ORIGINAL ARTICLE

Area-based management of blue water fisheries: Current knowledge and research needs

Ray Hilborn[1] | Vera N. Agostini[2] | Milani Chaloupka[3] | Serge M. Garcia[4] |
Leah R. Gerber[5] | Eric Gilman[6] | Quentin Hanich[7] | Amber Himes-Cornell[2] |
Alistair J. Hobday[8] | David Itano[9] | Michel J. Kaiser[10] | Hilario Murua[11] |
Daniel Ovando[1] | Graham M. Pilling[12] | Jake C. Rice[13] | Rishi Sharma[2] |
Kurt M. Schaefer[14] | Craig J. Severance[15] | Nathan G. Taylor[16] | Mark Fitchett[17]

[1]School of Aquatic and Fishery Sciences and Center for Sustaining Seafood, University of Washington, Seattle, Washington, USA

[2]Fisheries and Aquaculture Division, Food and Agriculture Division of the United Nations, Rome, Italy

[3]Ecological Modelling Services Pty Ltd and Marine Spatial Ecology Lab, University of Queensland, Brisbane, Queensland, Australia

[4]IUCN-CEM Fisheries Expert Group, Gland, Switzerland

[5]Center for Biodiversity Outcomes, Arizona State University, Tempe, Arizona, USA

[6]Pelagic Ecosystems Research Group, The Safina Center, Honolulu, Hawaii, USA

[7]Australian National Centre for Ocean Resources and Security (ANCORS), University of Wollongong, Wollongong, New South Wales, Australia

[8]CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia

[9]Honolulu, Hawaii, USA

[10]The Lyell Center, Heriot-Watt University, Edinburgh, UK

[11]International Seafood Sustainability Foundation (ISSF), Washington, District of Columbia, USA

[12]Oceanic Fisheries Programme, Pacific Community (SPC), Noumea Cedex, New Caledonia

[13]Department of Fisheries and Oceans, Ottawa, Ontario, Canada

[14]Inter-American Tropical Tuna Commission, La Jolla, California, USA

[15]Anthropology Department at University of Hawaii Hilo, Hilo, Hawaii, USA

[16]International Commission for the Conservation of Atlantic Tunas, Madrid, Spain

[17]Western Pacific Fishery Management Council, Honolulu, Hawaii, USA

Correspondence
Ray Hilborn, School of Aquatic and Fishery Sciences and Center for Sustaining Seafood, University of Washington, Box 355020, Seattle, WA 98195, USA.
Email: hilbornr@gmail.com

Abstract

The pelagic fisheries beyond the continental shelves are currently managed with a range of tools largely based on regulating effort or target catch. These tools comprise both static and dynamic area-based approaches to include gear limitations, closed areas and bycatch limits. There are increasing calls for additional area-based interventions, particularly expansion of marine protected areas, with many now advocating closing 30% of the oceans to fishing. In this paper, we review the objectives, methods and successes of area-based management of blue water fisheries across objectives related to food production and environmental, social and economic impacts. We also consider the methods used to evaluate the performance of area-based regulations and

provide a summary of the relative quality of evidence from alternative evaluation approaches. We found that few area-based approaches have been rigorously evaluated, and that it is often difficult to obtain requisite observational data to define a counterfactual to infer any causal effect for such evaluation. Management agencies have been relatively successful at maintaining important commercial species at or near their target abundance, but success at meeting ecological or social goals is less clear. The high mobility of both target and bycatch species generally reduces the effectiveness of area-based management, and shifting distributions due to climate change suggest that adaptive rather than static approaches will be preferred. We prioritize research and management actions that would make area-based management more effective.

KEYWORDS

area-based management, closed areas, dynamic ocean management, high-seas fisheries, marine protected areas, tuna fisheries

1 | INTRODUCTION

As the global demand for fisheries resources beyond continental shelves (particularly tuna and tuna-like species, Scombridae) continues to increase (Coulter et al., 2020), so does the need to effectively manage the blue water ecosystems that produce these valued resources. Blue water ecosystems span from the edge of continental shelves, often within states' exclusive economic zones (EEZs), to high-seas areas beyond national jurisdiction (ABNJ).

Global tuna and billfish fisheries operating in blue water ecosystems represented 10% of global landings worth $11.7 billion ex-vessel value in 2018 (McKinney et al., 2020). Unlike nearshore ecosystems where fisheries resources are usually more static in distribution, blue water ecosystems pose a broader and different array of challenges and scientific needs. Fishery resources in blue water ecosystems are often highly mobile and traverse jurisdictional boundaries, dynamically concentrate relative to ecosystem features such as fronts, and have time-varying spatial vulnerabilities to multiple fisheries (Block et al., 2011; Pons et al., 2017). Resource distributions are likely to shift due to climate variability (Lehodey et al., 2013; Senina et al., 2018), including El Nino-Southern Oscillation events (Lehodey et al., 1997). As international competition and fishing capacities among distant water fishing fleets increase around the world, the role of area-based management tools (ABMTs), such as time-area closures, selective area-based fishery/gear closures, marine protected areas (MPAs) and adaptive/real-time management, in blue water ecosystems has become a leading topic in fisheries management (Curnick et al., 2020; Game et al., 2009; Gilman et al., 2019; Hobday et al., 2010; Sala et al., 2021).

Fishing mortality rates of highly migratory tunas, which are the principal species among blue water fisheries, are now primarily at or near the level that would produce maximum sustainable yield (Pons et al., 2017), with some exceptions that are above and below that level. Efficacy of the current largest no-take areas to ensure sustainable management of targeted tuna species may be complicated by the species' migratory behaviour, resulting in increased catch

outside closed areas if fishing effort is simply redistributed (Davies et al., 2014). The improved status of some highly migratory tunas has resulted from prescriptive management actions carried out by tuna Regional Fishery Management Organizations (RFMOs) as well as key national groups (Pons et al., 2017). Some of these management measures were ABMTs, and thus it seems necessary to evaluate a broad range of ABMTs to achieve a variety of management goals for blue water ecosystems.

While static no-take areas are the best known form of ABMTs, management tools that do not close areas to all extractive anthropogenic activity have also been shown to be effective at achieving both ecological and socio-economic management goals. Common examples are areas closed to bottom contact gear (e.g. bottom trawl nets) to protect benthic biota, areas restricting specific fishing gear for bycatch concerns and area-based catch or effort regulation. Discernible conservation benefits are more likely to arise from no-take areas when placement encompasses overexploitation threats, restrictions are enforceable, and the area is large enough to reduce susceptibility of capture by being commensurate with movement range (Kuempel et al., 2019). These conditions are often not met and there is considerable concern that many no-take areas do not provide the expected ecological or socio-economic benefits (Edgar et al., 2014).

Area-based management tools may be designed to promote sustainable exploitation, biodiversity protection (including bycatch mitigation), socio-economic benefits—or all three. Applicable ABMTs

may also be dynamic, including time-area closures, which may prohibit fishing activity for certain or all gear types in a predefined area over a definitive time period or season. Time-area tools may also be implemented to allocate catch or effort over spatially defined areas to particular gears. This approach requires close to real-time monitoring of catch and effort, which is not uncommon in tuna- and tuna-like fisheries management through the implementation of observers, vessel monitoring systems (VMS), electronic monitoring (EM) and electronic reporting (ER). Dynamic spatial fisheries management can increase the efficacy of fisheries management as opposed to the aforementioned static time-area approaches by precisely overlaying ABMTs over dynamic spatial delineations that correspond to oceanographic or ecosystem features (Hobday et al., 2010). Other

TABLE 1 Requirements or associated costs (monitoring and scientific needs) versus capabilities of static and dynamic ABMTs

ABMT class	Requirements/costs	Benefits/capabilities
Static	*Monitoring*: Seasonal/annual, catch/effort limits or gear restrictions by general area; VMS; basic in-season accountability measures; basic surveillance and enforcement *Scientific needs*: Species displacement information; species habitation by area, time, or ontogeny	• Ease of enforcement and compliance monitoring • Can be commensurate with political boundaries or have simple spatial delineations • Protection of biomass in statically defined habitat • Reduce stakeholder conflicts by area via limited access (fleet, gear, etc.)
Dynamic	*Monitoring*: Continuous, near real-time reporting of catch and effort through ER; VMS or near real-time surveillance; quick response time for in-season accountability measures; continuous and precise enforcement capability; sufficient fishery observer coverages or EM *Scientific needs*: Robust scientific knowledge base of how target, non-target, and avoided species' vulnerabilities correspond to oceanographic or ecosystem features; predictive capabilities of species demographics and/or life history dynamics; access/processing capabilities of near real-time ecosystem products; temporal economic information	• Minimizing catch of non-target or avoided species without compromising yield of target species in fisheries • "Move-on rules" can be implemented for vessels at-risk of reaching catch limits by area or at-risk of encountering species of concern • Potential reduced costs or increased profits to fishing vessels while achieving management objectives • Reduce stakeholder conflicts by reduced direct competition • Dynamic rules are agreed by stakeholders ahead of time promoting acceptance and collaborations • Have been implemented in some fisheries by fishing cooperatives themselves

Abbreviations: ABMT, area-based management tool; EM, electronic monitoring; ER, electronic reporting; VMS, vessel monitoring systems.

real-time adaptive management measures may include shifting fishing effort away from an area, triggered by interactions of non-target species or by real-time accountability measures. Requirements and benefits of static and dynamic ABMTs discussed above are summarized in Table 1.

The use of ABMTs in blue water ecosystems is often implemented and governed by RFMOs, which are bodies established by international agreements, or treaties, that are signed by countries that share a practical and/or real (financial) interest in managing and conserving fish stocks in a defined region. A number of RFMOs have been established to oversee the management of tuna and tuna-like resources, including the International Commission for the Conservation of Atlantic Tunas (ICCAT), the Indian Ocean Tuna Commission (IOTC), the Inter-American Tropical Tuna Commission (IATTC), the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) and the Western and Central Pacific Fisheries Commission (WCPFC). Each "tuna RFMO" has a unique political structure with differing mandates and management priorities. Table 2 summarizes ABMT implementation by tuna RFMOs or key groups within RFMO memberships.

Area-based management tools are currently an important topic in international fisheries policy negotiations being conducted at the United Nations (UN). Global agreements to address managing blue water ecosystems were strengthened with the ratification of the UN Convention for the Law of the Sea (UNCLOS) in 1982 and its Straddling Fish Stocks Agreement in 1995 (FAO, 1995a), which was followed that year by the UN Food and Agriculture Organization (FAO) Code of Conduct for Responsible Fisheries. In 2015, the UN General Assembly agreed to develop an international legally binding Implementation Agreement under UNCLOS and adopted Agenda 2030, which are global-scale policies through 17 Sustainable Development Goals (SDGs) and 169 targets to be achieved by 2030. Negotiations are underway to develop a new legally binding Implementation Agreement for the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction (herein referred to as the BBNJ Treaty). There are four main themes of the new agreement, including ABMTs. Among other topics, criteria for selecting areas to implement ABMTs on the high seas and the process for the evaluation of these are subjects of debate in the current BBNJ Treaty negotiation process.

