frontiers in Marine Science

ORIGINAL RESEARCH
published: 24 March 2022
doi: 10.3389/fmars.2022.827068

Evaluating Conditions for Moored Fish Aggregating Device Fisheries Development in the Caribbean and Bermuda

Margaret W. Wilson, Julia M. Lawson, María Ignacia Rivera-Hechem, Juan Carlos Villaseñor-Derbez and Steven D. Gaines*

Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA, United States

OPEN ACCESS

Edited by:
Oscar Sosa-Nishizaki, Center for Scientific Research and Higher Education in Ensenada (CICESE), Mexico

Reviewed by:
Marcus Geoffrey Haward, University of Tasmania, Australia
Marlon Roman, Inter-American Tropical Tuna Commission, United States

****Correspondence:***
Margaret W. Wilson
mwattswilson@gmail.com

Specialty section:
This article was submitted to Marine Fisheries, Aquaculture and Living Resources, a section of the journal Frontiers in Marine Science

Received: *01 December 2021*
Accepted: *19 January 2022*
Published: *24 March 2022*

Citation:
Wilson MW, Lawson JM, Rivera-Hechem MI, Villaseñor-Derbez JC and Gaines SD (2022) Evaluating Conditions for Moored Fish Aggregating Device Fisheries Development in the Caribbean and Bermuda. Front. Mar. Sci. 9:827068. doi: 10.3389/fmars.2022.827068

Moored fish aggregating devices (MFADs) are promoted in small-scale fisheries around the world as tools to increase fisher incomes, enhance food security, and ease pressure on degraded inshore fisheries. Despite their growing popularity, the biophysical and socioeconomic contexts in which MFAD fisheries are implemented - and the implications of these contexts for MFAD fishery success - remain poorly understood. Here we develop a framework identifying and evaluating factors likely to influence MFAD fishery outcomes and apply it across states in the insular Caribbean region. We highlight the heterogeneity in MFAD regulatory strength, catch marketability, social need, and costs among states and discuss best approaches for optimizing MFAD benefits across different socioeconomic scenarios.

Keywords: Moored fish aggregating devices, FAD fisheries, regulatory strength, catch marketability, biophysical suitability, social need

INTRODUCTION

Moored fish aggregating devices (MFADs) have been promoted as a means of increasing fisher incomes, enhancing food security, and shifting fishing pressure from degraded inshore resources toward pelagic fish (Sharp, 2011; Beverly et al., 2012; Taquet, 2013; Sidman et al., 2014; Bell et al., 2015). MFADs consist of floating materials anchored in pelagic environments designed to capitalize on the natural aggregation of fish around physical structures to seek protection from predation and increase feeding efficiency (Ritz et al., 2011). By increasing fish densities at known locations, MFADs can reduce fishers' search costs and increase catch per unit effort (Buckley, 1986; Castro et al., 2001; Cabral et al., 2014; Bell et al., 2015), making pelagic species, such as tunas (*Thunnus* spp.) and mahi mahi (*Coryphaena hippurus*), more accessible to small-scale-fishers.

While MFADs are widely promoted for these potential economic benefits, they can conversely have negative social and ecological impacts. Unmanaged MFAD fisheries can lead to overfishing of pelagic resources (Bush and Mol, 2015), while unregulated fishing of inshore resources may make MFADs ineffective in reducing inshore fishing pressure (Mathieu et al., 2014). MFADs can also fuel territorial disputes, leading to conflict among fishers (Guyader et al., 2018; Tamura et al., 2018; Pittman et al., 2020), and generate substantial marine debris when they eventually become lost (Sinopoli et al., 2020).

The goal of this article is to understand the biophysical and sociopolitical conditions likely to influence the social and ecological consequences of MFAD fisheries. Factors such as the cost of deploying or utilizing MFADs (Samples and Sproul, 1985; Sharp, 2011), the presence of existing MFAD fishery management (CRFM, 2013; Sadusky et al., 2018), and the ability to commercialize species caught in MFAD fisheries (CRFM, 2013; Mosquera et al., 2013) are crucial in determining the outcome of MFAD fisheries. Identifying limitations and opportunities for successful MFAD fisheries and methods for assessing them will allow us to better inform MFAD fishery development. Here, we develop an operational framework for assessing the conditions likely to influence MFAD fisheries outcomes and apply it to 30 states in the insular Caribbean and Bermuda.

