health while balancing human and ecological needs. Marine protected areas (MPAs) are common, well-studied area-based tools that can contribute to comprehensive ocean management and governance. The International Union for the Conservation of Nature (IUCN) defines a protected area as "a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (IUCN WCPA, 2018). Extensive scientific research has revealed broad ecological benefits from protecting specific ocean areas from destructive and extractive activities (Claudet et al., 2008; Lester et al., 2009; Giakoumi et al., 2017; Friedlander, 2018; Zupan et al., 2018; Marcos et al., 2021), particularly when they are fully or highly protected (Grorud-Colvert et al., 2021). Furthermore, the protection MPAs provide to ecosystems and biodiversity can produce benefits that extend to local communities, fisheries, and economies (Angulo-Valdés and Hatcher, 2010; Goñi et al., 2010; Ban et al., 2019a; Naidoo et al., 2019; Wilson et al., 2020a). To produce these benefits, MPAs must be underpinned by positive enabling conditions, such as use of appropriate ecological and social design principles, adequate enforcement, and inclusion of indigenous ecological knowledge and wisdom, community needs and engagement, scientific research, and monitoring of key species, ecosystems, and ecosystem services (Kikiloi et al., 2017; Fulton et al., 2019; Grorud-Colvert et al., 2021).

In recognition of the important benefits that protected areas can provide, calls are increasing to update global targets for protected and conserved area coverage to reflect the urgency of the biodiversity and climate crises. These targets may be achieved by a mix of Protected Areas and Other Effective Area-Based Conservation Measures (OECMs; see **Box 1**). OECMs may have a variety of objectives (e.g., fisheries, sustaining cultural practices) but by definition are areas that also effectively conserve biodiversity (Jonas et al., 2014; Gurney et al., 2021). In relation to these global targets, recent scientific syntheses have led to a growing consensus about the need to meaningfully protect a much larger share of the planet than that which is protected to date. A range of percent coverages have been suggested to address specific goals, with some studies suggesting a need for at least 30% (Gaines et al., 2010; O'Leary et al., 2016; Dinerstein et al., 2019; Jones et al., 2020; Roberts et al., 2020; Waldron et al., 2020; Sala et al., 2021) or 50% (Wilson, 2016; Tallis et al., 2018) of the coastal and open ocean, and/or 100% of marine areas beyond national jurisdiction (White and Costello, 2014; Sumaila et al., 2015). Others flag

BOX 1 | Types of Area-Based Management in U.S. Waters.

An array of tools to safeguard biodiversity. A wide variety of place-based ocean management tools exists for U.S. waters (**Table 1**). These range from large-scale protected areas covering hundreds of thousands of square miles, to Areas of Special Biological Significance (ASBS) managed for water quality protection in the State of California, which are as small as 0.02 mi^2 (https://www.waterboards.ca.gov/). The primary intent of different area types varies widely, for example to ensure human health and safety (e.g., a Military Closed Area) or to preserve cultural resources (e.g., a closure around a historic shipwreck) (**Table 1**). We note that by definition MPAs have the conservation of nature as their explicit and primary goal (IUCN and WCPA, 2018). Thus, they are broadly used and their management interventions and outcomes are specifically tracked to report progress on global biodiversity conservation targets (IUCN, 2016). MPA activities must align with the outcome of conserving nature and the benefits it provides. But in practice, other area-based management tools may also deliver meaningful conservation benefits if they adequately protect ocean biodiversity from impactful extractive and destructive activities. Evaluating conservation potential requires determining whether conservation goals in non-MPA areas are competing with other goals since trade-offs inherent in pursuing other objectives can result in lower returns for biodiversity conservation.

Non-MPA areas that curb harmful activities for biodiversity and achieve effective conservation should be evaluated for their overall impact alongside MPAs to better understand their contribution, including to the target to protect at least 30% of the U.S. ocean by 2030 (Conserving and Restoring America the Beautiful, 2021). These areas may meet the definition of Other Effective Area-based Conservation Measures (OECMs). OECMs are areas managed with a variety of objectives – including human uses such as harvesting food and maintaining cultural identity and rights – but that sustain biodiversity and thus have the potential to meaningfully contribute towards conservation goals and targets (Jonas et al., 2014; Gurney et al., 2021). When well-designed and managed, OECMs and MPAs can play complementary roles, for example by improving connectivity and representation across regional networks and improving equity and ability to meet local needs (Gurney et al., 2021). International guidelines for recognizing and reporting OECMs were published in 2019 (IUCN-WCPA Task Force on OECMs, 2019). Identifying OECMs ultimately will depend on an area's ability to demonstrate effective conservation outcomes. This cataloging is ongoing in the U.S. and may include some of the area types listed in **Table 1**. For example:

- **Exclusion zones**, such as those around coastal military bases and NASA installations, often designate no-access marine areas for security purposes, and thus may provide conservation benefits (Esgro et al., 2020). Similarly, exclusion zones around other marine activities, such as oil and gas rigs, aquaculture net pens, coastal nuclear power, LNG facilities, wind farms, and maritime transportation lanes, or around private property, may provide some biodiversity conservation benefits even though they are not designated as MPAs (Rogers-Bennett et al., 2013).
- **Fisheries management areas** provide regulations with the primary goal of sustaining long-term production of targeted species, with fish population conservation as an important consideration. In pursuing this goal, fisheries management areas may disallow (permanently or temporarily) activities that degrade biodiversity. Area-based tools implemented for fisheries management include designation of essential fish habitat, habitat areas of particular concern, and time/area- and gear-based restrictions. However, many fisheries management measures do not necessarily represent long-term biodiversity conservation, as the focus is on targeted stocks with the goal to reopen fisheries once these stocks begin to recover. Identifying where fisheries management does contribute effective durable conservation through improving biodiversity and ecosystem health, and categorizing these areas as OECMs, may help foster cooperation between sectors (Gurney et al., 2021).

Overlapping jurisdictions. Fisheries management areas often overlap in space with MPAs and directly control the impacts of activities within their specific jurisdiction. For example, most MPAs in federal waters must work cooperatively to address fishery impacts with NOAA Fisheries and the relevant regional fishery management councils established under the Magnuson-Stevens Act. When strategically designed together, management measures provided by MPA and fisheries management authorities can offer lasting and durable protection to marine resources if sufficient area is given for each and if conservation measures are long-term. For example, in portions of the area surrounding the Farallon Islands, California, multiple fishery management regulations (including Rockfish Conservation Area and other gear closures) complement the protections within the Farallon Islands National Marine Sanctuary and the Farallon Islands National Wildlife Refuge (Sletten et al., 2021). In other cases, gaps in protection allow extractive uses that are not compatible with biodiversity conservation goals, for example if fishery management measures are temporary and impactful fishing is allowed to resume within the MPA (violating the "long-term" stipulation in the IUCN definition of an MPA), or the MPA is not at a level of protection that sufficiently conserves biodiversity, through allowing impactful extractive and destructive uses to occur. These situations may arise due to active opposition from some user groups (e.g., see **Box S1**).

TABLE 1 | Types of area-based management in U.S. waters.

Type		Examples	Primary Conservation Intent
MPAs		Marine Reserves, Marine National Monuments, National Marine Sanctuaries, National Parks, National Wildlife Refuges, National Estuarine Research Reserves, similar state-managed areas	Conservation of nature with associated ecosystem services and cultural values
Other areas	Fishery Management Areas	Essential Fish Habitat, Habitat Areas of Particular Concern, Deep Sea Coral Protections	Sustainable production
	DeFacto MPAs	Military Closed Areas, Vessel Traffic Areas	Health and human safety
	Water Quality Protection Areas	Areas of Special Biological Significance (CA)	Water quality
	Other	Shipwrecks, war graves, permanent fishery closures	Various

Areas that fall in "Other areas" rows may be identified as "Other Effective Area-based Conservation Measures" (OECMs) if they meet OECM criteria, including but not limited to effective conservation of biodiversity.

the importance of considering ecological representation; some ecosystems are underrepresented in current protected areas whereas others predominate area-based conservation, and this can vary greatly among countries (Roberts et al., 2019; Bohorquez et al., 2021). These results indicate that increasing ecological representation, in addition to expanding protection, is a key need.

In response to these calls for greater protection, negotiations continue around the post-2020 Global Biodiversity Framework draft target to protect at least 30% of the global ocean by 2030 in effectively and equitably managed, ecologically representative, and well connected MPAs and OECMs (IUCN, 2016; CBD, 2021). The IUCN has put forward definitions for representativeness and connectedness (WCPA/IUCN, 2007). The ≥30% target is not a precise end-goal but instead a useful directional target based on current scientific understanding of the minimum area needed to support healthy, functioning ocean ecosystems, and generate associated benefits for people (Woodley et al., 2019; Laffoley et al., 2020). Achieving this target *via* areas that are effectively designed and implemented could be one of the best means to reduce threats to biodiversity and enable ecosystems to meet peoples' needs through sustainable, equitable use while protecting the full spectrum of life in the ocean.

In line with these global targets, the U.S. has indicated a strong interest in employing existing and new MPAs to provide social and ecological benefits, including climate change resilience. A target of conserving at least 30% of U.S. waters was proclaimed at the Federal level in January 2021 (Conserving and Restoring America the Beautiful, 2021; Executive Order 14008, 2021), accompanied by similar targets and support among various Tribal leaders (Allen et al., 2021) and states (e.g., California Executive Order N-82-20; the Hawaii Governor's Sustainable Hawaii Initiative). If current and future U.S. MPAs are guided by scientific research and community needs, achieving a 30% target has the potential to improve biodiversity and human well-being outcomes. However, without a thorough accounting of the status and efficacy of existing U.S. MPAs, it is unclear what actions are required to meet this potential. Both quantity and quality are key for realizing the benefits MPAs can deliver for U.S. ecosystems, communities, and economies now and in the future (Grorud-Colvert et al., 2021).