Given that some portions of blue water ecosystems also fall under national jurisdiction, the conservation targets agreed to under the Convention of Biological Diversity (CBD) are also important to consider. The use of ABMTs has already been included in global targets, where Aichi Biodiversity Target 11 (herein referred to as Target 11) aimed to improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity through area-based conservation and included aspirations as outlined by SDG 14 for at least 10% of marine ecosystems under some form of area-based management (https://www.cbd.int/aichi-targets/target/11; https://sdgs.un.org/goals/goal14). Target 11 included reference to the use of a suite of ABMTs, including traditional protected areas and "other effective area-based conservation measures (OECMs)."

This study synthesizes and analyses current knowledge on the effectiveness of using ABMTs in blue water ecosystems for the management of highly migratory target species, including tuna and tuna-like species. We then identify a pathway to fill knowledge gaps so that ABMTs can be most effective. We focus on six families of ABMTs: space-time closures of fishing, adaptive real-time closures (dynamic ocean management), permanent closures, input/output controls, spatial implementation of gear or fishing method modification, and access and tenure rights. Recognizing that there are multiple objectives for ABMTs, we discuss the trade-offs between these objectives, which ought to be considered prior to any ABMT implementation. For each ABMT type, we review objectives and performance metrics, alternative approaches to spatial management, available data to investigate the efficacy and impact of these measures on performance, the approaches and limitations for the evaluation of impacts, and the research needed to be better able to predict and evaluate the consequences of alternative approaches.

2 | OBJECTIVES OF BLUE WATER FISHERIES MANAGEMENT

2.1 | What are the objectives?

There are a wide range of objectives relevant to ABMTs ranging from fisheries management to increasing biodiversity to maintaining/restoring ecosystem function to socio-economic. National fisheries management agencies and RFMOs have regulated fisheries with a primary goal of optimizing harvests and minimizing harmful impacts. For blue water fisheries, the text from the UN Fish Stocks Agreement (FAO, 1995a) summarizes this and states that "The objective of this Agreement is to ensure the long-term conservation and sustainable use of straddling fish stocks and highly migratory fish stocks." This overarching objective is also included into the European Union's (EU) Common Fisheries Policy (CFP; European Union, 2013) whose objectives are "to ensure that fishing and aquaculture are environmentally sustainable in the long-term to achieve economic, social and employment benefits and contribute to food supplies." Similarly, in the United States, the objective of the overriding fisheries legislation is to provide for the conservation and management of the fisheries, (United States, 1996) and, more specifically, "to provide for the preparation and implementation, ... of fishery management plans, which will achieve ... the optimum yield from each fishery and for other purposes." Similar objectives are also embraced by most RFMOs, for example, "WCPFC's main objective is to ensure, through effective management, the long-term conservation and sustainable use of highly migratory fish stocks in the Western and central Pacific Ocean" (WCPFC, 2015). In all these national and international documents, the objectives of sustainable yield, and associated economic and social benefits are central but conservation is an essential element and is needed in order to provide social and economic benefits.

National and international fisheries management agencies also include in their mandates, objectives associated with protection of

TABLE 2 Examples of ABMT implementation by tuna RFMOs

RFMO	ABMT implementation	Source/evaluation
WCPFC	High-seas "pocket" closure for purse seine and longline fisheries in an area surrounded by EEZs of nations belonging to Parties of the Nauru Agreement (PNA) and Indonesia, closures in the EEZ of French Polynesia and high-seas waters adjacent to the nation.	Sibert et al. (2012), WCPFC (2020)
	In-season high-seas fishing aggregating device (FAD) closure for purse seine fisheries	WCPFC (2020)
	Vessel Day Scheme to balance fishing effort in high seas and access within EEZs of island nations at agreed rates; transshipment ban on high seas	PNA (2016), WCPFC (2020)
IATTC	Spatial-temporal closure for purse seines within the area known as "corralito" (the area between of 96°W and 110°W and between 4°N and 3°S)	IATTC (2020)
	Temporal closure of 72 days for all purse seiners to be selected from in one of the two periods proposed	
ICCAT	Seasonal closures in the Mediterranean Sea to reduce albacore (*Thunnus alalunga*, Scombridae) and swordfish juvenile mortality	ICCAT (2020), IATTC (2020)
	Seasonal (3 month) FAD closures in all convention area	
	Closures in the Gulf of Mexico to reduce bluefin tuna (*Thunnus thynnus*, Scombridae) spawning stock and juvenile mortality	
IOTC	Closure of a sizeable portion of the EEZ and high-seas waters off the Somali coast in the Western Indian Ocean for longlining and to purse seine fishing for 1 month a year	IOTC (2010), Martin et al. (2011), Davies et al. (2017)
	Past UK closures of the EEZ of the Chagos Archipelago in a MPA, Maldives has closed the outer extent of its EEZ to longlining	

Abbreviations: ABMT, area-based management tool; EEZ, exclusive economic zone; IATTC, Inter-American Tropical Tuna Commission; ICCAT, International Commission for the Conservation of Atlantic Tunas; IOTC, Indian Ocean Tuna Commission; MPA, marine protected area; RFMO, Regional Fishery Management Organization; WCPFC, Western and Central Pacific Fisheries Commission.

biodiversity beyond the conservation of target species required to maintain long-term yield. In particular, blue water fisheries management includes many issues that are directly related to conservation, such as habitat protection and avoiding bycatch of non-target species such as birds, mammals and sharks. Within national waters countries often have explicit legal frameworks for legal protection of biodiversity, and international RFMOs have specific objectives regarding reduction of bycatch and reducing ecosystem impact.

The FAO Code of Conduct for Responsible Fisheries (FAO, 1995b) also "sets out principles and international standards of behaviour for responsible practices with the aim of ensuring the effective conservation, management and development of living aquatic resources, with due respect for the ecosystem and biodiversity." In that respect, the FAO Common Oceans Project—Global Sustainable Fisheries Management and Biodiversity Conservation in the Areas Beyond National Jurisdiction Program (FAO, 2020), has the objective to ensure the sustainability of the fish resources and biodiversity conservation in the ABNJ applying the Ecosystem Approach to Fishery Management. More specifically, the deep-sea component of the project include as a specific objective "Reducing adverse impacts on VMEs (vulnerable marine ecosystems) and enhanced conservation and management components of EBSAs (ecological or biologically significant areas)" (FAO, 2020).

Most national governments also have legislation mandating the protection of biodiversity, which is applicable to their blue water fisheries. For instance, the EU CFP mandates the elimination of discards with the application of a landing obligation in order to minimize negative impacts on the marine ecosystem and the EU 2030 Biodiversity Strategy (European Commission, 2011) aims to "legally protect a minimum of 30% of the EU's sea area and integrate ecological corridors, as part of a true Trans-European Nature Network" as well as eliminate, or reduce to a level that allows full recovery, the bycatch of endangered species. In the U.S., fisheries management agencies are legally required to protect marine mammals and endangered species.

Marine conservation focused non-governmental organizations (NGOs) have brought environmental objectives to the forefront through their advocacy of MPAs and establishment of them, independently of fisheries management institutions. Their objectives are primarily associated with biodiversity conservation, and thus provide a much broader range of objectives than fisheries management. Some of these NGOs have been influential in setting benchmarks or aspirations for "strong" or "full" area-based protections, such as "30 × 30" initiatives, which aim to allocate 30% of marine and terrestrial areas for the purpose of conservation (O'Leary et al., 2019). Increasingly, countries are committing to having 30% of their EEZ as protected areas by 2030, including the United States, which set a goal of conserving at least 30% of its lands and waters by 2030 (Executive Office of the President, 2021).

Following the CBD Strategic Plan for Biological Diversity (2011–2020), in Target 11, OECMs have been defined by the CBD (Convention on Biological Diversity, 2018). These ABMTs are expected to be broadly mainstreamed in fisheries (Convention on Biological Diversity, 2018; Garcia et al., 2019, 2020). OECMs are

defined as "a geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity, with associated ecosystem functions and services and where applicable, cultural, spiritual, socio–economic, and other locally relevant values" (Convention on Biological Diversity, 2018). Employment of OECMs usually has the dual objective of optimizing fisheries sustainability while reducing collateral impact on the broader biodiversity. OECMs may also serve as tools towards achieving SDGs and targets prescribed under the overarching Agenda 2030 that may formulate conservation objectives applicable to blue water ecosystems.

Gilman et al. (2020) reviewed theoretical and empirical evidence of five specific management objectives that are met with MPAs placed in areas where pelagic fisheries are prosecuted:

1. Reduce or eliminate bycatch fishing mortality of pelagic species of conservation concern;
2. Reduce or eliminate fishing mortality at habitats that are important for critical life history stages of pelagic species;
3. Reduce the fishing mortality of target stocks to contribute to sustaining desired production levels (i.e. stay near target thresholds) and avoiding conditions where protracted or irreparable harm to the stock occurs (i.e. stay above limit thresholds);
4. Reduce fishing mortality of prey species of pelagic target stocks and species of conservation concern in order to stay near targets and above limits; and
5. Reduce trait-based selective fishing mortality and fisheries-induced evolution.