The Caribbean region is exemplary of the diverse political, cultural, economic, and biophysical conditions in which MFAD fisheries have developed, as well as the range of social and ecological impacts they can bring (Wilson et al., 2020). The insights generated by evaluating MFAD fisheries across these diverse scenarios can inform existing or prospective MFAD fisheries and highlight opportunities for improvement. While we develop this framework in the context of Caribbean MFAD fisheries, it is designed to examine global MFAD fisheries contexts and draw comparisons among regions.

Since initial introduction to the region in the late 1960s, the use of MFADs has expanded to at least 20 states in the insular Caribbean (Wilson et al., 2020). Particularly dramatic declines in the health of Caribbean coral reefs and concerns regarding the sustainability of coral reef fisheries (Hughes et al., 2003; Jackson et al., 2014) have made MFADs an appealing alternative for many governments, non-profits, and aid organizations seeking to improve small-scale fisheries in the region (Sharp, 2011; Albert et al., 2014; Bell et al., 2017). MFADs implemented by these larger organizations are typically public, meaning they are accessible to all eligible fishers (e.g., fishers with appropriate permits or belonging to a certain community). MFADs, however, are also frequently deployed by individual or small groups of fishers for exclusive use [though they may be utilized by other fishers with or without permission of the owner(s)]. These private MFADs make up the majority of the estimated over 3,500 MFADs currently deployed in the region (Wilson et al., 2020).

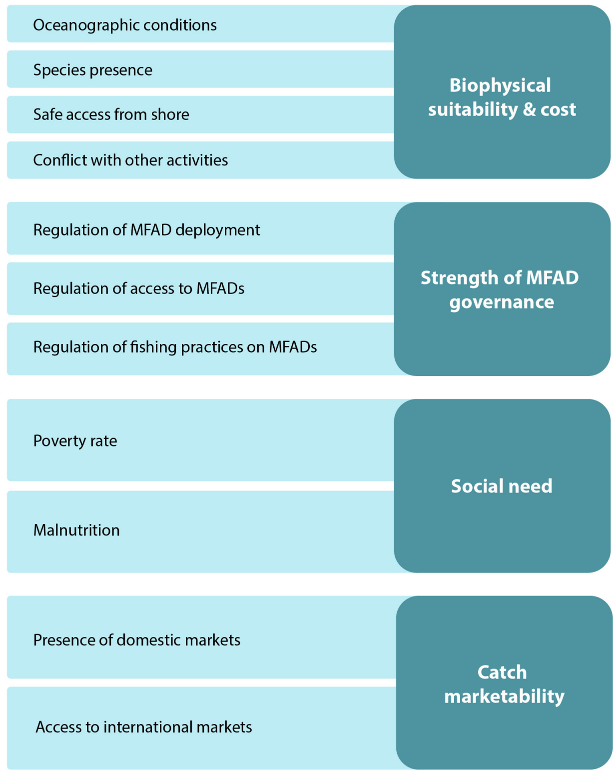

FIGURE 1 | Framework schematic. For details on specific variables and data sources used to evaluate each metric, see **Supplementary Table 1**.

MATERIALS AND METHODS

We identified numerous social and environmental factors influencing MFAD fisheries outcomes through an extensive review of gray and academic literature as well as interviews with key informants including managers and fishers from the Caribbean and Bermuda. From this synthesis, we established four central components and developed metrics with which to evaluate them (**Figure 1**). The first component evaluates the *biophysical suitability and cost* of MFAD fisheries in a given area through suitability mapping and spatial analysis. This component is intended to capture the oceanographic and ecological conditions that affect the feasibility of MFAD fishing operations and the costs of MFAD construction and utilization. The second component assesses the strength of *MFAD governance*. A lack of formal or informal regulations governing MFAD deployment and operations can lead to overfishing, the dissipation of fishing rents, and conflicts among fishers (Guyader et al., 2018; Pittman et al., 2020). These effects can undermine the social and ecological benefits attributed to MFAD fisheries. The third component, *social need*, encapsulates the socioeconomic and nutritional needs that can be ameliorated through successful MFAD fisheries. While the potential for MFADs to increase fisher incomes and local food security can arguably benefit any community, the social need component reflects the relatively greater impacts these benefits could bring to areas of greater need (Albert et al., 2014; Bell et al., 2015, 2017). The fourth component, *catch marketability*, refers to the existence of or access to markets for MFAD fisheries' catch. The ability to commercialize increased landings of pelagic species is central to accruing broader economic benefits from MFAD fisheries (Vallès, 2015).