We evaluated the status of ocean protection in the 50 largest U.S. MPAs, which account for 99.7% of the total area of U.S. MPAs, using a new framework that enables assessment of MPA quality in addition to quantity (Grorud-Colvert et al., 2021). We examine key opportunities for MPAs to contribute to climate resilience, healthy fisheries, and other goals, and highlight the importance of equity and justice as essential conditions for effective MPA design and management. Here we define effective protection as the ability of an MPA to return positive conservation outcomes for biodiversity, which are also integral for human well-being. We present a case for expanding benefits to biodiversity, ecosystem services, and human well-being by utilizing a strategic approach for increasing the total area, overall level of protection, and representativeness of U.S. MPAs. We identify gaps in understanding and offer recommendations, based on the current state of science, for improving the design, management, and governance of U.S. MPAs.

2 MPAs IN THE US: COVERAGE AND PROTECTION LEVELS

Marine protected areas have been part of the U.S. government's approach to ocean and coastal conservation since the early 1900s. The U.S. has nearly 1,000 implemented MPAs, including marine and coastal national parks, national marine sanctuaries, national wildlife refuges, and similar areas managed by states and territories (**Table S1**). These MPAs cover 26% of U.S. waters (Exclusive Economic Zone or EEZ, from 0-200 nautical miles), containing over 17% of state waters (including inland bays and estuaries; NOAA, 2020). Thus, on a national scale, the U.S. is currently 4% away from achieving a 30% spatial target for MPA extent. However, this coverage must be effective and representative, as defined above, to achieve the goal of conservation of nature to benefit biodiversity and people. Achieving a spatial target does not necessarily ensure achieving objectives. We need to know what protections U.S. MPAs are currently providing, and what outcomes can be expected from those protections.

We examined the 50 largest MPAs in the U.S. ocean to better understand the status and efficacy of MPA protection in U.S. waters. To do so, we employed a recent scientific synthesis, *The MPA Guide*, which provides a framework and common language for describing and evaluating the effectiveness of MPAs locally to globally (Grorud-Colvert et al., 2021). Briefly, *The MPA Guide* consists of four elements (**Table S3**): (1) stage of establishment, which describes the degree to which the MPA is in operation and actively protecting biodiversity; (2) level of protection provided to biodiversity from extractive and destructive activities; (3) enabling conditions, which describe the principles and processes underlying MPA effectiveness in its local context, both ecologically (e.g., size, spacing, connectivity) and socially (e.g., community engagement, communication and transparency, adequate funding and staffing); and (4) outcomes that can be expected from MPAs or zones at a particular level of protection, assuming enabling conditions are in place and the MPA is at an implemented or actively managed stage of establishment. Many benefits, including habitat and biodiversity, are greatest when MPAs are fully or highly protected from abatable threats such as destructive fishing, overfishing, dredging, mining, or high-impact infrastructure (Grorud-Colvert et al., 2021; **Table S3**). Furthermore, when key enabling conditions are in place, positive outcomes from fully and highly protected MPAs, such as community involvement and improved income, are more likely for coastal cultures, livelihoods, and economies over the longer term (Ban et al., 2019a). As a result, regions with predominantly lightly or minimally protected MPAs represent opportunities where changes in MPA regulations and governance could result in significant increases in conservation outcomes.

We investigated stage of establishment and level of protection for the 50 largest MPAs by area in the U.S. ocean (**Figure S1** and **Table S4**). Because these 50 MPAs comprise over 99% of the total U.S. MPA coverage (3,177,840 of 3,186,862 km^2), quantitative statements about the overall status of U.S. protected areas are possible using this analysis of a subset of MPAs. However, this analysis did not encompass the breadth of smaller MPAs in U.S. waters, which provide important social and ecological benefits and include some that are well designed and networked (e.g., some of the California MPA network; **Box 2**); future work should assess the stages and levels of these smaller-scale MPAs. MPA areas were obtained from the Marine Conservation Institute's Marine Protection Atlas (MPAtlas.org) database and the National Oceanographic and Atmospheric Administration's (NOAA's) Marine Protected Areas Inventory (NOAA, 2020). Certain large MPAs also overlapped with other large MPAs of different jurisdiction; when this occurred we evaluated the level of protection of each management area individually, based on the activities happening in that specific area. Some of these large MPAs also include smaller MPAs within their boundaries which may afford different levels of protection. We did not assess these here, as the total area coverage of these small MPAs was negligible relative to the large MPA in almost all cases. However, 21.9% of the Channel Islands National Marine Sanctuary is covered by a network of other smaller MPAs, many of which are fully and highly protected (see **Table S7**). This area covers 3.0% of California state waters. The level and stage of an MPA are best assessed by local experts, such as managers, with first-hand experience of the impacts to biodiversity in an area. Whenever possible, we used this level of information. To find evidence for the criteria required for each stage of establishment and for each of the activities assessed for level of protection (Grorud-Colvert et al., 2021; see http://mpa-guide.protectedplanet.net; **Table S4**), we recorded information on management, regulations, allowed and active uses and their impacts, including fishing gear types in use, and current threats to biodiversity found in a management plan, scientific literature, and *via* overlaying regulations from overlapping jurisdictions. These were identified *via* extensive online searches using management- and activity-based keywords. We contacted individual MPA experts (e.g., the MPA manager or staff) to request further information if needed, for example on active management and activity impacts. New information, regulations, or changes in human activities may affect these levels and stages.

Applying *The MPA Guide* framework to these 50 largest U.S. MPAs, we found 25.2% of the U.S. ocean is fully or highly protected, out of the total 26.0% in any kind of MPA (**Table 2**). However, total MPA area (and fully and highly protected area) is overwhelmingly concentrated in a few large fully or highly protected MPAs in the central Pacific (3.07 million km^2 out of 3.19 million km^2, or 96%; 99% of fully/highly protected area; **Figure 1** and **Table 3**). Outside this region, only 1.9% of U.S. waters are protected in any kind of MPA (120,976 km^2). Thus, the ecosystems in the current U.S. ocean protection regime are not representative of an adequate spectrum of marine biodiversity and habitats (see also Gignoux-Wolfsohn et al., *in review*). Our assessment included almost 93% of MPA area outside the Pacific region, and 22% of that area is fully or highly protected (**Table 3**). The other 77% allows moderate- to high-impact human activities (with 1% unknown). Indeed, some of these areas may experience human activities at a scale and impact that are incompatible with the conservation of nature (e.g., industrial-scale fishing, which is incompatible with protected areas under IUCN Resolution 066).

All of the U.S. MPAs that we analyzed were at least implemented, with management of the area "in force" in the water and not just "on paper" (see **Table S3**). Most of the zones we analyzed were in the actively managed category (the most advanced stage of establishment; 72 of 91; 79%), indicating that

BOX 2 | Case Study: California's Marine Life Protection Act.

The Marine Life Protection Act (MLPA) created an unprecedented MPA network within California state waters (Carr et al., 2019) including many fully protected State Marine Reserves (California Department of Fish and Wildlife, 2016; Murray and Hee, 2019). The long process revealed important lessons about how to successfully design and implement MPAs and the importance of community engagement along with scientific input (Yaffee, 2020).

In 1999, the MLPA mandated California to redesign its existing MPA system, guided by six goals (Gleason et al., 2010; Fox et al., 2013; Sayce et al., 2013). A team of scientists planned a science-based MPA network and presented this plan to communities. Communities, who were not consulted in these initial MPA designs, reacted so negatively to the proposed design that the attempt was terminated in 2002 (Scholz et al., 2004; Weible, 2008; Fox et al., 2013). A second attempt was unsuccessful as well, due to insufficient funding, a lack of organization, and the overwhelming task of planning for the whole state (Fox et al., 2013; Carr et al., 2019).

The third attempt was successfully completed, largely due to increased public participation in the planning process (Sayce et al., 2013), adequate funding through a public-private partnership, and better organization. It incorporated the best available science to inform network design (Botsford et al., 2014), but it was also supported by Regional Stakeholder Groups and used an innovative graphic interface for public input (Merrifield et al., 2013). Because community groups were included from the onset, it was largely well-supported by local communities (Fox et al., 2013; Gleason et al., 2013; Sayce et al., 2013; but see Ordoñez-Gauger et al., 2018). It has also been a success ecologically – baseline and subsequent monitoring have shown more abundant mature fish in MPAs, increasing connectivity between populations, and fish spillover from MPAs into fishing areas (Hamilton et al., 2010; California Ocean Science Trust and California Department of Fish and Wildlife, 2013; Caselle et al., 2015; Starr et al., 2015; Baetscher et al., 2019; Murray and Hee, 2019; Jaco and Steele, 2020; Lenihan et al., 2021).