We can summarize the yield and ecosystem conservation objectives to be achieved through ABM of blue water ecosystems by clustering into the following categories:

1. *Maintain and enhance sustainable food production*. This is a traditional goal of fisheries management and supplies society with food, jobs, and profit. Many of the area-based management approaches have been developed to achieve this through regulating catch and effort, protecting spawning and juvenile fish and protecting critical habitat. Related to this is provision of food security, which we discuss under categories six and eight below.
2. *Protect non-target species*. Pelagic fisheries often have bycatch of these species, most frequently marine mammals, turtles, marine birds and non-target fishes such as sharks.
3. *Protect critical habitats*. This has mainly been represented in pelagic fisheries via protection of static habitats such as seamounts, but dynamic habitats defined by physical oceanographic processes also become relevant when we look at the spatial distribution of pelagic species and their prey across life history stages in blue water systems. Feeding and spawning habitats for pelagic species that primarily occupy waters above the bathypelagic zone may be driven spatially and vertically by physical processes conducive to enrichment, concentration and retention mechanisms (Bakun, 1998), rather than defined by site-fidelity, natal homing or association with static habitats. Some ABMTs are focused on restricting or zoning activities such as seabed mining, oil exploration and extraction, and wind energy facilities.
4. *Maintain ecosystem structure and function*. Ecosystem structure and functions are at the core of ecological theory and their maintenance has long been considered a priority for conservation, sustainable use and ecosystem restoration, in the World Conservation Strategy (IUCN, 1980), the CBD Ecosystem Approach (Secretariat of the Convention on Biological Diversity, 2004) and the Ecosystem Approach to Fisheries (Garcia & Cochrane, 2005). Pelagic fisheries predominantly affect high trophic level species such as tunas, billfish and sharks and the overall trophic structure of pelagic ecosystems is largely unchanged by fishing except at trophic level four and above (Essington, 2007). There is evidence that fishing these higher trophic levels increases the abundance of their prey at trophic level three (Polovina et al., 2009), which may impact ecosystem dynamics at even lower trophic levels by impeding trophic cascades that would occur under unfished conditions.
5. *Maintain or increase ecosystem resilience to climate change*. Climate change impacts blue water systems by shifting the distribution and productivity of marine resources with consequences for ecosystem structure and function. It is generally thought that the resilience of marine ecosystems is increased by the elimination of stressors such as fishing and pollution, but there are alternative arguments. Côté and Darling (2010) argued that disturbed systems may have lost the species most sensitive to climate change, and thus are more resilient. Overall, there is a relatively sparse literature on climate change resilience in blue water systems.
6. *Provide employment*. Pelagic fisheries provide direct employment, both in coastal state small-scale fisheries and in the industrial fisheries, as well as indirectly through the supply chain (e.g. canneries in the coastal states; Weng et al., 2015). The UN Fish Stocks Agreement (Munro, 2000) specifically provides for protection of the interests of developing states and assuring that they do not carry a disproportionate burden of conservation. This objective is relevant to items six, seven and eight listed here.
7. *Facilitate economic benefits*. Economic benefits from the fishery accrue to individual crew and plant workers, to workers in the supply/distribution chain, to workers in retail/sales, to the vessel owners, to plant owners and to the coastal states who charge for access fees.
8. *Support communities and culture*. Blue water fisheries can provide or impact food security, cultural and social support to local communities through food provision, employment and existence values (Vierros et al., 2020). Some area-based measures specifically protect local artisanal fisheries to safeguard food security (Hobday et al., 2015; Weng et al., 2015); typically banning industrial fisheries while maintaining access for artisanal fleets. In contrast, others ABMTs have been criticized for damaging local communities (Bennett et al., 2017).

TABLE 3 Fisheries management objectives, example metrics and how they can be evaluated

Objective	Performance metric	Evaluation methods
Maintain and enhance sustainable food production	Harvest of fish, stock abundance and fishing mortality in relation to reference points	Fisheries stock assessments, harvest control rules and management strategy evaluation
Protect non-target species	Bycatch trends of endangered, threatened or protected species and the status of these species Status of non-target fish species.	Bycatch trends from observers or electronic monitoring Data poor stock assessment models Fishery indicators (e.g. catch per unit effort [CPUE]) Population studies of the species
Protect critical habitats	Status relative to undisturbed Proportion of habitats protected from fishing	Ecological surveys Ecosystem modelling
Maintain ecosystem structure and function	Trophic structure Survey data Size structure Age structure	Ecosystem modelling
Maintain or increase ecosystem resilience to climate change	Change in habitat distribution of species, displacement of species, ecosystem structure changes Surveys of abundance of species	Habitat modelling Ecosystem modelling
Provide employment (both local and global)	Number of direct permanent jobs Number of indirect permanent jobs Number of temporary direct and indirect jobs Gross Domestic Product (GDP) related to fisheries	Economic surveys
Facilitate economic benefits	Profit Price of access fees (% of profit due to access fees) and revenue	CPUE Landing records Fisheries logbooks Economic surveys Country economic information Economic modelling Infrastructure development
Support communities and culture	Food security for local communities Livelihoods associated with access to the marine area that are maintained % of local residents involved in fishing or processing activities Presence of alternative livelihoods	Household surveys Key informant interviews Social vulnerability variables (e.g. poverty, social stability, labour force structure, gentrification)

2.2 | What are the available performance metrics?

Synthesizing the available explicit objectives and metrics of spatial management measures for pelagic ecosystems, we propose the following list of possible management objectives and performance metrics that could be used to evaluate success (Table 3).

3 | ABMTS FOR BLUE WATER FISHERIES AND EVIDENCE OF EFFICACY

This section describes static and dynamic features of pelagic marine ecosystems that structure conditions that determine the suitability of habitats for pelagic apex predators and affect the distributions and aggregations of these species. The section then discusses how these different features are suitable for the application of different ABMTs. Table 4 defines categories of ABMTs that are relevant to blue water systems. These categories could be further split into higher resolution groupings according to whether they apply spatial or temporal management and whether they are static or dynamic.

Different pelagic apex predators, and in some cases different size classes and sexes within species, occur at different static and dynamic pelagic habitats (Bailey & Thompson, 2010; Gilman et al., 2016; Hyrenbach, Keiper, et al., 2006; Hyrenbach, Veit, et al., 2006; Hyrenbach et al., 2000; Muhling et al., 2011; Polovina et al., 2004; Vandeperre, Aires-da-Silva, Fontes, et al., 2014; Vandeperre, Aires-da-Silva, Santos, et al., 2014). Their geospatial and vertical distributions are determined, in part, by their physiology, prey availability and environmental variables of hydrostatic pressure, temperature and dissolved oxygen (Bernal et al., 2010; Beverly et al., 2009; Brodziak & Walsh, 2013; Lehodey et al., 2011, 2015; Muhling et al., 2011; Musyl et al., 2003, 2011; Schaefer et al., 2009). Static features, such as shallow seamounts and atolls, as well as dynamic features, including gyres and fronts, structure these conditions and determine the distributions of pelagic predators, including when and where they aggregate. These features structure

TABLE 4 Categories of ABMTs and illustrative examples from pelagic fisheries

ABMT	Examples
Seasonal time/area closure	• Seasonal spatial closures to tuna purse seining adopted by tuna RFMOs were designed to reduce bigeye tuna (*Thunnus obesus*, Scombridae) fishing mortality (IATTC, 2017; Torres-Irineo et al., 2011)
Permanent closure	• Of the 35 "very large" global MPAs, 25 include no-take zones, or the entire area is no take, where commercial fishing is prohibited (Atlas of Marine Protection, 2019) • The "Mackerel Box" off Southwestern England protects juvenile mackerel (*Scomber scombrus*, Scombridae) by banning directed fishing for mackerel by purse seiner and pelagic trawl vessels, and effectively banning other types of pelagic fishing, other than handline, through a 15% mackerel bycatch limit (Sweeting & Polunin, 2005) • The Great Barrier Reef Marine Park prohibits pelagic longline fishing throughout the park (GBRMPA, 2004; Gilman et al., 2019; Government of Australia, 1983) • Some Pacific island states prohibit pelagic longline fishing within specified distances of shallow submerged features (e.g., Government of the Federates States of Micronesia, 2014; MIMRA, 2018)
Real-time dynamic spatial management	• Voluntary fishing industry fleet communication programmes identify real-time bycatch hotspots that can be avoided by vessels participating in the program (Gilman et al., 2006) • In Hawaii's tuna longline fishery, when a seasonal limit of catching and causing mortality or serious injury to two false killer whales (*Pseudorca crassidens*, Delphinidae) is reached, this triggers the closure of a portion of the fishing grounds near the main Hawaiian Islands (NMFS, 2012) • In Hawaii's tuna longline fishery, when seabirds are present, vessels are required to strategically discard offal during setting or hauling to distract seabirds from areas where there is a risk of capture on baited hooks (NMFS, 2005) • Australian Southern bluefin tuna fishery where only SBT quota holders are allowed to operate in the SBT area, which have been predicted/estimated for each season/year using real-time SBT habitat distribution models (Hobday & Hartmann, 2006)
Spatially explicit restriction on gear designs and fishing methods	• Tuna RFMO seabird bycatch mitigation methods are required when fishing in specified higher latitude areas: WCPFC (2018), IOTC (2012), ICCAT (2011) and IATTC (2011)
Spatially explicit input and output controls	• Various arrangement provide sub-regional access to tuna purse seine and pelagic longline vessels to fish an allocated number of fishing days in the EEZs of Parties to the Nauru Agreement in the Western and central Pacific Ocean (Aqorau, 2009; PNA, 2016) • The Hawaii tuna longline fishery is subject to a seasonal limit of catching and causing mortality or serious injury to two false killer whales in a portion of their fishing grounds (NMFS, 2012)
Other area-based measures	• Areas zoned for defence, prohibitions on fishing to prevent damage of data buoys, privately protected areas, and areas protected by indigenous peoples and local communities (Gannon et al., 2017; WCPFC, 2009) may restrict pelagic fishing and achieve positive in-situ biodiversity and other outcomes (Convention on Biological Diversity, 2018)

Abbreviations: ABMT, area-based management tool; EEZ, exclusive economic zone; MPA, marine protected area; RFMO, Regional Fisheries Management Organization; SBT, Southern Bluefin Tuna.

the distribution of nutrients, primary producers as well as the distributions and aggregations of prey species of pelagic apex predators (Hyrenbach, Keiper, et al., 2006; Hyrenbach, Veit, et al., 2006; Hyrenbach et al., 2000; Kavanaugh et al., 2016; Selles et al., 2014; Vandeperre, Aires-da-Silva, Santos, et al., 2014). Pelagic features and habitats differ in their suitability for spatial management due to differences in their spatial and temporal predictability and their size.

Some bathymetric structures with fixed positions concentrate and enhance the residency time of pelagic predators and their prey. This includes shallow submerged features like seamounts and reefs, areas with steep seabed gradients such as shelf breaks and near islands as well as coastal features that create small-scale eddies and fronts (i.e. island mass effect; Doty & Oguri, 1956; Gilman et al., 2012; Hyrenbach et al., 2000; Kavanaugh et al., 2016; Morato et al., 2008, 2010; Worm et al., 2003). Depending on their physical characteristics and location, these static features can alter local currents and possibly isotherm distributions, create oceanographic perturbations, such as through advection and dispersion, and increase

upwelling and mixing (Pitcher et al., 2007; White et al., 2007). The influence of these features in concentrating productivity and aggregating pelagic predators can be coupled with hydrodynamic conditions, such as current direction and strength. Thus, while the feature is fixed in location, its concentration of productivity can be temporally variable. Static but temporally dynamic ABMTs, which are often species-specific, can be designed to account for these latter features.