After developing this framework, we apply it throughout the insular Caribbean and Bermuda. We define spatial units as "states," whether referring to independent sovereign countries, territories subject to external sovereignty, or other associated status. With the exception of the biophysical suitability and cost component, all metrics are normalized to a scale of 0–1 and weighted equally when integrated into a component score.

Biophysical Suitability and Cost

Our first component in evaluating optimal MFAD fishery conditions involves a spatial analysis of MFAD fishery suitability and how costly it would be to deploy and operate around MFADs within these suitable areas. To evaluate both suitability and costs, we use depth and surface current speed gridded data from the Global Marine Environmental Datasets (GMED; Basher et al., 2018), which have a 5 arc-minute (approx. 9.2 km) resolution. We also use coastline boundaries to calculate distance from shore over this 5 arc-minute grid. For identification of suitable areas we use gridded species distribution probability models from AquaMaps (Kascher et al., 2010) for four pelagic species of high fisheries importance [*Coryphaena hippurus* (mahi mahi), *Thunnus albacares* (yellowfin tuna), *Acanthocybium solandri* (wahoo), *and Katsuwonus pelamis* (skipjack tuna)] at 0.5° resolution, as well as existing marine zoning including shipping lanes (Halpern et al., 2015). We downsample these layers to match the resolution of environmental layers using a bilinear interpolation method.

Biophysical Suitability

The first step in our suitability analysis is to remove areas where environmental conditions would impede a safe or profitable MFAD fishery. For example, risk of MFAD loss will be high in areas with sustained high currents or in shipping lanes, while MFADs deployed too far from shore will increase travel costs as well as safety concerns for small-scale fishers. We retain areas where there is a 25% probability of having at least one of our identified target species, water depth is between 100 and 3,000 m, distance to land is less than 50 nautical miles (57.6 conventional miles; 92.57 km), surface currents are less than 0.65 m/s, and there is no overlap with recognized shipping lanes.

Cost

The cost of deploying and utilizing a MFAD is highly dependent on environmental conditions. For the purpose of this exercise we focus on a common float-and-sink design, which combines the use of floating and sinking rope to create an "S" shape that can extend in strong currents without leaving surplus rope on the surface during periods of slack current (see **Supplementary Figure 1**). In principle, the depth at which the "loop" floats can be set by whoever deploys the MFAD. In this case, the loop depth (d_l) is given by $d_l = 0.2 \times d$.

The total rope length (L_r) is given by a combination of depth (d) and current:

$$L_r = d \times r$$

Where r is a scaling factor that varies with current speed (s):

$$r = \begin{cases} 1.2, & if\ s \leq 0.02. \\ 1.5, & if\ s(0.02,\ 0.05) \\ 2, & otherwise \end{cases}$$

Since prices (p_r) of floating and sinking rope are similar (∼\$0.3 USD/meter), we use estimated L_r to calculate the variable part of cost of deploying a MFAD (C_d) as $C_d = L_r \times p_r$. We then incorporate fixed costs (C_f) for anchor blocks and surface buoys at an estimated constant of \$1,100 USD.

$$C_d = C_f + (L_r \times p_r)$$

The above calculations help us estimate the cost of materials to build a MFAD for a given location. We must also incorporate the cost of visiting these MFADs to obtain estimates of total costs. The travel cost to visit a MFAD (C_v) is given by:

$$C_v = \frac{2 \times D}{V} \times E_f \times P_f \times N$$

Where costs are given by the product of the round-trip time to get to a grid cell $\left(\frac{2\times D}{V}h\right)$, the fuel consumption per hour (E_f L/h), the price of fuel (P_f USD/L) and the number of trips. We assume that an MFAD is visited twice a week, resulting in 104 trips per year (N). We assume a constant speed of 30 km/h (V) using an outboard motor with a fuel consumption of 20 L/h (E_f) and constant fuel price of \$1.20 USD/L.