There can be conflicting management objectives for traditional Tribal harvesting (Berkey and Williams, 2019) and supporting climate resilience and adaptation (Hofmann et al., 2021). While MLPA regulations recognized cultural and subsistence resource use, some Tribes, especially in the Northern California MPAs, found their practices unacceptably restricted (Berkey and Williams, 2019). Traditional harvest regulations in some Marine Conservation Areas were amended in response to these concerns (Berkey and Williams, 2019). The 2016 Master Plan calls for a review of the MPA Management Program in 2022 that will deliberately and formally incorporate Indigenous knowledge (California Department of Fish and Wildlife, 2016). A recent report to guide the evaluation process stressed the necessity of Tribal partnerships to co-manage, combine Indigenous knowledge and wisdom with western science, and further evaluate the effects of the MPAs on human wellbeing (Hall-Arber et al., 2021). Moreover, additional research and action is needed to support climate resilience (Hofmann et al., 2021).

TABLE 2 | U.S. MPA area (km^2) in the largest 50 U.S. MPAs, assessed by level of protection and stage of establishment (excluding proposed/committed and designated, which are not yet in force on the water) using *The MPA Guide*.

		Stage of Establishment					
		Implemented		Actively Managed		Total	
		Area (km^2)	Percentage	Area (km^2)	Percentage	Area (km^2)	Percentage
Level of Protection	**Fully Protected**	216,892	1.8%	3,845	0.0%	220,737	1.8%
	Highly Protected	1,320,855	10.8%	1,544,648	12.6%	2,865,504	23.4%
	Lightly Protected	12,528	0.1%	12,204	0.1%	24,732	0.2%
	Minimally Protected	631	0.0%	64,363	0.5%	65,267	0.5%
	Total	1,550,906	12.6%	1,625,333	13.2%	3,176,239	25.9%

Percentages are out of total U.S. ocean area (12,269,628 km^2). MPA area assessed in the largest 50 U.S. MPAs but with an unknown level of protection or stage of establishment is 1,730 km^2, or 0.05% of this analysis, and is not included in this table.

there is ongoing monitoring, adaptive management, and/or other elements needed for effective protection (**Table S3**). These actively managed MPAs represent 51% (1,625,116 km^2) of the total area covered by the largest 50 MPAs, primarily because the second and third largest MPAs—Pacific Remote Islands and Marianas Trench Marine National Monument—are not yet actively managed. Although protection is "in force" and can begin to generate conservation outcomes, these areas do not yet have official management plans that would clearly establish goals, objectives, and proposed management actions.

The number, size, and level of protection of U.S. MPAs in our analysis varied widely among regions (**Figure 1** and **Table 3**). For example, 4.7% of the Northeast region is covered by MPAs of which about two-thirds is highly protected (in the Northeast Canyons and Seamounts Marine National Monument, where commercial crab and lobster fishing will be phased out by 2023) and one-third is minimally protected (in the Stellwagen Bank National Marine Sanctuary and the Massachusetts Ocean Sanctuaries, which allow large impacts from human activities like fishing; see **Table S4**). In the Northwest region, 4.2% of the

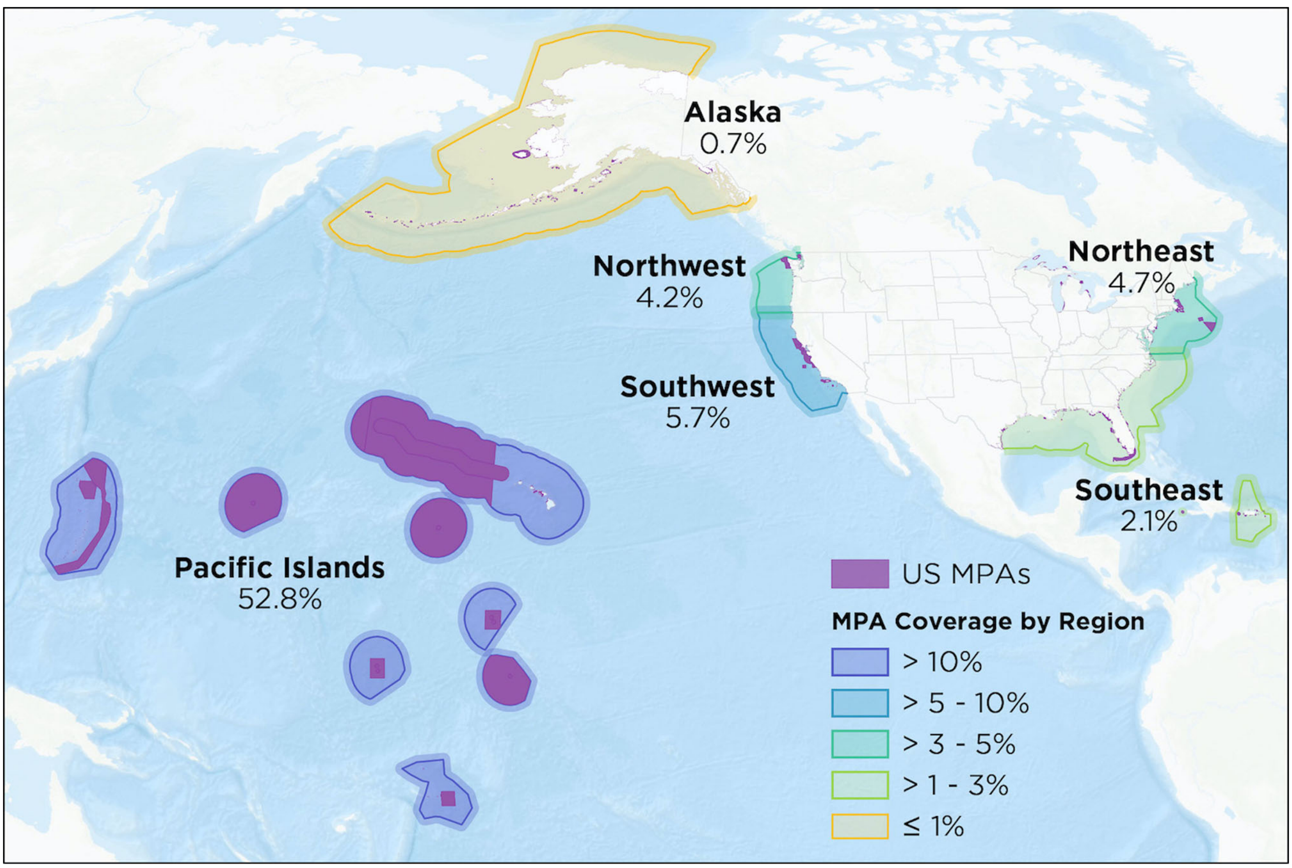

FIGURE 1 | Percent marine area in any kind of implemented MPA by U.S. Region.

TABLE 3 | Area and percent of MPAs in each U.S. Region that fall within the largest 50 U.S. MPAs (analysis presented here, excluding area for which level of protection was unknown – 0.05% of analysis), by level of protection.

Region	Total Marine Area (km^2)	Total MPA area (km^2)	Percent of Total Marine Area in MPAs	Percent of Total MPA Area within this Largest 50 Analysis	Percent of Total MPA Area in this Largest 50 Analysis			
					Fully	Highly	Lightly	Minimally
Alaska	3,710,339	24,190	0.7%	93.6%	15.4%	4.3%	68.2%	8.4%
Northeast	514,011	24,324	4.7%	97.8%	0.0%	66.9%	0.0%	33.2%
Northwest (OR, WA)	247,799	10,305	4.2%	93.0%	0.0%	0.0%	0.0%	100.0%
Pacific (HI, Am Samoa, Guam, CNMI)	5,802,156	3,065,885	52.8%	100.0%	7.0%	92.9%	0.0%	0.1%
Southeast (includes Gulf of Mexico, Puerto Rico, US Virgin Islands, & Navassa)	1,421,348	29,549	2.1%	83.2%	8.9%	7.2%	22.3%	59.2%
Southwest (CA)*	573,975	32,607	5.7%	96.5%	0.0%	0.0%	12.1%	87.9%
Grand Total	12,269,628	3,186,862	26.0%	99.7%	7.0%	90.2%	0.8%	2.1%

*Total marine area in each region represents all ocean areas, including State, Federal, and Territorial waters. The regions are as follows (see **Figure 1**): Northeast – Maine to Virginia; Southeast – North Carolina to Texas, including the Gulf of Mexico; Northwest – Oregon, Washington; Southwest – California; Pacific – Hawaii, American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands; Alaska.*
see **Table S7 for a case study from California.*

area is covered by MPAs of which more than 80% is minimally protected in the Olympic Coast National Marine Sanctuary (**Table 3**). Further, analyses of regions at a more granular level than what is presented here reveal important gaps in protection for some areas of coastline and ecoregions (**Table S5**). For example, MPAs cover only 0.3% of the mid-Atlantic region (off the coast of Virginia, Maryland, Delaware, and New Jersey), and all area included in our assessment was minimally protected (in the Jacques Cousteau NERR). Single (or few) very large MPAs drive the overall MPA level of protection for many regions. Comprehensive assessments of coverage for all MPAs in each region helps identify areas and habitats where additional targeted protection could help achieve goals.

Many of the U.S.'s MPAs are very small. The median area is 1.1 km^2 (average 3,929 km^2), with 48% being less than 1 km^2 and the smallest <0.01 km^2 (NOAA, 2020). Furthermore, because they were developed over time through multiple, sometimes disconnected, federal, state, and local programs, most U.S. MPAs are not part of larger, functional ecological networks. Small MPAs outside of a network are unlikely to achieve biogeographic objectives such as representativeness, replication, and connectivity. MPAs that are designed as functioning networks explicitly consider ecological connectivity, such as size and spacing of MPAs relative to movement and dispersal of larvae and adults to support persistent populations of relevant species (Carr et al., 2017). Some U.S. MPAs, however, were designed with these objectives in mind, such as the California MPA network which explicitly considered connectivity, replication, and representation (**Box 2**) or the National Estuarine Research Reserve (NERR) program, which has representativeness as a core design criterion.