Spatially dynamic hydrographic features affect the distribution of pelagic predators. Some are broad scale, such as currents and frontal systems that are temporally persistent, occurring over years to decades and over entire ocean basins. Others are mesoscale, such as upwelling plumes, eddies and frontal systems, persisting over tens to hundreds of days (or seasons) and occurring over tens to hundreds of kilometres. Other hydrographic features are fine-scale, including some fronts and eddies, which are ephemeral (i.e. very short-lived), lasting only for days, and occurring over 100s of metres to kilometres (Hazen, Suryan, et al., 2013; Hyrenbach et al., 2000; Kavanaugh et al., 2016; McGlade & Metuzals, 2000;

Polovina et al., 2001). Aggregations of pelagic species at ephemeral, fine-scale, dynamic, pelagic habitats are difficult to map and manage in real-time for the exclusion of fishing effort and no ABMTs for these types of mobile features are known. Individual and networks of natural and artificial floating objects, including fish aggregating devices are another type of pelagic habitat that some pelagic species associate near or aggregate at, possibly because the floating objects provide shelter, foraging opportunities and "meeting points" (Castro et al., 2002; Fréon & Dagorn, 2000; Hall & Roman, 2013). As with static habitats, dynamic but persistent habitats are relatively predictable, enabling dynamic pelagic restriction boundaries to be defined more easily, but they may need to be extremely large to achieve some ecological objectives (Della Penna et al., 2017; Gilman et al., 2019; Hyrenbach et al., 2000).

Individual and networks of static and mobile ABMTs could protect relatively small sites that are important for critical life history stages of pelagic species, if the sites are temporally and spatially predictable (Gilman et al., 2019). This includes pelagic areas used for spawning (Bakun, 2013), mating and calving/pupping (Vandeperre, Aires-da-Silva, Santos, et al., 2014), foraging hotspots (Hyrenbach, Keiper, et al., 2006; Oppel et al., 2018; Peckham et al., 2007), juvenile/nursery and nesting areas (Sweeting & Polunin, 2005), and migratory corridors (Block et al., 2011).

Dynamic spatial management measures could be designed to protect hotspots with high ratios of bycatch-to-target catch (Dolder et al., 2018; Hazen et al., 2018; Hobday et al., 2013; Lewison et al., 2015; Maxwell et al., 2015). Such management aims to change in space and time in response to the shifting nature of the ocean and its users, based on the integration of new biological, oceanographic, social and/or economic data in near real-time (Maxwell et al., 2015). The approach can address time scales from daily to seasonal to decadal and is responsive to short-term and long-term changes in ocean climate (Hazen, Jorgensen, et al., 2013). Using dynamic management also provides an opportunity to manage the conflicting goals of sustainable fisheries and protected species management with the aim of providing win-win solutions in marine spatial management (Hazen et al., 2018). One example is a near real-time dynamic spatial management of Southern bluefin tuna (*Thunnus maccoyii*, Scombridae) bycatch by the Eastern Australia pelagic longline fishery through the use of a habitat model (Hobday & Hartmann, 2006; Hobday et al., 2010). A retrospective analysis of the efficacy of this dynamic fisheries management system found that it has been successfully mitigating bycatch of Southern bluefin tuna (Hobday & Hartmann, 2006; Hobday et al., 2009, 2010). A simpler form of dynamic management is "move-on rules" where vessels are required to move a certain distance, typically if bycatch exceeds a certain threshold. Implementation of "move-on rules" require only reliable monitoring of catches and vessel locations.

Theoretical approaches have also been developed for dynamic temporal and spatial management of pelagic fisheries based on the variable position of pelagic habitats and variable ecosystem processes. One application of this approach provides maps, which identify near real-time locations of predicted thermal habitat of loggerhead (*Caretta caretta*, Cheloniidae) and leatherback sea turtles (*Dermochelys coriacea*, Dermochelyidae), to Hawaii's shallow-set swordfish (*Xiphias gladius*, Xiphiidae) longline vessels; information that could, theoretically, enable fishers to voluntarily avoid these marine turtle bycatch hotspots (Howell et al., 2008, 2015). A comparable tool for the California drift gillnet swordfish fishery identifies near real-time areas with high ratios of bycatch-to-target-catch for leatherback sea turtles, California sea lions (*Zalophus californianus*, Otariidae) and blue sharks (*Prionace glauca*, Carcharhinidae; Hazen et al., 2018).

Expanding the scope of objectives and records of the review by Gilman et al. (2019), Table 5 summarizes, for each ABMT category defined in Table 4, the theoretical and empirical evidence of the ABMT meeting each of the management objectives defined in Table 3. ABMT-objective combinations lacking empirical evidence are excluded from Table 5. Table 5 shows that there is a paucity of both theoretical and empirical evidence of impacts of pelagic ABMTs. Much of the evidence is equivocal and relatively little stands up against the rigorous statistical analysis that is discussed in the next section. Part of the explanation for this lack of evidence is the relatively recent establishment of many ABMTs in blue water systems and the difficulty of collecting relevant data: within blue water systems, there is little if any potential for the use of replication, control and randomization, the three pillars of experimental science.

There is great potential to advance both theoretical and empirical analysis of blue water ABMTs. Data on fishing fleets' responses to ABMTs and other management interventions are available from logbook and observer/EM programmes, and from satellite-based VMSs and Automatic Identification Systems. In addition, abundance estimates for many major tuna and billfish stocks, and some shark stocks, are made by RFMOs, which could be used to support robust assessments of the responses to ABMTs using approaches described in the following section.

4 | INFERRING CAUSAL IMPACTS OF ABMTS

4.1.1 | Quasi-experimental approaches with observational data

In the previous section, we saw that while some ABMTs are promoted as an effective spatial management intervention for protecting biodiversity and supporting sustainable pelagic fisheries (O'Leary et al., 2019; White et al., 2017), the evidence is equivocal (Gilman et al., 2019). Part of this uncertainty is due to fundamental issues in inferring the causal impact attributable to the implementation of an ABMT and so there have been few retrospective evaluations of the impact of ABMTs.

This section discusses the underlying difficulty in evaluating the impacts of ABMTs, and the conceptual foundation of any statistical analysis of their effects. The great bulk of ABMT evaluation in the scientific literature has focused on coastal no-take areas. Almost all of these evaluations have serious conceptual flaws, which we

TABLE 5 Evidence of blue water ABMTs meeting management objectives. Records from studies providing empirical evidence are followed by those from studies providing evidence from theoretical simulations

ABMT	Objective	Evidence
Seasonal time/ area closures	Maintain and enhance sustainable food production	• During a 1-month annual closure to tuna purse seine fishing in an area in the Eastern Atlantic Ocean with a high density of juvenile bigeye tunas, purse seine vessels fished the line. Following establishment of the closed area, in a control area, catch levels of juvenile tunas increased (Torres-Irineo et al., 2011), possibly due to spillover, but possibly due to other variables • In the Ecuador EEZ adjacent to the Galapagos Islands, and on the open ocean in "El Corralito," (an area west of the Galapagos that is seasonally closed to tuna purse seine vessels) significantly smaller-sized yellowfin tunas (*Thunnus albacares*, Scombridae) were caught by tuna purse seiners throughout the Eastern Pacific Ocean. After the reserve was established, yellowfin and skipjack tuna (*Katsuwonus pelamis*, Scombridae) catch rates with standardized effort significantly increased in the Ecuadorian EEZ adjacent to the reserve and in El Corralito, perhaps because local abundance increased (IATTC, 2017) • The reductions in catch of principal target species caused by a 1-month closure to tuna purse seine and pelagic longline fisheries in the Indian Ocean were expected to be negligible due to effort redistribution (Murua et al., 2011)
	Protect non-target species	• The US Pacific Leatherback Conservation Area, which seasonally prohibits driftnet fishing, reduced leatherback turtle and marine mammal bycatch levels (Martin et al., 2015; Moore et al., 2009; NMFS, 2001) • Seasonal closures that varied spatially and temporally, with different areas closed during different months of the year, were simulated to be more effective at reducing seabird, turtle and shark bycatch and at maintaining target species catch relative to seasonal and permanent static closures for South Africa's pelagic longline fishery (Grantham et al., 2008)
	Protect critical habitats	• Theoretically, seasonal fishery closures could protect bluefin tuna spawning grounds during spawning periods (Collette et al., 2011; Muhling et al., 2011) • For vulnerable bycatch species with temporally and spatially predictable at-sea aggregations, seasonal, mobile and static spatial management measures theoretically could be used to reduce fishing effort in areas and during periods with high local abundance of the vulnerable species. For example, some seabird species have predictable pelagic foraging hotspots (Hyrenbach, Keiper, et al., 2006; Oppel et al., 2018), some pelagic sharks have predictable pupping, nursery and mating aggregations (Litvinov, 2006; Vandeperre, Aires-da-Silva, Fontes, et al., 2014), and juvenile loggerhead sea turtles have predictable aggregating sites (Kobayashi et al., 2011; Peckham et al., 2007)
	Support communities and culture	• An economic and social impact study found that a court-ordered closure of the Hawaii swordfish longline fishery to protect sea turtles had a differential and severely negative impact on income, family stability and community cohesion for Vietnamese-American fishers and their families (Allen & Gough, 2006)
Permanent closure	Maintain and enhance sustainable food production	• Tuna purse seine nominal catch rates, fishing effort and catch levels in an area adjacent to and down current of the Galapagos Marine Reserve were higher after enforcement of a ban on industrial tuna fishing began compared to a period before enforcement, and purse seiners "fished-the-line." Based on these observations, the authors hypothesized that the Reserve caused an increase in the local abundance of tropical tunas, with spillover across the Reserve boundary, but recognized that other variables may have been responsible (Boerder et al., 2017) • During two longline fishery closures in the Pacific Ocean Mexican EEZ, local and regional abundance of striped marlin (*Kajikaia audax*, Istiophoridae) increased possibly in response to the closure or possibly a consequence of other extrinsic environmental variables (Jensen et al., 2010) • No evidence was found of improvements in standardized CPUE indices of target species in the area surrounding the British Indian Ocean Territory MPA. The average size of caught yellowfin and bigeye tunas increased both inside the MPA and across the equatorial Indian Ocean, suggesting that any MPA effect was in combination with other regional drivers (Curnick et al., 2020) • A hypothetical large MPA covering the Chagos Archipelago in the Indian Ocean was simulated to have a minor effect on absolute skipjack tuna biomass (Dueri & Maury, 2013). An MPA covering a large portion of the Western Indian Ocean where most skipjack catches occur, however, was simulated to cause a large reduction in fishing mortality and stabilization of skipjack spawning biomass (Dueri & Maury, 2013) • High-seas closures to tuna purse seine fishing in the Western and central Pacific Ocean, with effort displaced outside the closed areas, were simulated to cause a small (0.1%) increase in absolute (stock-wide) adult bigeye biomass (Sibert et al., 2012). High-seas closures to both purse seine and pelagic longline fisheries, with the longline closures located within part of a bigeye spawning area, with effort displacement, were predicted to cause a 1% increase in absolute adult bigeye biomass (Sibert et al., 2012)