The total cost (C) of deploying and visiting an MFAD in a particular location is then given by:

$$C = C_d + C_v$$

Moored Fish Aggregating Device Regulatory Strength

To assess the strength of MFAD governance in each state, we use metrics evaluating the strength of regulations regarding (1) MFAD deployment, (2) MFAD access rights, and (3) fishing practices around MFADs. For each regulation type, we calculate a metric by multiplying the status of regulations (0 being non-existent, 0.5 being drafted, and 1 being established formal or informal regulations) by reported levels of enforcement (0.5 being not enforced, 1 being enforced). We then averaged these three regulatory components and normalized the resulting means from 0 to 1 to calculate a final regulatory strength score. Data for these metrics were collected through a survey of key informants throughout the insular Caribbean and Bermuda in 2019 (see Wilson et al., 2020).

Social Need

To evaluate social need within each state, we use malnutrition and poverty rate measures as indicators of the relative value of increased food security and fisher incomes that MFAD fisheries can generate. We use the dietary energy supply adequacy estimate (hereafter energy adequacy) from the FAO's suite of food security indicators to reflect malnutrition (FAO, 2020). This metric is a 3-year average of a state's energy supply expressed as a percentage of the average dietary energy requirements of that state's population. Since higher levels of energy adequacy translate into lower levels of malnutrition, our indicator for malnutrition was computed as one minus energy adequacy. We use the percentage of the population falling below the poverty line as reported in The World Factbook (Central Intelligence Agency, 2020) as a measure of poverty rates. We normalize both of these metrics to a scale from 0 to 1 and then average them to calculate a component score for social need.

Catch Marketability

We assess catch marketability as a function of both the presence of domestic markets for marine fish in a given state and the access of that state to international markets. Currently, seafood imports in the Caribbean have a negative impact on domestic fisheries and are positively correlated with tourism and domestic real income (Nguyen and Jolly, 2010). However, the existence of domestic markets suggests that there is a demand for seafood that could be met locally rather than through international imports. Additionally, existing seafood exports suggest that a given state has the capacity to store, process, and ship locally caught seafood that meets international import standards, suggesting another possible pathway for catch marketability (Mosquera et al., 2013). As such, the presence of domestic markets is evaluated using two metrics: (1) the per-capita annual imports of all marine fish from 2014 to 2016, and (2) the per-capita annual number of foreign tourists for the year 2015. The annual imports of marine fish metric is intended to evaluate the potential for MFAD catch to be marketed domestically and offset imports of other marine fish. To evaluate access to international markets, we measure annual exports (including re-exports) of all marine fish. This metric is intended to reflect the level of infrastructure and trade relationships already established for marine fish products that could be adapted to incorporate MFAD fisheries catch.

We obtain values for annual imports, exports, and re-exports of marine fish from the FAO Fishery Commodity and Trade database (FAO, 2017), except for Puerto Rico and the US Virgin Islands, which were obtained from NOAA (2021) the majority of foreign tourist numbers come from the Caribbean Tourism Organization (2015), with the exception of foreign tourist numbers for Bonaire, Saint Eustatius, and Saba, Guadeloupe, Saint Saint Barthélemy, Saint Martin (Siegel et al., 2019), and Bermuda (Caines, 2015) which were not included in the CTO database.

RESULTS

Biophysical Suitability and Cost

All states possess suitable areas for MFAD fishery development, with the cost of deploying and utilizing MFADs within them varying substantially both among and within state EEZs (**Figure 2** and **Table 1**). The most restrictive cropping factors were depth and distance from shore, with species distributions being relatively widespread throughout the region at the resolution of available data. Relatively nearshore dropoffs around Bermuda, the Cayman Islands, Puerto Rico, and the east coast of the northern Lesser Antilles reduce travel costs and keep average costs of utilization low. In states where the average cost of MFAD deployment and utilization are high (e.g., Trinidad and Tobago and Barbados), economically feasible areas do exist within these EEZs.

Catch Marketability

Marketability of MFAD catch is highest in Curaçao, Aruba, and Bermuda (**Figure 3** and **Table 1**, Q1 and Q4). This reflects high existing exports of marine fish in Curaçao, high tourism levels and high imports of marine fish in Aruba, and high imports in Bermuda. Remaining states have relatively low catch marketability levels (Q2 and Q3), with particularly low scores for Haiti and Cuba due to low levels of marine fish imports and exports as well as per capita tourism.