Although here we assessed protection by region, not habitat or ecosystem type, parallel research has found that U.S. MPAs have critical gaps. For example, in 2021, an expert working group completed the first quantitative assessment of U.S. biodiversity and MPA network representativeness (Gignoux-Wolfsohn et al., *in review*). This work concluded that total MPA area varies substantially across U.S. regions, and few regions are effectively protecting biodiversity – with the Pacific Islands regions as closest, and regions in Alaska furthest, from achieving conservation goals for representativeness, connectivity, replication, viability, adequacy, and coverage of important areas for specific taxa (per Convention on Biological Diversity (CBD) guidance). Some states are moving toward protecting 30% of state waters, which contain important habitats and biodiversity. However, MPA coverage is highly variable across states (**Table S2**), and state waters represent a small fraction of federal waters (3 nautical miles vs. 200 nautical miles) and therefore a small amount of U.S. MPA area. Further, more and higher quality protection is needed to adequately protect biogenic habitats like corals (particularly cold water corals and those outside of the Pacific Islands), seagrasses, mangroves, shellfish beds, and deep-sea sponges (Gignoux-Wolfsohn et al., *in review*). These habitats are highly vulnerable to multiple stressors, are important biodiversity components, and some are important blue carbon reservoirs (Sweetman et al., 2017; Kendrick et al., 2019; Pendleton et al., 2020). An important next step will be to determine the overlap between MPA level of protection and stage of establishment with representative and important areas for biodiversity.

Few data are available on open-ocean pelagic and deep-sea habitat protection relative to coastal habitats. The vast majority of protection for U.S. pelagic and deep-sea habitats is in the Central Pacific marine national monuments (Gignoux-Wolfsohn et al., *in review*). Open ocean habitats and species protection is complicated by the system's dynamic nature and the difficulty of delineating specific pelagic habitats, as well as questions of governance and international jurisdiction. However, protection of pelagic species like tuna, billfishes, marine mammals, and turtles is crucial, as many play important ecological roles for ecosystem structure and functioning (Myers et al., 2007; Heithaus et al., 2008; Ferretti et al., 2010; Silber et al., 2017; Bornatowski et al., 2018). Deep sea habitats are also data-poor and poorly protected in most ecoregions (Morato et al., 2010; Clark et al., 2012; Kennedy et al., 2019). These systems close attention to coupled conservation and management efforts through ocean governance. The biogeographic processes and ecological functioning of pelagic and deep sea systems are tightly linked; activities happening in the water column can impact the benthic species and habitats these areas are intended to protect. For this reason, IUCN is opposed to vertical zoning in MPAs (ICUN and WCPA, 2018). Some U.S. areas are vertically zoned, such as the Marianas Trench Marine National Monument, which only protects the benthos and not the water column above.

Protected areas (PAs) in the Great Lakes are included in the U.S. National MPA center database and were created to protect cultural resources like shipwrecks (https://oceanservice.noaa.gov/facts/mpaloc.html). Indeed, many of these areas may be OECMs, not PAs, based on their objectives (see **Box 1**). Biodiversity decline and defaunation in freshwater ecosystems has been disproportionately severe (Young et al., 2016; WWF, 2020), and the need for freshwater protection is gaining attention (Abell et al., 2007; Hedges et al., 2010; Acreman et al., 2020). Freshwater PAs have been a focus of multiple U.S. agencies and organizations and they are included in the U.S. National MPA Center inventory (Pearsall et al., 2013). The Laurentian Great Lakes hold roughly 21% of the world's surface freshwater and support substantial biodiversity (Pearsall et al., 2013). They contain PAs of multiple types totaling 13,565 km^2, varying from 0% protection in Lake Ontario to 45.5% in Lake Huron, and 8.2% in the Great Lakes overall (**Table S6**) (updated from Parker et al., 2017). Freshwater PAs represent <0.5% of U.S. MPA coverage. We did not include freshwater PAs in our assessment of the 50 largest U.S. MPAs, but an assessment of level of protection could inform re-evaluation of activities allowed, as no Great Lakes PAs are likely fully protected from abatable extractive and destructive activities (Parker et al., 2017).

3 MAKING THE MOST OF U.S. MPAS: KEY FOCAL AREAS

The U.S. has a long history of policies for ocean conservation and management, and is considering new domestic policies to address the global climate and biodiversity crises. These include most recently the target of conserving at least 30% of U.S. lands and waters by 2030 in Executive Order (EO) 14008. With this target, the U.S. Government set a national goal for conservation of nature in recognition of the vital importance of healthy ecosystems for American well-being, to address the climate and biodiversity loss, and to increase equitable access to nature. To achieve policy goals, as outlined in the Report "Conserving and Restoring America the Beautiful" (2021), U.S. policymakers have been charged to "listen to science and meet the moment" (EO 14008). Our analysis reveals that the system of U.S. MPAs can be improved to deliver these outcomes more effectively. Below, we review the state of science for several crucial focal areas to guide the U.S.'s continuing actions around MPAs.

3.1 Climate Mitigation and Adaptation

Marine protected areas have important but underutilized potential for contributing to climate change mitigation and adaptation on local to global scales (Roberts et al., 2017; Tittensor et al., 2019; Wilson et al., 2020a; O'Regan et al., 2021). Furthermore, to continue to meet conservation goals in the face of current and future climate changes, MPAs should be designed and managed with the reality of climate impacts in mind. "Climate-ready" MPAs must be designed to best provide benefits that match the pace and magnitude of climate change impacts, which we discuss below. The science to inform the design of MPAs that can continue to function in a changing climate and contribute to mitigation and adaptation is only now emerging. However, even early scientific guidance is crucial for informing decisions being made now, as expectations for climate impacts and benefits arise from fundamental, first-principle understanding of how MPAs affect biological and ecological attributes that drive physical and biogeochemical processes and resilience at multiple scales of biological organization (Roberts et al., 2017; Hofmann et al., 2021).

Climate change mitigation *via* MPAs can manifest in physical and chemical conditions at the individual to system scale. By fully and highly protecting biogenic habitats, including kelp forests, coral reefs, oyster reefs, tidal wetlands, and mangroves, MPAs can maximize climate mitigation services these ecosystems provide to humans, such as attenuating waves and buffering storm surges (Løvås and Tørum, 2001; Ferrario et al., 2014). Macrophytes such as seaweeds may also play a role in regulating pCO_2 and producing oxygen, potentially partly ameliorating the local effects of ocean acidification and hypoxia (Hendriks et al., 2014; Koweek et al., 2017; Nielsen et al., 2018; Hirsh et al., 2020), though such local effects appear to be scale- and site-dependent and restricted in size. Macrophytes can also help mitigate the effects of eutrophication and water-borne diseases that compound climate stressors on coastal ecosystems and communities; for example, seagrass beds can serve as nutrient sinks (Aoki et al., 2020) and have been shown to reduce the prevalence of human and wildlife pathogens (Lamb et al., 2017). MPAs also safeguard the carbon stored in seafloor sediments against disturbance from activities like dredging, mobile bottom fishing gears, future seabed mining, or other activities that release and remineralize carbon (United Nations Environment Programme, 2009; Atwood et al., 2020; Sala et al., 2021). Furthermore, marine macrophyte systems such as mangroves, seagrass beds, and salt marshes hold, as well as sequester, large stocks of organic carbon on a global basis, at rates up to ten times larger than terrestrial systems (Lubchenco et al., 2020; Macreadie et al., 2021). Protection of marine and coastal "blue carbon" systems thus represents a key lever for climate change mitigation in the U.S. (Lubchenco et al., 2020) and should be considered when identifying areas for protection (Sala et al., 2021).

In addition to mitigation, MPAs can enhance adaptive capacity at organismal, population, community, and ecosystem levels (Kroeker et al., 2019; Hofmann et al., 2021). Essentially, MPAs can provide a portfolio effect against climate-induced stressors and disturbances. Increased organism body sizes can confer greater individual tolerance to thermal and other climate stressors (Micheli et al., 2012; Barneche et al., 2018). Larger population sizes with a broader age distribution, as commonly found in fully and highly protected MPAs (Lester et al., 2009; Baskett and Barnett, 2015), may speed up recovery following disturbance including *via* maintenance of greater demographic and genetic diversity (Blasiak et al., 2020) and of reproductive output and juvenile recruitment (Micheli et al., 2012; De Leo and Micheli, 2015). Community and ecosystem resilience can be provided by maintenance of taxonomic and functional diversity as well as trophic and other species interaction linkages; for example, after a marine disease outbreak decimated populations of the predatory sea star *Pycnopodia helianthoides* along the U.S. west coast, other large predators (California sheephead and California spiny lobsters) inside MPAs suppressed purple sea urchin density and allowed canopy-forming kelp and understory algae to grow (Eisaguirre et al., 2020). Outside of MPAs, where sheephead and spiny lobster are smaller and less abundant due to fishing pressure, urchin populations grew dramatically, leading to kelp loss and the formation of urchin barrens (Eisaguirre et al., 2020). Fully and highly protected areas that minimize anthropogenic impacts provide the best chance for climate resilience, especially at organismal and population levels (Grorud-Colvert et al., 2021).