TABLE 5 (Continued)

ABMT	Objective	Evidence
	Protect non-target species	• A counterfactual assessment found that the U.S. Pacific Remote Islands Marine National Monument caused a reduction in blue shark catch rates by Hawaii's pelagic longline fishery (Gilman et al., 2020). The Monument was also found to have protected bycatch hotspots for some at-risk species (oceanic whitetip (*Caracharhinus longimanus*, Carcharhinidae), silky (*Carcharhinus falciformis*, Carcarhinidae) and blue sharks, and olive Ridley sea turtle (*Lepidochelys olivacea*, Cheloniidae)) but cold-spots for others (albatrosses (*Phoebastria* spp., Diomedeidae), shortfin mako shark (*Isurus oxyrinchus*, Lamnidae) and striped marlin; Gilman et al., 2020) • Small MPAs adjacent to African penguin (*Spheniscus demersus*, Spheniscidae) colonies that removed purse seine fishing for pelagic forage fishes may have improved penguin foraging efficiency, chick survival and condition, and increased population growth at one of the colonies. The local abundance of prey resources may have increased within the MPAs as a result of the cessation of fishing mortality, while at a "control" penguin colony with no MPA there may have been increased fishing mortality due to displaced fishing effort from the MPAs (Pichegru et al., 2010, 2012; Sherley et al., 2015, 2018) • During a court-ordered area closure of Hawaii's swordfish longline fishery, established to protect marine turtles, there was an increase in swordfish catch by non-U.S. longline fleets that had higher turtle bycatch rates than the U.S. swordfish fishery (Chan & Pan, 2016) • A hypothetical closed area for the U.S. Northwest Atlantic swordfish longline fishery located in a hotspot of pelagic species richness and density was simulated to reduce catch levels of some pelagic sharks and teleosts without reducing swordfish catch levels (Baum et al., 2003) • One existing and two hypothetical Mexican MPAs that ban gillnet fishing were simulated to cause an increase or at least slow the rate of decline of vaquita porpoise (*Phoceana sinus*, Phocoenidae) abundance (Gerrodette & Rojas-Bracho, 2011)
	Protect critical habitats	• The "Mackerel Box" off Southwestern England reduced juvenile mackerel mortality (Sweeting & Polunin, 2005) • A seasonal closure to purse seine fishing in an area of the Eastern Pacific Ocean may have reduced juvenile bigeye tuna catch rates (IATTC, 2017) • Theoretically, restricting pelagic fishing at shallow submerged features could reduce catch rates of juveniles of target tuna species (Adam et al., 2003; Fonteneau, 1991; Gilman et al., 2020; Itano & Holland, 2000; Sibert et al., 2000) • 85% of the foraging habitat around breeding colonies of three species of tropical boobies (*Sula* spp., Sulidae) were within two U.S. closed areas (Young et al., 2015). There may have been indirect benefits to the booby populations from removing tuna longline fishing in the MPAs. This is because tunas and possibly other surface predators drive seabirds' prey species to the surface, making them available to foraging seabirds (Ballance et al., 1997; Spear et al., 2007). If banning tuna fishing in the MPAs caused an increase in the local abundance of tunas, this may have increased the availability of prey to boobies • Tuna spawning habitat occurs within MPAs of the tropics. This was recently observed and incorrectly interpreted by Hernández et al. (2019) that the presence of tuna larvae in an MPA means that the MPA is protecting habitat critical for tuna spawning. For these and other similar highly fecund broadcast spawners, protecting a small proportion of spawning habitat, or a small proportion of the distribution of spawning stock biomass, likely has minimal effect on recruitment or absolute biomass, where only at extremely low population sizes would egg production likely be a limiting factor for recruitment (Essington, 2010; Gilman et al., 2019; Myers et al., 1999)
	Maintain ecosystem structure and function	• Mean trophic level of the catch of Hawaii's tuna longline fishery was significantly higher around the U.S. Pacific Remote Islands Marine National Monument than at open ocean fishing grounds (i.e. a larger proportion of the pelagic community that is susceptible to capture in pelagic longline gear in the Monument is made up of top predators than in open ocean areas), suggesting that that the Monument contains a relatively undisturbed pelagic community structure (Gilman et al., 2020)
	Provide economic benefits	• MPAs within the Great Barrier Reef, some of which include pelagic habitat, led to a 35%–36% reduction in catch and ex-vessel value (Fletcher et al., 2015), however, this conclusion is complicated by additional measures to reduce fishing capacity (Hughes et al., 2016) • Lynham et al. (2020) estimated that MPAs did not cause a decrease in CPUE, distance travelled or total catch by Hawaii's pelagic longline fleet. Conversely, Chan (2020) found that the subset of Hawaii's tuna longline fleet that had previously fished in the MPAs experienced decreased CPUE and catch and increased distance travelled following establishment of the MPAs

TABLE 5 (Continued)

ABMT	Objective	Evidence
	Support communities and culture	• Ban et al. (2015) found mixed results in estimated trends in wellbeing of user groups dependent on fisheries affected by 12 MPAs, using proxies such as monetary income and access to education • A global meta-analysis found that low levels of stakeholder participation in large MPAs were correlated with declines in wellbeing, while high levels of participation were correlated with improvements in wellbeing (Ban et al., 2017) • Interview-based assessments of the designation process of the Marianas Trench Marine National Monument as a large-scale MPA found that the stakeholders perceived that the process did not follow MPA guidelines and generated much opposition. Advocates and opponents criticized the process for the speed, top-down nature, and involvement of external entities leading to lasting resentment (Richmond et al., 2019) • An interview-based study compared two proposed and three established large-scale MPAs, finding that social outcomes arise even in remote MPAs, they arise at all stages, can produce outcomes at a higher level of social organization, and can produce social change processes that lead to social impacts. These social effects of the MPAs may be intended or unintended, positive or negative (Gruby et al., 2017)
Real-time, dynamic spatial management	Maintain and enhance sustainable food production	• A dynamic management system for the eastern Australian yellowfin and bigeye tuna and billfish longline fishery to avoid bycatch of southern bluefin tuna resulted in increased catch of target yellowfin tuna (Hobday et al., 2009, 2010; Hobday & Hartmann, 2006) • A simulation of the US Northeast Multispecies Fishery compared the ability of closures across a range of spatial and temporal scales to meet a common management goal of reducing regulatory discards of undersized/juveniles of Atlantic cod (*Gadus morhua*, Gadidae), the target species, while minimizing affected marketable catch and the time–area closed. The coarser scale, static ABMTs (annual time–area closures and monthly full-fishery closures) affected up to four to five times the target catch and required 100–200 times the time–area of the dynamic measures (grid-based closures and move-on rules; Dunn et al., 2016)
	Protect non-target species	• A dynamic management system for the eastern Australian tuna and billfish longline fishery reduced bycatch of southern bluefin tuna (Hobday et al., 2009, 2010; Hobday & Hartmann, 2006) • A model that identifies near real-time areas with high ratios of bycatch-to-target-catch for leatherback sea turtles, California sea lions and blue sharks for the California drift gillnet swordfish fishery (Hazen et al., 2018) could theoretically be applied as a dynamic spatial management tool to reduce vulnerable bycatch • A model that identifies near real-time locations of predicted thermal habitat of loggerhead and leatherback marine turtles within the fishing grounds of Hawaii's swordfish longline fishery (Howell et al., 2008, 2015) could theoretically be applied as a dynamic spatial management tool to reduce marine turtle bycatch
Spatially explicit restrictions on gear designs and fishing methods	Maintain and enhance sustainable food production	• WCPFC seasonal closures on fishing on fish aggregating devices by tuna purse seine vessels have been estimated to have reduced bigeye tuna catch levels by over 20% (Pilling et al., 2019; SPC-OFP, 2010; Williams & Reid, 2019) • Spatially explicit requirements for the employment of seabird bycatch mitigation methods resulted in a 67% significant reduction in the seabird catch rate with standardized effort in Hawaii's tuna longline fishery (Gilman et al., 2008). A regional assessment of the performance of the WCPFC spatially explicit seabird bycatch measure was inconclusive due to data quality constraints (Peatman et al., 2019)
Spatially explicit input and output controls	Provide economic benefits	• The Vessel Day Scheme of the Parties to the Nauru Agreement (PNA) establishes spatially explicit input controls, and also includes closures of key high-seas areas to tuna purse seine vessels that are licenced to fish within EEZs of PNA member countries. The high-seas closures caused increased revenue gained from the sale of fishing opportunities to the PNA member countries (Miller et al., 2014)

Abbreviations: ABMT, area-based management tool; CPUE, catch per unit effort; EEZ, exclusive economic zone; MPA, marine protected area; RFMO, Regional Fisheries Management Organization; WCPFC, Western and Central Pacific Fisheries Commission.

identify and then we outline how proper causal inference could be conducted.

The gold standard for conducting a retrospective impact evaluation is a randomised controlled trial or RCT (Backmann, 2017; Pynegar et al., 2021). RCTs are used to estimate the counterfactual or potential outcome (Rubin, 2005) by comparing the expected outcome of the sampling units that received the treatment with the expected outcome of those sampling units that did not receive the treatment. Here the causal effect is defined counterfactually using RCTs and is the basis of evidence-informed medicine for instance.

However, most MPAs are a single policy event with no variation in the intensity of application of the intervention—so it's an "all-or-none" binary event. And management interventions are usually imposed rather than randomly assigned (Hayes et al., 2019; Stevenson

et al., 2020). The problem is that it is not possible to assign sampling units at random to different treatments for estimating the causal effect of a binary intervention ("impact" vs. "control"). Therefore, non-randomized studies of an intervention need to account for differences in baseline characteristics between treated and reference/control sampling units when estimating the treatment effect.

The creation of a blue water ABMT is a non-randomized binary policy intervention with few or only one treatment unit (Curnick et al., 2020) and so evaluation depends on observational data and quasi-experimental statistical procedures to define the counterfactual to infer any causal effect (Boesche, 2019). Here we outline several quasi-experimental approaches with observational data that have been applied for conservation policy evaluation. See Butsic et al. (2017), Larsen et al. (2019) and Samartsidis et al. (2019) for details of methodologies and conceptual framework.

The quasi-experimental approaches to inferring causal inference based on observational data are (a) instrumental variables, (b) interrupted time series, (c) regression discontinuity designs, (d) matching methods, (e) difference-in-differences (DiD) and (f) synthetic controls. These are the main approaches used to estimate a causal effect attributable to a conservation policy intervention when randomization is not an option and so are dependent on using observational data.