Moored Fish Aggregating Device Regulatory Strength

Of the 24 states with data regarding the presence and enforcement of MFAD fishing regulations, five states (Haiti, Bahamas, Cuba, Aruba, and Trinidad and Tobago) have no reported regulations in place. Nineteen states have some form(s) of MFAD regulations in place with predominantly low levels of enforcement. Antigua and Barbuda, Saint Vincent and the Grenadines, and Bermuda score relatively highly in terms of MFAD regulatory strength (**Figure 3** and **Table 1**, Q1 and Q2) with the remainder of states falling below 0.50 (Q3 and Q4). The majority of these low regulatory strength states also have low catch marketability (Q3).

Social Need

Haiti receives the highest social need score by far, with its maximum normalized score of 1 followed by Grenada with only 0.65. This results from Haiti's overwhelmingly high poverty rate and low energy adequacy. Numerous other states also have low energy adequacy (e.g., Antigua and Barbuda, Grenada, St. Kitts and Nevis) but substantially lower poverty rates than Haiti. Trinidad and Tobago has the lowest level of social need due to its high energy adequacy and relatively low poverty rates, followed closely by Barbados, the Bahamas, and Bermuda.

DISCUSSION

Our framework identifies four key social and environmental components (i.e., biophysical suitability and cost, regulatory strength, social need, and catch marketability) likely to affect MFAD fishery outcomes and establishes methods for evaluating these components. By operationalizing our framework in the insular Caribbean and Bermuda, we demonstrate how the quantitative assessment of these factors highlights opportunities and limitations for MFAD development and offer insights as to how to maximize MFAD benefits in specific scenarios.

In the Caribbean, MFAD fisheries are touted to bring economic and ecological benefits by improving catches for small-scale fishers and relieving pressure on inshore reef fisheries. In reality, there is little evidence to support these claims, and growing evidence that poorly managed MFADs can create new challenges for fishers and overexploited pelagic stocks (Bealey and Moreno, 2017; Guyader et al., 2018; Tamura et al., 2018; Pittman et al., 2020). Over the past 40 years MFAD fisheries have expanded rapidly throughout the Caribbean with limited management in many regions (Wilson et al., 2020). Despite the risks, thoughtfully implemented MFAD fisheries show potential to help improve resilience within the Caribbean region (Pinnegar et al., 2019). Our framework was designed to address this important knowledge gap to help guide and prioritize pending projects and improve existing MFAD fisheries.