A well-designed MPA network can provide additional resilience through the protection of replicate and connected habitats or those that are essential to different life stages, promoting adaptive capacity and providing insurance against catastrophic disturbance, the risks of which rise with climate change (Allison et al., 2003; Sheehan et al., 2021). Across a network, many independently fluctuating populations can provide stability to the metapopulation (Anderson et al., 2015; Hammond et al., 2020). Well-designed networks of fully and highly protected MPAs – with attention to effective design principles such as connectivity, representation, and replication – working in concert with effective management outside their borders are crucial to ensure MPAs effectiveness lasts. These networks can provide additional resilience to species undergoing climate-induced range shifts, but the statistical effect size for species targeted by fisheries will depend on the extent to which MPAs reduce total fishing pressure (Fuller et al., 2015). Furthermore, recent models show how MPA network designs that take environmental conditions into account can improve outcomes. Modeling in coral reef systems revealed that MPA network designs that included warm, cool, and intermediate reefs (relative to only single or paired warm and cool environmental exposures) worked best to preserve coral cover (Walsworth et al., 2019). The authors credit active dispersal among reefs in the model, and the importance of warm reefs to provide adaptive power, moderate reefs to provide stepping stones, and cool reefs to provide better habitats after the ocean has warmed. Understanding how climate is likely to affect an area (e.g., considering climate velocity; Brito-Morales et al., 2018) will allow MPA design characteristics and adaptive management at the individual and network scale to address specific climate stressors and their outcomes, including shifts in species distributions, community composition, or connectivity (Rassweiler et al., 2020). For example, if protection is geared towards seagrass beds for blue carbon, adaptive MPAs should account for shifting distributions not only with warming waters, but also with sea level rise (McHenry et al., 2021) and ocean acidification (Chan et al., 2019).

The timeline for creating or modifying MPAs in the U.S. does not align with the increasing severity and speed of climate change impacts on marine ecosystems. Furthermore, inclusion of human needs and interests represents a major challenge in designing and implementing climate-ready MPAs (Basurto, 2013). Currently, very few MPAs or MPA networks globally integrate climate change into planning and design (Tittensor et al., 2019; O'Regan et al., 2021); however, some useful examples exist, including the Greater Farallones National Marine Sanctuary in California, which incorporates a climate vulnerability assessment, recommendations, and implementation plan explicitly in its management plan (U.S. Department of Commerce et al., 2016); a recent assessment of climate impacts and recommendation for actions for supporting climate resilience of the California MPA network (Hofmann et al., 2021); and Papahānaumokuākea Marine National Monument, which produced one of the first climate vulnerability assessments that incorporates Indigenous perspectives (Kikiloi et al., 2017).

Governance in a changing ocean calls for novel institutional arrangements (Spalding and de Ycaza, 2020) and careful consideration of equity for those most vulnerable (Bennett et al., 2021). Emerging knowledge about the role of biodiversity and healthy coastal ecosystems in "buffering" against climate change impacts can help inform climate-ready governance solutions for which MPAs play a critical role. For example, polycentric governance describes a structure where multiple, semi-autonomous, overlapping and coordinated institutions are responsible for decision-making (Ostrom et al., 1961; Ostrom, 2005; Yadav and Gjerde, 2020). Applied to MPAs, polycentric governance may represent a unique opportunity to match the recommended ecological and spatial modularity of a climate-ready MPA with the appropriate policy-based enabling conditions (Carlisle and Gruby, 2018; Brodie Rudolph et al., 2020). It is critical to consider the ecological design principles and implications for marine ecosystems, but also the overarching governance structures and management processes that can support effective MPAs and associated natural and social outcomes.

3.2 Justice, Equity, Inclusion, and Access

3.2.1 Supporting Full Diversity of Local Communities to Engage, Lead, and Benefit

An effective MPA depends on input, buy-in, and engagement from surrounding communities (Pollnac et al., 2001; Voyer et al., 2015; Basurto et al., 2016; Gollan and Barclay, 2020). Many groups, particularly tribal rights holders or local communities, are often systematically excluded from the MPA decision-making process, through top-down mandates, including at the Federal level. For a recent comprehensive review of equity issues in marine conservation, see Bennett et al. (2021). Excluded communities are often those that have suffered the greatest environmental injustices, such as exposure to environmental hazards, and have the least access to natural spaces and resources (e.g., people of color, low-income communities, Indigenous peoples; Reineman et al., 2016; Österblom et al., 2020; California Ocean Science Trust, 2021). Excluding these groups not only perpetuates systemic inequity and injustice but sidelines a wealth of leadership, wisdom, knowledge, and creativity that is needed to address urgent conservation challenges. Including and respecting diverse voices and perspectives is essential to move effective stewardship forward. Doing so will shape the questions that are asked, the concerns that are defined and addressed, and the solutions that are proposed to restore and protect the ocean, its resources, and equitable access to healthy ocean spaces. The Marine Life Protection Act process in California offered valuable lessons learned on the importance of involving local communities in MPA decision-making processes (see **Box 2**).

Furthermore, the positive biological and ecological outcomes of MPAs can drive resilience benefits for human wellbeing, especially for vulnerable populations living near coastlines. These benefits range from protection of community and physical infrastructure from storms to long-term support for livelihoods, cultural identity, and physical, mental, and emotional health (Ban et al., 2019b; Naidoo et al., 2019; Jones et al., 2020; Marcos et al., 2021). Designing and implementing MPAs for climate resilience also requires considering the needs and values of local communities and providing opportunities for local action to support climate justice; in some cases, these values and needs may involve trade-offs. Careful consideration must be given to who has the rights and responsibilities, and who is afforded the opportunity, to address these trade-offs in a given place.

3.2.2 Respecting and Empowering Indigenous Rights and Leadership

Indigenous peoples in the U.S. and worldwide are the original conservation stewards of marine spaces, with rights, responsibilities, wisdom, knowledge, and connections to the places they have lived in and sustained for generations (Johannes, 1978; Berkes, 2018; Ban et al., 2019b; Lukawiecki et al., 2021; Office of Hawaiian Affairs et al., 2021). MPA managers at all governance levels have the responsibility and opportunity to work in partnership with and, where appropriate, enact co-management with Indigenous peoples (Cinner et al., 2012). U.S. federal agencies, specifically, have a legal responsibility to respect treaty rights and protect Tribal resources, and to consult with federally recognized Tribes on policies with Tribal implications. However, beyond this legal obligation, the deep and long-term connections and knowledge that Indigenous peoples hold for their lands and waters are vital for informing effective long-term management undertaken by federal and state agencies. For example, traditional knowledge of Bering Sea ecosystems held by Indigenous communities is now incorporated into the North Pacific Fisheries Management Council's Bering Sea Ecosystem Plan (Raymond-Yakoubian et al., 2017; North Pacific Fisheries Management Council, 2019).

Moving forward in mutual, trust-based relationships and partnerships between Indigenous peoples, management agencies, and stakeholders is critical to the success of MPAs and must be developed and sustained over the long-term, often beyond typical research, funding, and project timelines. The California statewide MPA network was broadly criticized and legally challenged for not addressing the rights of coastal Tribes and has worked to strengthen these partnerships and elevate the role of Tribes in natural resource management in recent years (**Box 2**). Indigenous groups, including the Chumash in California and the Aleut communities of the Pribilof Islands in Alaska, have expressed interest in establishing new MPAs *via* nominations for National Marine Sanctuary status to protect their traditional waters and address their conservation and sustainable use priorities (nominate.noaa.gov); NOAA has announced plans to designate the Chumash Heritage National Marine Sanctuary. In Hawaii, Papahānaumokuākea Marine national monument was named to commemorate the union of two Hawaiian ancestors – Papahānaumoku and Wākea – and is a place of great spiritual importance to Native Hawaiians (Kikiloi, 2010). Native Hawaiian leadership worked directly towards implementing this National Monument, and it is now co-managed by the Office of Hawaiian Affairs, along with state and federal partners, with management actively guided by Native Hawaiian knowledge systems, values, and practices (Kikiloi et al., 2017; Office of Hawaiian Affairs et al., 2021). Currently, Pacific Islanders, including Hawaiians, Chamorros, Samoans, and other native peoples in Micronesia, are stewards of more than 99% of the area currently protected in U.S. MPAs. Recognition and inclusion of Indigenous knowledge, leadership, and stewardship is crucial for directing and informing MPA decision-making, including design, monitoring, management, monitoring, and enforcement.

3.3 Other Sectors

Implementing new or more highly protected MPAs has the potential to help meet, or conflict with, societal needs across other sectors (see below). Understanding these conflicts and opportunities relies on deepening scientific understanding of how specific activities may impact marine ecosystems and their services to people, and whether those impacts are compatible with the conservation goals of MPAs. Historically, the fishing sector has been the industry stakeholder that has most actively engaged with MPAs (see below "Fisheries sector"). However, as global and U.S. blue economies diversify and accelerate, interactions between MPAs and industry will necessarily diversify (Jouffray et al., 2020; Posner et al., 2020). Navigating these dialogues and decisions requires attention to whether and how goals can align across different area types (see **Box 1**). OECMs in particular may incentivize cooperation between sectors, bringing new voices into conservation decision-making (Laffoley et al., 2017a; Gurney et al., 2021; Gissi et al., 2022), for example by giving OECM recognition to areas that are managed for fisheries or renewable energy and also provide meaningful outcomes for biodiversity conservation. The "effectiveness" criterion is critical for identifying OECMs (Laffoley et al., 2017; Gurney et al., 2021). Aligning diverse sectors with the biodiversity protection goal of MPAs is crucial to stemming biodiversity loss and requires careful planning. Below we outline considerations for certain sectors that can affect, and be affected by, MPAs.