4.1.2 | Instrumental variables regression approach

This is a common approach used in econometrics for modelling intervention effects (Angrist et al., 1996). Let Y = the response variable and X = the independent variable that Y is a linear or non-linear function of. An instrument is a covariate Z for instance that affects X but not the response variable, Y. Modelling the effect of X on Y given Z helps estimate the latent or unobserved correlation between Y and X (Angrist et al., 1996). It is a procedure to infer causality through indirect inference that is not commonly used in ecology (Butsic et al., 2017). Examples include exploring Florida scrub-jay (*Aphelocoma coerulescens*, Corvidae) life history trade-offs (Kendall, 2015) and unravelling the impact of forest fragmentation on Lyme disease incidence (MacDonald et al., 2019).

4.1.3 | Interrupted time series approach

Here, a single time series of an outcome is modelled using segmented regression to estimate any trend in the sampling period prior to a known intervention date and then again in the post-intervention period (Hudson et al., 2019). Each segment has its own slope and intercept, and then compare the two segmented regression models to derive any causal effect. It is a form of a before-after design (Christie et al., 2019) but with a time series structure. As an illustrative example of an ITS impact evaluation within a MPA context, we use data from a recent study on the 2004 expansion of the Great Barrier Reef Marine Park (Fletcher et al., 2015). Here we fit a segmented regression using generalised least squares with Gaussian likelihood and AR(1) autocorrelation

structure for the residuals to explicitly account for the time series nature of the 19-year data series of commercial fishery catch. The ITS model fit is summarised in Figure 1 with an estimated significant decrease in commercial catch in the GBRMP region at the intervention data (mid-2004) of approximately 750 metric tonnes (95% confidence interval: 163–1,452). Shackell et al. (2021) investigated OECMs and fishery closures as means to operationalize SDGs for Canadian groundfish fisheries through an ITS impact evaluation, using per capita growth rate of 24 common groundfish species as a performance metric. The authors determined that three long-term area-based fishing fleet closures did not enhance per capita population growth rates.

4.1.4 | Regression discontinuity design approach

In a regression discontinuity study design (RDD), the pre-intervention and post-intervention time periods are selected at some cut-off time near to the intervention date (Bor et al., 2014). The cut-off metric could also be a spatial boundary rather than a temporal discontinuity and such geographic discontinuities are often used in political science quasi-experiments (Keele & Titiunik, 2015). Butsic et al. (2017) provide an ecological case for using RDD for modelling the impact of wildfire on plant species richness. A theoretic ecological example is provided in Larsen et al. (2019). The RDD is a form of control-impact design (Christie et al., 2019) but where the sampling units for control and impact are "close" to the geographic boundary. RDD might work for assessing benthic (sessile) impacts for georeferenced sites but is of limited prospect for assessing pelagic systems with highly mobile species.

4.1.5 | Matching method

Statistical matching is an approach used for matching (or near-matching) of treatment and control/reference sites given covariate adjustment to account for confounding baseline information in quasi-experiments with observational data (Stuart, 2010). Propensity score matching is one method and is the probability of treatment or control site assignment conditional on baseline covariates determined using a statistical procedure such as logistic regression or random forests (Austin, 2011). Propensity score methods are not suitable when there are few sampling units assigned to the intervention as there will be insufficient information to estimate the model parameters (Samartsidis et al., 2019). Ahmadia et al. (2015) use propensity scores and covariate matching in their evaluation of an MPA network monitoring program in the Bird's Head Seascape (Indonesia). Butsic et al. (2017) and Hayes et al. (2019) provide discussion of matching methods for environmental impact evaluation.

4.1.6 | Difference-in-differences

The most common way to evaluate the effect of a conservation policy intervention is to use some form of before-after-control-impact

interrupted time series regression model of the effect
of the 2004 no-take area expansion in the Great Barrier Reef region

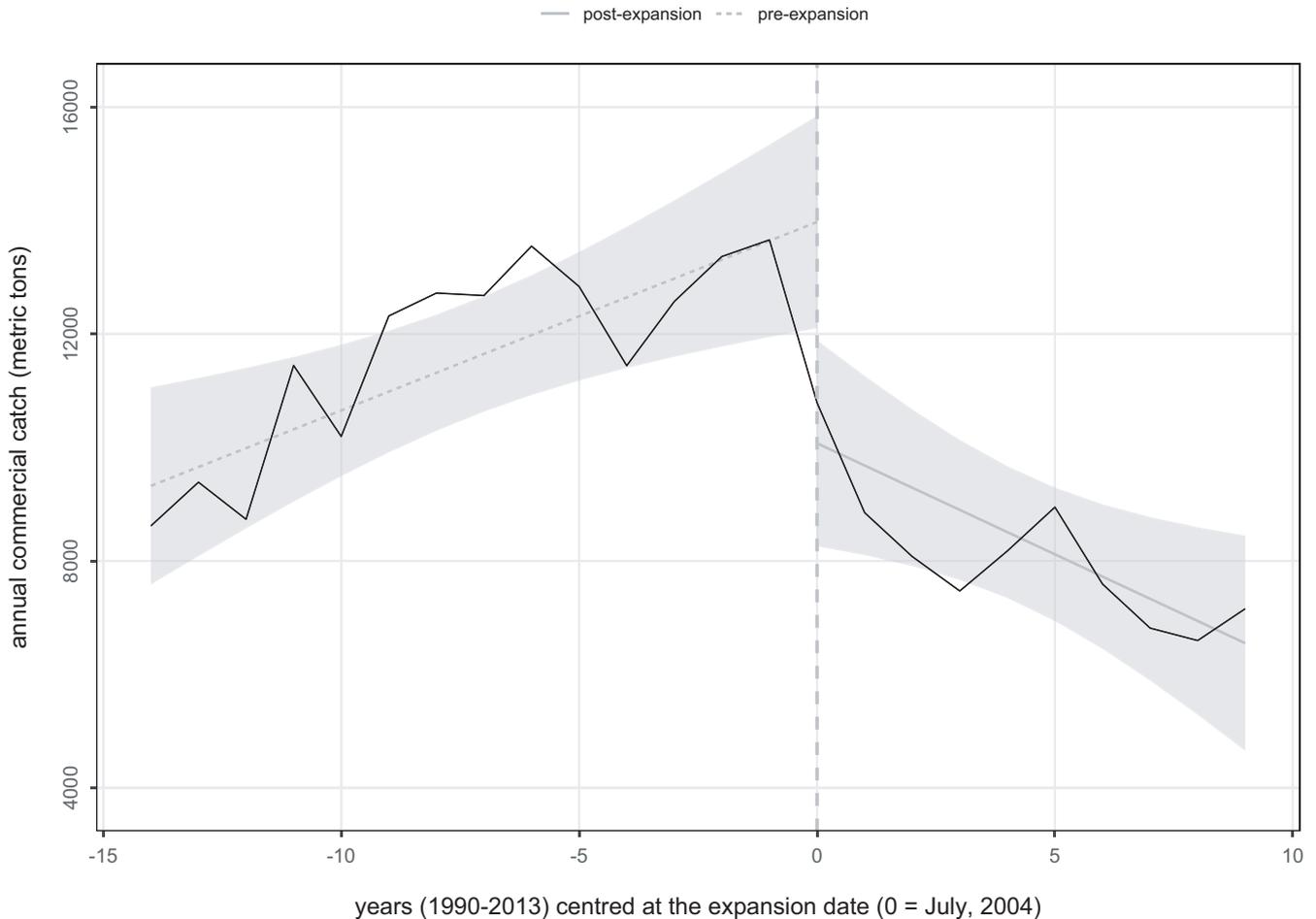—— post-expansion   - - - pre-expansion

FIGURE 1 Interrupted time series model for evaluating the impact of the 2004 Great Barrier Reef Marine Park no-take expansion on the Great Barrier Reef commercial fishery catch rates (Data sourced from Fletcher et al., 2015)

or BACI study design (Chevalier et al., 2019; Christie et al., 2019). In its simplest form, BACI is a before/after sampling at the impact site compared with a simultaneous before/after sampling at a control site (Christie et al., 2019). The causal impact is assessed by the DiD method although often not recognized as such in the ecological BACI literature.

There are many variants of the BACI-type study design for impact evaluation including paired sample BACI design (BACIPS: Stewart-Oaten & Bence, 2001) and the progressive-change BACIPS that accounts for the time series nature of the observational data series (Thiault et al., 2019). A BACI design can be combined with treatment/control matching to strengthen the counterfactual as used for example to evaluate social marketing interventions for biodiversity conservation (Veríssimo et al., 2018). Kerr et al. (2019) identified a number of limitations with BACI-type approaches while Chevalier et al. (2019) propose additional metrics that might be helpful for supporting BACI-based inference given some of those concerns.

As an illustrative example of BACI (BACIPS), we continue with Fletcher et al. (2015) who assessed the impact of a substantial expansion of the GBR no-take closures to commercial fisheries in the GBRMP region. The impact on commercial catch 4 years before and then 4 years after the mid-2004 closure was assessed using BACIPS with the annual commercial catch for two non-GBR regions nearby combined as a composite control or reference series.