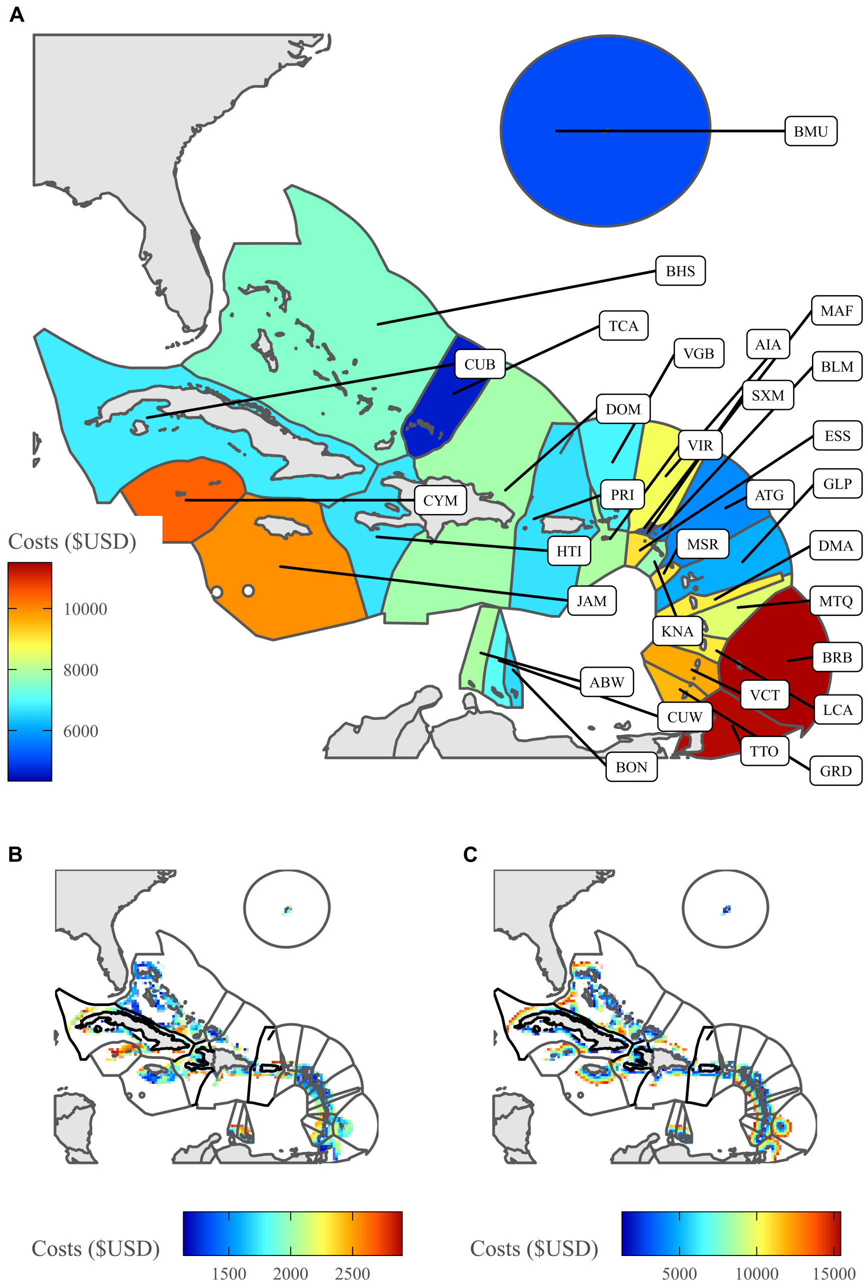

FIGURE 2 | Estimated cost of Moored Fish Aggregating Device (MFAD) deployment and utilization based on site depth and current and using a standardized MFAD design. Suitable sites are restricted to those within 50 nautical miles of shore, between 100 and 3,000 m depth, with less than 0.65 m/s surface current, and outside of formal shipping lanes. Shape outlines represent EEZs. **(A)** Mean costs across EEZ, **(B)** costs of MFAD deployment in suitable sites, **(C)** costs of MFAD utilization in suitable sites.

Our results show that while all states have feasible areas for MFAD deployment and operation, the placement of MFADs within these seascapes can have dramatic effects on MFAD fishery costs. For example, while Trinidad and Tobago scores highest for relative MFAD deployment and utilization costs, Tobago has one of the largest MFAD fisheries in the insular Caribbean, demonstrating their utilization of feasible areas within their larger EEZ. While MFAD construction costs will vary with MFAD design, we chose a standardized and relatively durable design for the purposes of demonstrating cost variations based on deployment location. Less expensive MFADs may cut costs in the short term but require frequent replacement and increase marine debris inputs, while the opposite may be true for more industrial designs. Within feasible areas there are oceanographic features (e.g., ridgelines, dropoffs, and currents) that will likely have a strong influence on how many fish and what species a

TABLE 1 | Framework component values by state.

State	Biophysical suitability and cost	MFAD regulatory strength	Social need	Catch marketability
Aruba	0.51	0.00	–	0.72
Anguilla	0.61	–	–	–
Antigua and Barbuda	0.21	1.00	0.44	0.41
Bahamas	0.45	0.00	0.12	0.30
St. Barthélemy	0.20	0.50	–	–
Bermuda	0.11	0.67	0.16	0.77
Bonaire	0.32	0.50	–	–
Barbados	1.00	–	0.10	0.54
Cuba	0.35	0.00	–	0.00
Curaçao	0.39	0.33	–	1.00
Cayman Islands	0.86	0.17	–	–
Dominica	0.65	0.33	0.22	0.29
Dominican Republic	0.50	0.17	0.35	0.06
Sint Eustatius and Saba	0.67	0.17	–	–
Guadeloupe	0.26	0.67	–	–
Grenada	0.72	0.42	0.65	0.18
Haiti	0.34	0.00	1.00	0.01
Jamaica	0.79	–	0.18	0.22
St. Kitts and Nevis	0.48	–	0.39	0.29
St. Lucia	0.65	0.25	0.47	0.24
St. Martin	0.14	0.50	–	–
Montserrat	0.65	0.25	–	–
Martinique	0.58	0.50	–	–
Puerto Rico	0.33	0.67	–	0.09
Sint Maarten	0.00	0.33	–	–
Turks and Caicos Islands	0.04	-	–	0.93
Trinidad and Tobago	0.99	0.00	0.00	0.21
Saint Vincent and the Grenadines	0.75	1.00	0.25	0.08
Virgin Islands, British	0.36	–	–	–
Virgin Islands, United States	0.51	0.51	–	–