3.3.1 Fisheries Sector

Effective MPAs and sound fisheries management are both essential tools for ocean management and provide complementary benefits (see **Box 1**). Fisheries management approaches can include area-based measures, including bottom-trawling closures and essential fish habitat conservation areas. By definition, MPAs focus on long-term protections for biodiversity and ecosystems, whereas fisheries management aims to sustainably manage commercial and recreational fisheries stocks for optimum, sustained yield of targeted species. Both have an important role to play in ensuring healthy ecosystems and human communities. Perceptions of a false dichotomy between fisheries management "vs" MPAs impedes progress towards sustainable management, a common goal for people who identify as fishers, conservationists, or both.

Although most existing U.S. MPAs were not purposefully created to benefit fisheries, they can be designed to do so (White et al., 2008; Gaines et al., 2010; Cabral et al., 2019; Sala et al., 2021). The most readily demonstrated benefit of MPAs to fisheries is the small-scale spillover effect (Kellner et al., 2007), with increased abundances and catches near MPA borders documented around the world (Roberts et al., 2001; Russ et al., 2004; Abesamis and Russ, 2005; Halpern et al., 2009; Kerwath et al., 2013; Di Lorenzo et al., 2020; Lenihan et al., 2021). Individual fish in well-protected MPAs reach larger sizes than in areas exposed to fishing mortality and larger fishes have significantly higher reproductive potential than smaller individuals (Baskett and Barnett, 2015; Marshall et al., 2019). MPAs that successfully protect spawning aggregations can significantly benefit surrounding fisheries through the export of eggs and larvae outside of the protected area (Beets and Friedlander, 1999; Erisman et al., 2015). However, region-wide fisheries benefits of MPAs may be difficult to detect empirically, even when they occur (Ovando et al., 2021).

Certain coastal U.S. MPAs have benefited adjacent fisheries, both commercial (Murawski et al., 2000; Murawski et al., 2005; Kay et al., 2012) and recreational (Roberts et al., 2001; Stamoulis and Friedlander, 2013). For example, there were a disproportionate number of world record size fishes caught in the waters adjacent to Merritt Island National Wildlife Refuge in Florida (62% of record-size black drum, 54% of red drum, and 50% of spotted sea trout caught between 1939 and 1999; Roberts et al., 2001). After an MPA network was established protecting 35% of the West Hawai'i coast from aquarium fish harvest, target species and fishery value increased (Friedlander et al., 2008; Grorud-Colvert et al., 2014). The more recent expansion of large Marine National Monuments in the Pacific Ocean has resulted in only minor species-specific catch changes (Gilman et al., 2020) and no changes to U.S. commercial longline fisheries catch rates (Lynham et al., 2020), although effects may be better detected when more time has elapsed since MPA implementation. The creation of large-scale oceanic MPAs by other nations has resulted in increases (Boerder et al., 2017; Bucaram et al., 2018) or no changes (Curnick et al., 2020) to commercial catches and fisheries profits for highly mobile pelagic species.

Not all U.S. MPAs yield clear fisheries benefits and instead can have negative impacts or no appreciable impact (Guenther et al., 2015; but see Lenihan et al., 2021). An MPA's ecological and social impact on fisheries can involve important tradeoffs, especially in the short-term and across different user groups. For example, there were negative effects of two Gulf of Mexico MPAs on catches in a reef-fish fishery 4.5 years after implementation, though life history strategies of targeted species suggest that potential MPA benefits may not have had time to accrue (Smith et al., 2006). Furthermore, implementation of MPAs can increase conflict, particularly among fishers and other interested groups; understanding how to manage different groups' expectations and mitigate negative conflict is crucial to positive outcomes (Ban et al., 2019a). Designing MPAs to reduce conflict may impact effectiveness. For example, prior to MPA implementation, densities of economically important sea cucumbers in the Galapagos were higher in fished zones than in areas set aside as "no take", a pattern that may result from siting MPA zones in resource-poor areas to minimize impacts on fisher livelihoods (Edgar et al., 2004).

While U.S. marine conservation organizations typically advocate strongly for MPAs, different fisheries groups have different perspectives on MPAs. Some have advocated for their specific use, while others are opposed. For example, in Biscayne National Park, a proposed fully protected area employing scientific design principles and with broad public support was framed by certain recreational fishing groups and the State of Florida as an either-or proposition – either enhanced fisheries management or a fully protected MPA – when both could be implemented for positive outcomes for depleted species (**Box S1**).

Improved partnership, communication, and knowledge-sharing across sectors can help resolve this perceived dichotomy. For example, long-term stakeholder engagement in collaborative research can give members of different sectors first-hand experience with MPA outcomes and improve research outputs, for example as local fishers share on-the-water knowledge and experience (Mason et al., 2020). The California Collaborative Fisheries Research Program has coordinated a 15-year partnership among volunteer fishers, researchers, the fishing industry, and resource managers to monitor groundfishes in California's MPA network. Co-creating collaborative monitoring protocols has increased communication and trust among sectors and the availability and scale of fisheries- and MPA-relevant data (Yochum et al., 2011), ultimately improving participating fishers' opinions about MPAs (Mason et al., 2020).

3.3.2 Energy Sector and Mining

Diverse offshore energy development is expanding rapidly in the U.S. and management approaches to address this growth are in the early stages. Integrating energy platforms with MPAs represents both an opportunity and a potential conflict. Offshore energy platforms – oil, wind, solar, or hydrokinetic – have been suggested as "de facto" MPAs (or potential OECMs) because they often reduce or exclude other human uses, and can attract species by providing habitat structure or increased prey productivity (Schroeder and Love, 2002; Ashley et al., 2014). However, impacts exist, including those related to noise, electromagnetic fields, turbine collision, entanglement, increased vessel traffic, benthic habitat disruption, and energetic costs associated with platform avoidance (Furness et al., 2013; Bailey et al., 2014; Bergström et al., 2014; Schuster et al., 2015). More research is needed on renewable energy structure impacts on marine biodiversity and fisheries, particularly as U.S. targets for offshore wind increase (e.g., The White House Briefing Room, 2021). Oil platforms represent a considerable potential impact, as oil spills can have long-lasting impacts, and oil and gas extraction exacerbates climate change. Flower Garden Banks National Marine Sanctuary in the Gulf of Mexico is in an area with high oil and gas activity, including within its borders, with associated threats to biodiversity conservation (US Department of Commerce, National Oceanic and Atmospheric Administration, and Office of National Marine Sanctuaries, 2012). Decommissioning oil and gas platforms should be done strategically to minimize ecosystem impacts–"rigs-to-reefs" programs, for example in the Gulf of Mexico and California, can convert some portions of platforms into artificial reefs provided there is careful attention to weighing benefits (e.g., habitat preservation, fish biomass) vs. potential costs (e.g., pollutant leakage from capped wells) (Meyer-Gutbrod et al., 2020).

Deep seabed mining in the U.S. is in an exploratory phase, and centers around rich mineral resources in the Central Pacific – including close to existing U.S. MPAs, such as the Pacific Remote Islands Marine National Monument. Seabed mining is not compatible with MPAs, since environmental impacts from mining and recovery times for biological communities are likely to be significant and may lead to permanent loss of species and ecosystem function (Van Dover, 2014; Levin et al., 2016; Boetius and Haeckel, 2018; Haugan et al., 2020). U.S. exploitation of seabed mineral resources in areas beyond national jurisdiction would depend on ratification of the 1982 Law of the Sea Convention and the 1994 Implementation Agreement, treaties that govern the prospecting, exploration and exploitation of resources designated as the "common heritage of mankind" (Willaert, 2021). Scientists have suggested that the International Seabed Authority implement high seas MPAs to protect key areas before approving any exploitation or new exploration contracts (Wedding et al., 2015). Any future seabed mining will require careful consideration to identify non-MPA locations and methods that minimize ecosystem impacts. Whether acceptable impact levels are possible is unknown. In the meantime, hundreds of ocean researchers have called for a pause on seabed mining outright (http://www.seabedminingsciencestatement.org). Oregon and Washington states have already banned seabed mining for hard minerals in state waters, and California has introduced a bill to do so.

3.3.3 Tourism and Recreation

The tourism sector can offer co-benefits with MPAs. Fully protected does not imply no-entry, and snorkelers, scuba divers, and others typically prioritize high biodiversity and large fishes and other marine fauna, all of which are important outcomes of MPAs (Sala et al., 2013). MPA-driven improvements of habitats, fish abundance and biomass, and species diversity increase the demand for diving and divers' willingness to pay to dive inside MPAs (Bhat, 2003; Grafeld et al., 2016; Shideler and Pierce, 2016). Higher levels of protection in MPAs can also result in higher support and perceived value by the general public relative to minimally protected MPAs (Turnbull et al., 2021). Hawaiʻi's Hanauma Bay is one of the most visited MPAs in the world (>1 million people/year in 0.41 km^2) and had a net present value of $650 million in 2004 (van Beukering and Cesar, 2014). Molokini Shoals MPA has over 350,000 visitors/year in 0.35 km^2. Displacement of important reef-associated predators occurs during peak hours of human visitation, which suggests the natural ecosystem function is compromised (Filous et al., 2017). Indeed, because of the high impact of non-extractive use, these MPAs would be considered lightly protected. Although non-consumptive uses like tourism are typically less impactful than many extractive activities, careful attention is needed to minimize impacts from potentially destructive activities like anchoring, infrastructure, dumping, and high-density recreation (Grorud-Colvert et al., 2021).