They estimated that the annual commercial catch declined by 35% between the 4 year aggregated pre- and post-closure assessment periods. They had times series of commercial catch for the reference and impacts sites for 19 years (10 years pre-closure) and so there was no need to use aggregated pre- and post-closure periods of, for instance, 4 years when all 19 years of the data series could be used in an explicit time series structured BACI. In fact, the way that Fletcher et al. (2015) structured their BACIPS by only using data from just prior to and then immediate post the 2004 intervention is essentially in the spirit of the RDD (Fletcher et al., 2015). Hughes et al. (2016) raised other concerns with that study but most can be accounted for in the re-use of this example in the "Synthetic Control Approach" section below.
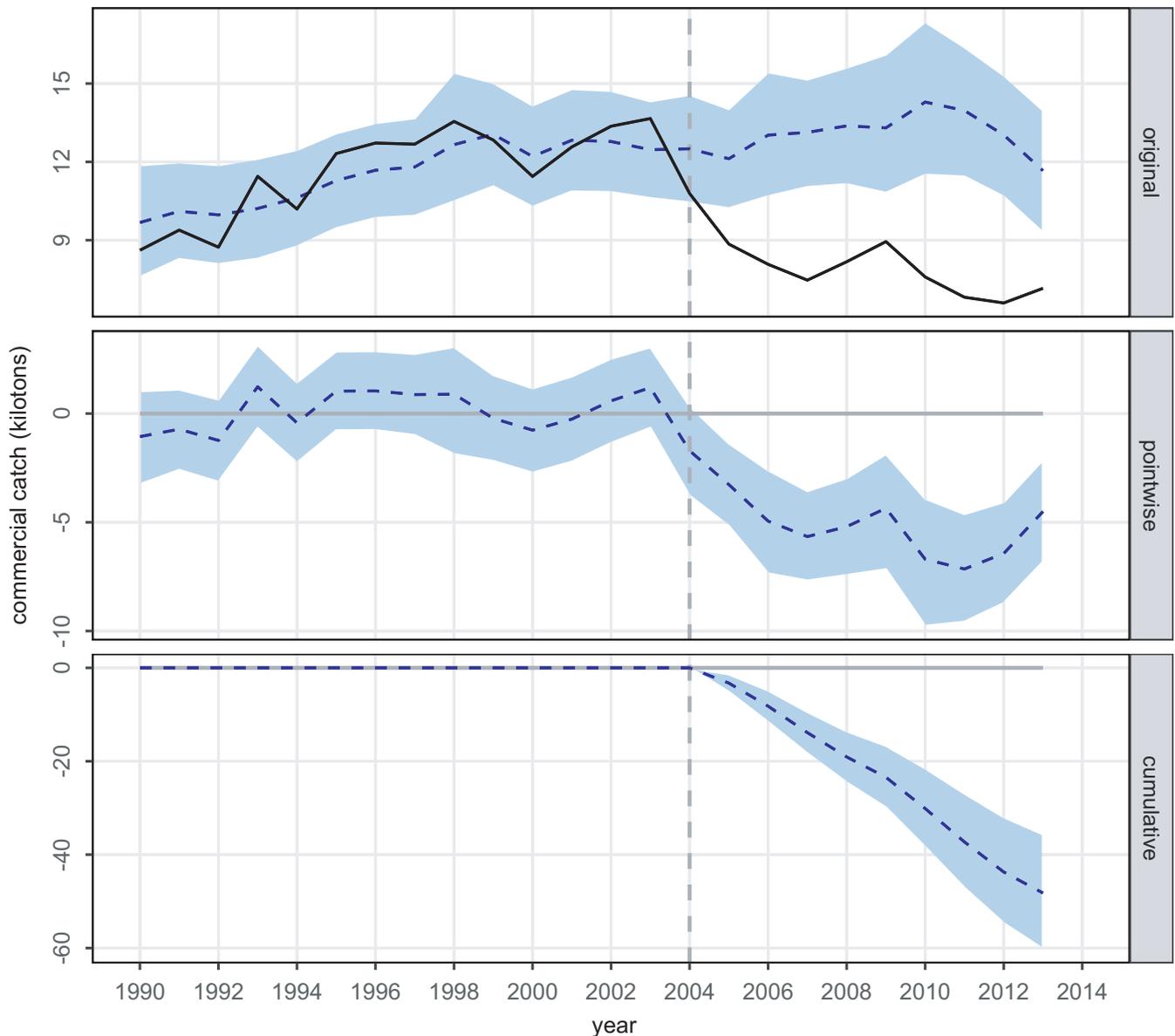
GBR no-take closure counterfactual plot

FIGURE 2 Counterfactual prediction summary plot for Great Barrier Reef (GBR) commercial catch (1990–2013) conditioned on six predictors (two non-GBR catch series as controls [Gulf of Carpentaria, East Queensland coast, Australia]) and four environmental predictors (such as the MEI index either lagged to 2 years or a GAMM smoothed series). MEI, multivariate ENSO index. (*Top panel*): Dashed blue curve and polygon show the counterfactual (and estimated uncertainty around the counterfactual prediction) from 50,000 stochastic realizations of a Bayesian state-space structural time series model fitted to the seven data series prior to the 2004 intervention and then predicted post-intervention. Solid curve is the GBR catch series from 1990 to 2013. (*Middle panel*): Pointwise difference between the two curves (GBR catch, counterfactual prediction in top panel) with 95% credible interval, which shows a significant loss of GBR catch following the intervention—the 95% credible band does not overlap the zero-baseline post 2004. This shows the temporal dynamics of the intervention impact. (*Bottom panel*): shows the significant cumulative negative impact on the commercial catch since closure (Data sourced from Fletcher et al., 2015)

Smith et al. (2017) is an example of the BACIPS form of DiD for evaluating the impact of MPAs on fisheries economic outcomes. Thiault et al. (2019) used the progressive-change BACIPS approach to evaluate the impact of a network of small MPAs on coral reef fish communities on Moorea (French Polynesia). Chan (2020) and Lynham et al. (2020) are recent examples of the progressive-change BACIPS type of DiD for evaluating the impact of MPAs on economic or ecological outcomes.

4.1.7 | Synthetic control approach

Counterfactual prediction-based synthetic control approaches are increasingly used to infer temporal causal impacts in a wide range of policy evaluation contexts including public health (Bruhn et al., 2017), water conservation initiatives (Schmitt et al., 2018) and radioactive spill impacts on seafood markets (Wakamatsu & Miyata, 2016). The synthetic control approach is an extension of the DiD approach.

There are two distinct counterfactual prediction-based modelling procedures using the synthetic control approach for inferring a causal effect: (a) the reduced form approach fit within a frequentist framework (Abadie et al., 2015) and (b) the structural component approach fit within a Bayesian state-space modelling framework (Brodersen et al., 2015). O'Neill et al. (2016) use the reduced form approach combined with matching methods for evaluating health service policy interventions. Schmitt et al. (2018) used the Bayesian structural time series approach combined with matching methods for evaluating water conservation policy interventions.

The Bayesian structural times series approach to inferring causal inference has very few and readily testable assumptions—the key assumption is that there is a set with the effect in place and a set, or ensemble of control time series, that are not affected by the intervention (otherwise an effect might be falsely inferred). Gilman et al. (2019) advocate the Bayesian structural time series-based approach for evaluating the causal effects of blue water MPAs and that approach was used recently in a comprehensive evaluation of the ecological responses to expansions of the large blue water MPAs of the Pacific Remote Islands Marine National Monument (Gilman et al., 2020).

As an illustrative example of the Bayesian structural times series modelling approach, we continue to use the Fletcher et al. (2015) study. The impact on GBRMP commercial fishery catch 13 years before and then 6 years after the mid-2004 closure was assessed using a Bayesian structural time series modelling approach with the annual commercial catch for the two nearby non-GBRMP regions (Gulf of Carpentaria, East Queensland coast) and several environmental predictors that were combined as a composite control or reference series. The counterfactual prediction summary is shown in Figure 2. There was a 41% decline in GBRMP commercial catch following the 2004 no-take closure (95% uncertainty interval: −50% to −30%). The impact was gradual and permanent—at least to 2013. The cumulative catch loss was 48 kilotonnes (95% uncertainty interval: −60 to −36 kilotonnes). The posterior probability of a causal effect attributable to the no-take GBR closure was >99%.

4.2 | A conundrum

Finally, it is important to be aware that causal effects estimated using counterfactuals (including RCTs) are claimed to lack application beyond the specific study and so lack external validity (Deaton & Cartwright, 2018). The epistemological issue here is that inference applies only to the specific ABMT intervention being assessed and not to ABMTs in general. If so, then a meta-analytic synthesis is needed of many such studies to draw broader deductive inference so long as the sample is "representative" of all ABMTs or specific types of ABMTs—this conundrum of lack of external validity applies to all quasi-experimental approaches considered here (Boesche, 2019).

5 | MOVING FORWARD WITH AREA-BASED MANAGEMENT PLANNING AND MANAGEMENT

5.1 | Key research needs

Our review and synthesis highlights a number of key gaps in our knowledge of how various forms of ABMTs can help achieve different objectives in blue water ecosystems. Here we summarize these knowledge gaps.

5.1.1 | The current evidence of blue water ecosystem responses to ABMTs is limited

Blue water fisheries differ from coastal ecosystems in that they are almost totally pelagic, and relatively few species are targeted. Many of the current blue water ABMTs were extremely lightly fished prior to the implementation of ABMT measures (Kuempel et al., 2019), potentially making them politically easier to implement and potentially reducing future risks rather than providing immediate conservation benefits. Blue water ecosystems remain extremely underrepresented in the body of literature assessing ecological responses of fisheries to various forms of ABMTs. More analysis of how blue water ecosystems have been impacted by fishing and by ABMTs is a high priority. Temporal dynamism of blue water ecosystems prohibits the ability to have representative counterfactuals. Many of the ABMTs used in blue water ecosystems to date have lacked a priori objectives with established means to evaluate their performance in achieving objectives.

5.1.2 | The effectiveness of different ABMT approaches for target species management depends on many factors

While there is some limited evidence that area-based catch and effort restriction have been effective at achieving sustainable exploitation rates for target species in some blue water fisheries, it is unclear if other forms of ABMTs, such as spawning ground closures would help improve target species management. It is also unclear what, if any, effects that large, closed areas will have on target species abundance and catch. The relative impacts of different AMBTs will depend greatly on the life history and movement patterns of the species, and better understanding of these is a high priority.

5.1.3 | Discerning which ABMTs will best contribute to reducing bycatch and protecting habitat for critical life history stages is contingent on knowledge of biological characteristics

Blue water ABMTs have relatively high promise to mitigate bycatch of vulnerable species and to protect areas critical for certain life history

TABLE 6 Summary of what we know about the use of ABMTs in blue water ecosystems and the next steps for the global community in using ABMTs to meet management objectives

Fisheries management objective	What we know	Next steps in management
Maintain and enhance sustainable food production	Area-based catch and effort restrictions have largely worked to maintain stocks in productive condition. Static pelagic closed area ABMTs would need to cover extremely large areas to significantly reduce the risk of capture of an individual pelagic fish throughout its lifetime (Botsford et al., 2003; Dueri & Maury, 2013; Gruss et al., 2011; Le Quesne & Codling, 2009) and spatial redistribution of fishing effort may negate perceived benefits (Kaplan et al., 2014; Martin et al., 2011). Theoretical analyses indicate that there will likely be no regional stock-level benefits for stocks that are not overexploited (Le Quesne & Codling, 2009), which is the case for most target pelagic species as well as for prey of pelagic predators (ISSF, 2021; Le Borgne et al., 2011; Olson & Watters, 2003)	• Reduce catch for species that are currently overfished • Improve compliance and monitoring by management agencies, aided by emerging technologies • Eliminate illegal fishing
Protect non-target species (endangered, threatened or protected species)	The major successes have been accomplished by gear and fishing method modification. Where there are fixed breeding sites, seasonal closed areas may be most effective. Concentration around important feeding sites would likely be best managed through dynamic closures around temporary oceanic features	• Implement key technologies shown to reduce bycatch • Analysis of the potential of ABMTs to contribute to bycatch reduction, particularly dynamic management options • Expedite regulatory response time to adaptive management
Protect critical habitats	This is generally not a significant issue with benthos in blue water systems. The benthic communities of concern are typically seamounts. Closure of sensitive bottom habitat to bottom contact gear has been shown to be effective	• More mapping of benthic systems of concern in blue water ecosystems • Closure of sensitive benthic habitats • Better understanding of the presence of critical pelagic habitats (e.g. pelagic spawning or feeding grounds) and if they could use some form of protection
Maintain ecosystem structure and function	Overall trophic structure of pelagic systems is largely intact and the main impact of fishing is on the highest trophic levels. Unless assessed and determined otherwise, there is no evidence that the structure and function of the blue water system is significantly modified by fishing	• No clear ABMT action is thought to benefit maintaining ecosystem structure and function
Increase ecosystem resilience to climate change	Pelagic habitats such as feeding and spawning areas are shifting in space with climate change. It isn't clear how ABMT would contribute to this	• Where various forms of management are appropriate for specific habitats, those need to change adaptively
Provide employment (both local and global)	Mostly results from allocation of tenure and access rights and governance	• Employment issues are very fishery and fleet specific and no general policy guidance can be given
Facilitate economic benefits	Substantial economic benefits result from commercial tuna and tuna-like species fisheries in blue water ecosystems Zone-based management of tuna fisheries (e.g. WCPFC vessel day schemes) are used to generate revenues for coastal states from distant water fishery access fees	• If management agencies have specific objectives regarding where benefits occur, management actions can be taken to direct those benefits • Ensure facilitation of economic benefits do not impede sustainability objectives
Support communities and culture	Fishing communities and cultures in many parts of the world depend on fisheries prosecuted in blue water ecosystems for food security, livelihoods, traditions and cultural activities There is very little information on how management actions impact communities	• Methods to improve community and cultural benefits will be highly dependent on local circumstances and no generic solutions exist