Dashed cells indicate insufficient data availability.

given MFAD tends to aggregate. Under certain circumstances, sites that were identified as relatively costly in our analysis could still sustain successful MFADs if high catches offset high costs. For example, while strong currents increase the risk of MFAD loss as well as the amount of rope needed to maintain surface buoys above water, high flow areas may also be areas that aggregate larger amounts of fish. Local experience and observations will be imperative in determining optimal MFAD placement within a given state's EEZ.

The wider Caribbean region is one of the most geopolitically complex regions in the world, leading to a range in governance capacity among the states examined in our analysis. This complexity is driven by geographical size, ties to sovereign states, and development status as the region includes some of the most developed (e.g., Bermuda, British Virgin Islands, and Aruba) and least developed (e.g., Haiti) states in the world (Fanning et al., 2013). Given this heterogeneity, some states will have capacity for effective top-down governance while other states may be more successful in bottom-up approaches (Sidman et al., 2014; Vallès, 2015). MFAD projects should only be considered in places where regulations or norms are in place and sufficient enforcement capacity exists. This is particularly important in areas where MFAD fishing is most affordable or profitable as there is increased risk of uncontrolled MFAD fishery development.

States with both high regulatory strength and high catch marketability scores indicate an opportunity for well-managed MFAD fisheries that are able to maximize product value. High marketability relies on demand for MFAD fish within a state (as evidenced by a high level of imports and a low-to-moderate level of exports), which is often driven by a relatively high level of tourism (Nguyen and Jolly, 2010). In such instances, MFAD fisheries may provide an opportunity to offset high imports through local MFAD fisheries. These countries also score highly for MFAD regulatory strength which suggests that they are more likely to sustainably manage MFAD fisheries. Bermuda was the only state that received a high score for both of these components, due to its comprehensive regulations, moderate levels of tourism, low exports, and very high imports. Imports and exports are influenced by Bermuda's physical isolation (600 miles to the nearest mainland), and sourcing locally from MFAD fisheries could improve the sustainability of Bermuda's food supply. Bermuda is currently developing MFAD fisheries to increase local pelagic fish catches and to incentivize a reduction in fishing pressure on reef fish (Wilson, 2021).

High regulatory strength states with low catch marketability have the regulations and enforcement capacity to manage MFAD fisheries, but have limited market opportunities for MFAD catch. States with high management and enforcement capacity tend to maintain healthy, sustainable fisheries (Hilborn et al., 2020). High-capacity governments may have the resources to develop domestic campaigns that can improve domestic consumption, which may be particularly relevant in cultures with preferences for plate-sized (typically demersal) fish (Kindsvater et al., 2017; Yadav et al., 2021), or to increase the value of catch through improved handling and/or processing. However, transboundary species such as those caught in MFAD fisheries are more vulnerable to overexploitation given inconsistent management intensity throughout their ranges (Liu and Molina, 2021). Indeed, some species caught by MFAD fisheries are already overexploited - of particular concern are Atlantic blue and white marlin (ICCAT, 2018, 2019). The International Convention on the Conservation of Atlantic Tunas (ICCAT) - a regional fisheries management agreement to which many Caribbean states are members - has attempted to reduce billfish harvest throughout the Atlantic, but catches and demand for billfish is increasing in the Caribbean region (Bealey and Moreno, 2017). In Guadeloupe and Saint Vincent, two of the states with high regulatory strength but low catch marketability, blue marlin are considered the species most frequently targeted by MFAD fishers (Bealey and Moreno, 2017). High-capacity governments that seek to increase