3.3.4 Mariculture

The interaction of MPAs and marine aquaculture (mariculture) has received limited research attention. Some mariculture may be compatible with the conservation objectives of MPAs, depending on the type, scale and practices of the operation, intensity of cultivation, siting of the farm, and whether the cultivated species is native to the region (Gentry et al., 2017; Laffoley et al., 2017b; Le Gouvello et al., 2017; Gentry et al., 2020; Naylor et al., 2021). In general, unfed mariculture (e.g., seaweed, bivalves) has lower environmental impacts than fed mariculture and has high but underused potential to contribute to nutritional security globally (Gephart et al., 2021; Naylor et al., 2021). Further, these types of mariculture can also contribute to habitat restoration (Theuerkauf et al., 2019) and other important ecosystem and cultural services (Alleway et al., 2019; Gentry et al., 2020). However, unregulated and impactful mariculture development can negatively impact environments and lead to social and economic conflicts (Naylor et al., 2000; Alleway et al., 2019). The U.S. mariculture sector is likely to grow in the coming decade (e.g., NOAA is currently identifying Aquaculture Opportunities Areas based on scientific information and community input to accelerate nearshore aquaculture; https://www.fisheries.noaa.gov/national/aquaculture/aquaculture-opportunity-areas). Development of coordinating mechanisms and best practices that carefully consider impacts is necessary to guide mariculture activities within MPAs (Lester et al., 2021).

3.3.5 Marine Transportation

Shipping is regulated under the International Maritime Organization (IMO) treaties, thus it is difficult to regulate vessels traversing individual MPAs. However, shipping can have important impacts on biodiversity, such as through ship strikes or noise interference with ecologically-important sounds, such as marine mammal communication and echolocation (e.g., Erbe et al., 2019; de Jong et al., 2020). Some researchers and MPA managers have worked with shipping companies and the IMO to reduce biodiversity impacts. For example, research on important feeding areas for humpback, finback, and North Atlantic right whales in the Stellwagen Bank National Marine Sanctuary resulted in the IMO moving the shipping lane northward, resulting in much lower whale interactions and risk of collision (Office of National Marine Sanctuaries, 2020). NOAA also regulates the speed of large ships in seasonal management areas of importance for right whales, which overlap with portions of the Sanctuary (Office of National Marine Sanctuaries, 2020). Similar efforts are underway in National Marine Sanctuaries and other regions on the west coast (Abramson et al., 2011), for example through the IMO-adopted Area To Be Avoided in the Channel Islands National Marine Sanctuary (Huntington et al., 2019), and the voluntary 2017 Vessel Speed Reduction program (https://channelislands.noaa.gov/management/resource/ship_reports.html). Further, ships in California ports will soon be subject to new Ocean-Going Vessels at Berth requirements for shore-based power, lowering emissions (https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation). These individual actions are making a difference, but more research and a holistic approach are needed to minimize transportation impacts on biodiversity.

3.4 Pressing Scientific Research Needs

Further research in key areas could help enable MPAs achieve their full potential. The following needs provide a useful starting point to guide research priorities.

a. Improve baseline understanding of U.S. marine biodiversity: Ecological monitoring efforts should prioritize building better understanding of biodiversity status, distribution, and trends both inside and outside of MPAs of varying protection levels across the breadth and depth of the U.S. EEZ (Gignoux-Wolfsohn et al., *in review*), and from there build a reliable and transparent process for assessing and enhancing MPA representativeness and connectivity. This work will require more coordinated and comprehensive monitoring and evaluation (e.g., through the NOAA MPA Center – see Recommendations below), and could benefit from new technologies (e.g., eDNA, remote sensing, and computer vision techniques; Duffy et al., 2013).

b. Establish links between conservation design, management, equity, and outcomes: Many ecological outcomes of fully and highly protected MPAs are well documented. More research is needed across the full spectrum of MPA levels of protection to better understand and to improve the equity of the diverse range of social, economic, cultural, and ecological outcomes (Grorud-Colvert et al., 2021) and in OECMs, especially in the face of climate change. This may be achieved through MPA management and review processes that explicitly include human dimensions monitoring and research.

c. Improve coordination with other sectors: U.S. ocean spaces are becoming increasingly crowded with diverse human uses, and comprehensive research is needed to ensure that MPAs and their goals complement and are not compromised by uses by other sectors such as renewable energy, tourism, mariculture, and fisheries (see Section Making the Most of U.S. MPAs: Key Focal Areas above). For the fisheries sector in particular, future natural and social science research should focus on incorporating fisheries management in MPA design and MPAs into fisheries management, in particular addressing the distribution of costs and benefits of MPAs to fishers (Weigel et al., 2014). Research could identify contexts where lower levels of protection for biodiversity might better balance conservation and fisheries goals, assuming sustainable extraction practices. Coordinated data gathering and sharing can inform and streamline both MPA and fisheries management efforts. MPA monitoring data can inform fisheries stock assessments. Data used for stock assessments, particularly life history information, can inform design, monitoring, and evaluation of MPAs (Hall-Arber et al., 2021). This will be particularly important for fishery-based OECMs, which must also demonstrate conservation benefits (Gurney et al., 2021).

d. Advance scientific understanding of the role of MPAs for building climate resilience: Long-term monitoring data (both ecological and environmental) provide opportunities to understand how MPAs can specifically impart climate resilience, including by identifying areas of refuge, resilience, and vulnerability within existing MPA networks and designing new MPAs with climate resilience, mitigation, and adaptation in mind (e.g., see Hofmann et al., 2021 and recommendations therein). For example, Oregon's fully protected marine reserves are serving as sentinel sites for monitoring ecosystem-level impacts of climate change (Chan et al., 2019). Further research is needed on resilience in the face of environmental stress encountered by populations inside versus outside MPAs and how MPAs may intersect with dynamic management tools such as temporary closures and mobile MPAs (see below). Active management interventions (e.g., habitat restoration, assisted migration, and species reintroduction in or around MPAs) that are most effective for mitigating and conferring resistance to and/or recovery from climate disturbance should be identified and implemented (Hofmann et al., 2021). There is a particular need for research outside of coral reef ecosystems (Wilson et al., 2020b).

3.5 Innovations in Science, Technology, and Governance

Significant recent effort focuses on understanding how technology can improve MPA outcomes, such as use of satellite data and analytics for MPA monitoring and enforcement (Witkin et al., 2016; Elahi et al., 2018; Bradley et al., 2019; White et al., 2020; Cavanaugh et al., 2021), eDNA for biodiversity monitoring and enforcement (Gold et al., 2021; Willette et al., 2021), Autonomous Underwater Vehicles for biodiversity assessments (Ferrari et al., 2018), and improved seafloor mapping techniques (Wölfl et al., 2019). These technological innovations are advancing MPA research and management at an unprecedented pace.

New governance structures can complement advances in science to confront emerging challenges with climate change and as human uses and priorities shift. MPAs are potential tools for meeting the goals of the Paris Climate Agreement. Many states have already framed their Nationally Determined Contributions with oceans in mind, including through fisheries management, marine ecosystem preservation, and coastal protection. In particular, protecting "blue carbon" ecosystems can contribute significantly to national level mitigation (Taillardat et al., 2018) since these coastal ecosystems sequester and store disproportionate quantities of organic carbon (Lovelock and Duarte, 2019).

One emerging innovation in science and governance is dynamic conservation areas. Marine species' ranges are already shifting with climate change, and species may occur outside of the MPA boundaries designed to protect them. For some species, adaptive MPAs plus the flexible boundaries of mobile MPAs could follow species through space and time and provide effective protection, with less area off limits to human uses (Dunn et al., 2016; Hazen et al., 2018; Maxwell et al., 2020). While no mobile MPAs exist yet, dynamic ocean management (Maxwell et al., 2015) is increasingly applied across a variety of sectors, including fishing and shipping. Mobile MPAs focus on protection across sectors, and could describe daily or weekly boundaries using habitat modeling techniques (Hazen et al., 2017) and acoustic or aerial surveys (Van Parijs et al., 2009; Wiley et al., 2013), particularly for the protection of iconic species (Maxwell et al., 2020).

Transnational and high seas MPAs present another opportunity for innovation (Boerder et al., 2019) and connectivity with existing U.S. MPAs, and highlight additional priority areas. Marine species do not adhere to national boundaries; their distributions and migrations can span ocean basins and multiple countries' jurisdictions while encountering a variety of threats, including concentrated fishing pressure outside of MPAs and in the high seas (White et al., 2017; Harrison et al., 2018; Boerder et al., 2019; Roberson et al., 2021). High seas conservation planning is currently underway with negotiations for a new legally binding instrument under UNCLOS for the biodiversity conservation in Areas Beyond National Jurisdiction, opening the door to MPAs in the high seas (Druel and Gjerde, 2014; Visalli et al., 2020). The world's largest MPA, the Ross Sea in Antarctica, was designated in 2016 by consensus of 25 States, is highly protected and is the first large-scale high seas MPA, providing a model for future high seas MPAs in ecologically important areas (Sykora-Bodie and Morrison, 2019; Brooks et al., 2021). Another area of high ecological value is the Sargasso Sea, including waters along the U.S. east coast (Laffoley et al., 2011). The Hamilton Declaration established by Bermuda and the U.S. (and now signed by ten additional adjacent countries) has formalized collaborative international efforts to conserve the Sargasso Sea, though the region is not yet an MPA (Freestone and Morrison, 2019).