Abbreviations: ABMT, area-based management tool; WCPFC, Western and Central Pacific Fisheries Commission.

stages (Collette et al., 2011; Hobday et al., 2010; Hyrenbach, Keiper, et al., 2006; Oppel et al., 2018; Peckham et al., 2007; Shillinger et al., 2008; Worm et al., 2003). Unlike the highly fecund target species of pelagic fisheries, many at-risk bycatch species in pelagic fisheries: (a) have "slow" life history traits, where even small changes in anthropogenic mortality levels can cause large changes in population sizes (Goñi, 1998; Hall et al., 2000); and (b) form bycatch hotspots of spatially and temporally predictable aggregations at manageable spatial and temporal scales (Block et al., 2011; Hyrenbach, Keiper, et al., 2006; Louzao et al., 2006; Morato et al., 2008; Peckham et al., 2007; Shillinger et al., 2008; Vandeperre, Aires-da-Silva, Fontes, et al., 2014; Vandeperre, Aires-da-Silva, Santos, et al., 2014). As with target species, the impact of different ABMTs will depend on life history and especially movement of the bycatch species. It is not clear, which form of ABMTs will be most effective at reducing bycatch mortality.

5.1.4 | The current evidence for socio-economic outcomes of blue water ABMTs is limited and inconclusive

If blue water ABMTs are to successfully contribute to meeting socio-economic objectives, they likely need to be one component of a suite of management tools (Hilborn et al., 2004; Kaiser, 2005). Some ABMTs can result in substantial adverse effects on fishing communities and other fisheries management tools, including other forms of ABMTs, might avoid these adverse effects while achieving the same objectives (Agardy et al., 2003; Hilborn et al., 2004; Kaiser, 2005). There are extremely few studies assessing socio-economic consequences of blue water ABMTs. The most common economic performance measures used in evaluating fisheries performance have been catch, effort, ex-vessel value, and CPUE. While profit would be a key economic measurement, it is rarely able to be estimated due to lack of cost data. The understanding of the economic impacts and benefits of blue water ABMTs in general is poorly understood (Boerder et al., 2019) and only a few studies have attempted to review the range of sociocultural and economic impacts that blue water ABMTs can have (Hanich & Ota, 2013). Given this, there is a need to better understand the potential for both positive and negative socio-cultural and economic impacts of the blue water ABMTs. There is also a need to study the effects of blue water ABMTs on fishing communities on a case-by-case basis.

5.1.5 | Displaced effort can prevent achieving objectives of ABMTs and lead to unintended consequences

Effort displacement in response to ABMTs can prevent achieving objectives (Martin et al., 2011; Sibert et al., 2012; SPC-OFP, 2010; Torres-Irineo et al., 2011; Vaughan, 2017). Studies are needed on

how fishing effort changes with implementation of different types of ABMTs.

Given the paucity of studies addressing these gaps, it would be prudent to use a precautionary approach to management of blue water ecosystems in order to have a higher probability that management goals can be met. In this context the precautionary approach would be to use management actions shown to be effective rather than those with uncertain consequences (Ban, Maxwell, et al., 2014; Druel & Gjerde, 2014).

5.2 | Summary of what we know and next steps

Area-based management tools have a long history in management and conservation of blue water ecosystems, which attempt to meet a wide range of objectives, including food production, and economic and social benefits, as well as conservation of species and ecosystems. As described in this paper, there are a number of ABMTs relevant to a diverse range of objectives. Table 6 summarizes the current state of knowledge about how ABMTs can help meet fisheries management objectives and the most immediate steps that need to be taken to operationally achieve these objectives.

5.3 | Challenges and opportunities

While it is critical to expand and strengthen conservation and management across blue water ecosystems, there are a number of challenges to be considered. Perhaps the largest challenge is that the oceans are vast and many species are widely spread or highly migratory, crossing jurisdictional boundaries on a regular basis (Ban, Bax, et al., 2014). In addition, the majority of blue water ecosystems are located outside of national jurisdiction or straddle jurisdictions, requiring international cooperation, costly research, and complicated enforcement and monitoring (Ban, Maxwell, et al., 2014). There are also large areas of the oceans in which many species are not governed by the mandate of existing RFMOs, leaving a large swath of the ocean "ungoverned." Data collection may also be limited to areas where such a capacity is established, presenting a challenge in monitoring highly migratory resources in areas where data collection capabilities are limited or absent. Lastly, blue water ecosystems are subject to increasing demands for food, competition with other use sectors for space and resources, climate change, and weak national governance systems (Meltzer, 2009). How we manage for multiple objectives and examine trade-offs remains a challenge.

A number of practices could be implemented and new technologies leveraged to address these challenges. Blue water ecosystems require management tools that can effectively deal with dynamic rapid change in the oceans while allowing regulatory regimes to react rapidly. Planning and implementation of blue water

ABMTs needs to quantitatively evaluate the benefits of the ABMT action across the wide range of uncertainties and decisions should be based on stated objectives, scientific evaluation of alternatives and have a clear plan for evaluation. In the planning process, ABMTs could be tested prior to their implementation through management strategy evaluation (MSE). The MSE process (Punt & Donovan, 2007) is designed to help find adaptive management approaches that have a high probability of meeting management objectives. MSE might then be used to evaluate different hypotheses to identify if proposed benefits of the ABMTs could be achieved with minimal trade-offs. MSE could contrast costs and benefits of ABMTs versus other management tools, such as reducing fishing mortality through input/output controls. It could also be used to identify key information gaps that need to be filled to support this performance.

Advances in technology (e.g. satellite imagery, electronic VMSs, artificial intelligence) and science (e.g. end-to-end modelling, decision rules, MSE) are providing new opportunities to better evaluate and monitor ABMT efficacy. Conservation and management of blue water ecosystems is now able to take advantage of improved data, enhanced monitoring, control and surveillance (Hobday et al., 2015) and more precise ways of tracking species, ecosystem and human health (Block et al., 2011; Queiroz et al., 2016).

It is clear that area-based management will likely have an increasingly important role in complementing other non-spatial management tools in blue water systems to (a) improve the protection of essential pelagic habitats; (b) reduce collateral impact on dependent and associated species; and (c) support human reliance on the ocean's resources. Food production, in particular, will require a sliding scale of management (from regional to local levels) that can only be accomplished through the use of multiple management tools in addition to ABMTs.

Sustainable use cannot exist without commensurate efforts to also conserve those resources for the long-term, indicating that a balance between sustainable use and protection of biodiversity are needed; the diversity of ABMTs at our fingertips will help deliver this. In many areas of the world, where MPAs represent a source of conflict that reduces their efficacy (Edgar et al., 2014; Hilborn et al., 2004; Spalding et al., 2013), other types of ABMTs present a real opportunity. The future may also greatly facilitate the integration of spatially based management of fishing operations with conservation through technological innovation, analytical improvements, economic incentives (e.g. bycatch credits) and improved regional collaboration (e.g. between MCS systems or between RFMOs).

A need does exist, however, to strengthen the spatial foundations of fisheries management, for example through more comprehensive mapping of fisheries resources, biodiversity features of concern impacted by fishing, and fishing activities and distribution of fishing pressure. ABMTs should be added to the management toolbox where they can improve or replace existing management tools (Caddy & Garcia, 1986; Crespo et al., 2020).

6 | CONCLUSIONS

A number of international processes are underway that directly relate to management of biodiversity in blue water ecosystems. The CBD's Post-2020 Global Biodiversity Framework and a new international legally binding instrument under UNCLOS regarding the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ), will likely include provisions for the use of ABMTs. These new agreements complement existing commitments (e.g. UNCLOS; UN Fish Stocks Agreement, RFMO agreements) to protect blue water ecosystems both within and beyond national jurisdictions. Within these international frameworks, there is a strong push from NGOs and support from many countries for a new target to establish 30% of the oceans as MPAs and OECMs by 2030 in order to effectively conserve marine biodiversity (Marine Conservation Institute, 2020; O'Leary et al., 2019). If this 30% target is adopted as part of the Post-2020 Framework, then countries and marine resource managers will have to work hard to integrate conservation objectives and outcomes into existing and new ABMTs. Assigning candidate ABMTs under international initiatives will require scientifically informed and thoughtful criteria to weigh numerous objectives with associated benefits and costs. Therefore, a thorough understanding of the types of ABMTs available and the evidence that exists to support specific outcomes will be critical.

DATA AVAILABILITY STATEMENT

All data used in this paper came from published works that are cited.

ORCID

Ray Hilborn https://orcid.org/0000-0003-2326-2305
Milani Chaloupka https://orcid.org/0000-0001-8109-005X
Serge M. Garcia https://orcid.org/0000-0001-5382-0844
Leah R. Gerber https://orcid.org/0000-0002-6763-6842
Eric Gilman https://orcid.org/0000-0002-4216-2513
Quentin Hanich https://orcid.org/0000-0001-9402-6233
Amber Himes-Cornell https://orcid.org/0000-0003-3695-2241
Michel J. Kaiser https://orcid.org/0000-0001-8782-3621
Hilario Murua https://orcid.org/0000-0001-8577-5291
Daniel Ovando https://orcid.org/0000-0003-2120-7345
Rishi Sharma https://orcid.org/0000-0002-3818-9393
Nathan G. Taylor https://orcid.org/0000-0002-7110-0995

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