Similarly, transnational cooperation highlights both existing U.S. MPAs and additional priority areas. The Gulf of Mexico encompasses national waters of the U.S., Mexico and Cuba and contains a large number of relatively small MPAs primed for network coordination (Nash and McLaughlin, 2014). The highly productive California Current along the west coast of U.S., Canada, and Mexico spans both well protected and largely unprotected swaths (Di Lorenzo, 2003; Klinger et al., 2017; Aburto-Oropeza et al., 2018). The underrepresented Arctic also has high potential for transnational MPA cooperation (Lalonde, 2010), particularly as sea ice loss opens the region to increasing exploitation.

Transnational cooperation has long been practiced in the Great Lakes. The Great Lakes Fishery Commission, an agency established in 1954 by the U.S. and Canada, facilitates cooperative fishery management among state, provincial, Tribal, and federal agencies and recognizes the potential benefits of freshwater PAs (Hedges et al., 2010). While there is no current comprehensive, collaborative protection plan in place, the Great Lakes Water Quality Agreement (Governments of the United States and Canada, 2012) and related planning and governance structures provide a framework for such a coordinated approach (Parker et al., 2017).

4 CONCLUSIONS AND RECOMMENDATIONS BASED ON SCIENTIFIC EVIDENCE

To make the most of U.S. MPAs, coordinated action is needed, both to establish the types of MPAs necessary for achieving the U.S.'s stated goals ("Conserving and Restoring America the Beautiful 2021", 2021) and to ensure that established MPAs are effective, climate resilient, equitable, compliment other sectors, and support research and innovations in technology and governance. Below we outline specific recommendations that have emerged from our analysis of existing U.S. MPAs:

1. **Establish more, and more effective, MPAs**. These must have protection levels aligned with site-specific goals to conserve biodiversity and benefits for people, including climate mitigation and adaptation. This goal includes establishing more fully and highly protected areas for greatest conservation outcomes, re-evaluating existing MPAs that are poorly protected, and making sure all MPAs are actively managed to optimize positive results. Achieving this objective may involve altering protections for MPAs that already exist, such as enhancing the level of protection of some National Marine Sanctuaries or National Estuarine Research Reserves or zones therein (e.g., by restricting extractive and destructive uses in these areas), as well as establishing new MPAs in areas that are lacking area-based protection but where biodiversity conservation is particularly important. This prioritization may include areas important for ecological, cultural, social, or climate reasons, and areas where other protections already exist (e.g., through fisheries management tools such as Essential Fish Habitat) but are not permanent or comprehensive of all impactful human activities.

2. **Establish new highly and fully protected, networked MPAs with better representation of U.S. marine biodiversity, regions, and habitats.** This ensures critical species, habitats, and areas of cultural importance have broad-scale and sufficient protection. An analysis of gaps in existing MPAs should be coupled with an understanding of their level of protection to identify additional protection needed to render current MPAs as effective, connected, functioning networks. Understanding of existing biodiversity coverage in MPAs in the U.S. should guide and prioritize expansion of current protection (Gignoux-Wolfsohn et al. *in review*). Fully and highly protected MPAs are overwhelmingly concentrated in the Central Pacific. These large MPAs have immense value and should be celebrated. However, the disproportionate share of MPA stewardship by Pacific Islanders in the U.S. and associated territories should be recognized and rectified by increasing the share of highly and fully protected MPAs in diverse ecosystems elsewhere in the U.S. This action is imperative, not only to achieve effective protection for biodiversity but to bring the benefits of MPAs within reach of diverse communities.
3. **Improve attention and commitment to equity in new and existing MPAs.** This includes explicit attention to an inclusive process, guaranteed access, and shared benefits. This requires shared leadership and engagement with Tribes and diverse stakeholders, and support for community-led conservation efforts particularly in vulnerable communities, such as through providing government-subsidized resources. Expand processes for prioritizing and expediting MPAs nominated and supported by Indigenous and other historically excluded communities, including developing best-practice guidelines for Indigenous-created and managed (or co-managed) MPAs. These communities/stakeholders should be positioned to advise on the America the Beautiful initiative to equitably achieve effective protection for biodiversity and climate resilience as well as access to ocean spaces and resources, including through a level of protection that aligns with stakeholder and rights holder goals. Improved environmental education and engagement within communities can play a key role in MPA effectiveness.
4. **Track and report progress towards not only a single coverage target, but also U.S. MPAs' ability to deliver desired outcomes based on level of protection.** The intention to create an American Conservation and Stewardship Atlas for tracking progress on the goals in the "Conserving and Restoring America the Beautiful" report (2021) sets the path for an interactive map of protected and conserved areas in the U.S. MPA outcomes depend on the types of activities that are allowed and their impact. Using existing frameworks such as The MPA Guide (Grorud-Colvert et al., 2021) helps identify those activities and clarify the level of protection, linking levels to the different types of conservation outcomes expected from different types of MPAs. This approach is similarly useful for tracking the outcomes provided by other non-MPA conserved areas, such as OECMs, as the U.S. works to achieve the national 30x30 (at least 30% by 2030) target.
5. **Ensure MPAs are durable so they will continue to work in the future.** Research and actions are needed to understand and support the role of MPAs in conferring climate resilience, and to guide the establishment and management of climate-ready MPAs (e.g., see recommendations in Hofmann et al., 2021). Governance structures and long-term capacity, including funding support for adequate staffing, monitoring, and adaptive management, should be established and strengthened to ensure MPAs' sustainability as bipartisan tools for conserving biodiversity.
6. **Build on existing State MPA initiatives and encourage and coordinate the development of MPA actions at the State level.** Opportunities exist for the states to lead in implementing new highly and fully protected MPAs as well as altering regulations in existing state managed MPAs. In fact, these actions will be required to achieve the federal goals of "Conserving and Restoring America the Beautiful 2021". State initiatives might include executive and legislative actions, outreach and education, and coordination with the federal government, local governments, Tribes, fishing groups, conservation groups and other states. Several states have introduced and/or passed resolutions relating to 30x30 planning (Nevada, Michigan, New York, South Carolina), and others have implemented plans through executive action (California) or other state government initiatives (Hawaii, Maine).
7. **Reinstate and empower the MPA Federal Advisory Committee (MPA FAC).** This committee can provide expertise to help advise, review, and assess the U.S.'s successful implementation of effective and equitable MPAs. From 2003–2019, the MPA FAC advised NOAA and the Department of the Interior on strengthening U.S. MPAs. It was composed of members representing Tribal and state governments, conservation, scientific researchers, commercial and recreational fisheries, and offshore energy, among others. However, the MPA FAC was terminated in 2019. If reinstated, this committee could play an important role advising agencies across the Federal Government during key upcoming decisions for achieving a ≥30% target and the priorities outlined in the America the Beautiful Report, providing a coordinating body representing diverse stakeholders and rights holder groups.
8. **Strengthen the NOAA MPA Center with long-term funding to support U.S. MPA design, stewardship, and effectiveness.** Many of the priorities for improving U.S. MPAs rely on a centralized source for updated data on U.S. MPA protection and outcomes, and for working cross-sector to align MPA programs not only with each other but with other ocean sectors in a comprehensive marine spatial planning framework. The National MPA Center within NOAA's Office of National Marine Sanctuaries is a partnership between NOAA and the Department of the Interior, tasked with improving U.S. MPAs, connecting MPA programs, and communicating and building public

support around MPAs. These efforts are capacity-limited, particularly if the expectation is to scale up reporting, research, communication, and other needs to effectively realize the goals of the "Conserving and Restoring America the Beautiful" Report (2021) and a U.S. 30x30 target. Improved resources such as long-term funding would ensure that clear, consistent, and useful information is available to inform these efforts.

9. **Revisit and update the U.S. National Ocean Policy (NOP) and Ocean Policy Committee for an integrated, whole-government approach to ocean planning and management.** The NOP was created in 2010 to enable a more cohesive, ecosystem-based, and scientifically informed approach to ocean management and policymaking, based on reports and recommendations from the Pew Oceans Commission (2003) and the U.S. Commission on Ocean Policy (2004), and their merger into the Joint Ocean Commission Initiative. The NOP represented an important framework and mechanism for connecting national and regional ocean management processes and enabling smart ocean planning and efficient communication. However, before action plans created under the NOP were implemented, it was repealed in 2018. The need for a national framework for ocean planning and management remains. Updating a National Ocean Policy is a critical starting point.

The work presented here highlights opportunities to strengthen and expand upon existing MPA protections to better safeguard biodiversity and its benefits, as well as key recommendations for achieving this vision. Although the context presented here is specific to the U.S., the themes highlight a global challenge, but one in which the U.S. is well-equipped to play an important leadership role by finding and scaling effective and equitable solutions. Rather than focusing on a single numerical target, we encourage scientists and policymakers to more holistically focus on developing an effective, representative, and equitable system of protection that will help the U.S. meet its stated goals to stem the biodiversity and climate crises.

AUTHOR CONTRIBUTIONS

JS-S and KG-C conceived the study, with early feedback from all authors. JS-S, EP, JMac, and RM led the data collection and analysis. RM made the maps and completed the spatial analysis. JS-S led the writing of the manuscript with the assistance of all authors. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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