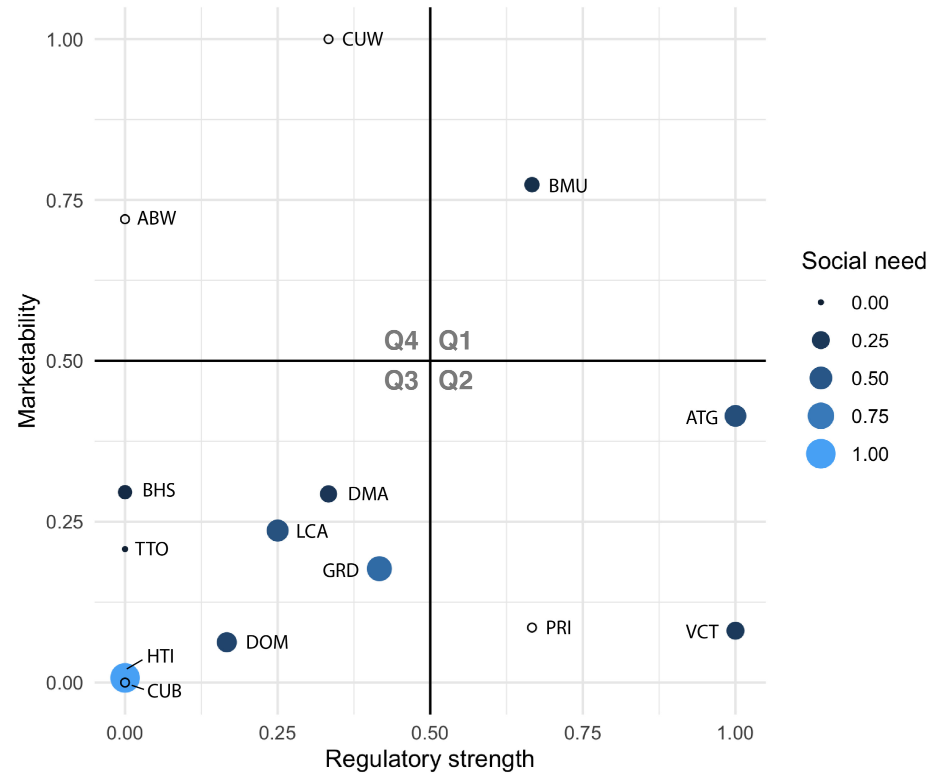

FIGURE 3 | Visualizing marketability, regulatory strength, and social need scores for insular Caribbean states and Bermuda to guide MFAD fishery approaches. Scores are scaled from 0 to 1 (see "Materials and Methods"), with states in Q1 having high regulatory strength and high catch marketability, states in Q2 having high regulatory strength but low catch marketability, states in Q3 having both low regulatory strength and catch marketability, and states in Q4 having low regulatory strength but high catch marketability. Circle size and color reflect social need scores, with open circles indicating social need data are not available. States without sufficient data to calculate marketability or regulatory strength scores are omitted here, but can be found in **Table 1**.

catch marketability should rely on their regulatory capacity to ensure sustainable fishing levels relative to each species' status.

There is a strong risk of unsustainable MFAD fishery proliferation among states where regulations and enforcement capacity are not in place and catch marketability is high. Curaçao and Aruba fall into this category, with Aruba having both high imports and a high level of tourism and Curaçao having high export potential. However, neither Curaçao nor Aruba have experienced uncontrolled expansion of their MFAD fisheries, with Curaçao having a moderately sized public MFAD fishery and Aruba having no active MFAD fishery despite early attempts at MFAD introduction there (WECAFC, 2002). Conversely, several states with low catch marketability scores (e.g., Dominican Republic, Guadeloupe) have exhibited rapid and largely uncontrolled MFAD fishery growth (Guyader et al., 2017; Wilson et al., 2020). While high catch value may incentivize the deployment of large numbers of MFADs, other factors clearly play a role in driving MFAD fishery size. These likely include alternative economic opportunities, biophysical and oceanographic conditions (e.g., strong currents in Aruba and Curaçao that likely limit the longevity of MFADs), cultural fishing preferences, and local knowledge.

The majority of states examined in our analysis fell into the category of having low regulations and enforcement capacity and low marketability. Our analysis predicts that MFAD fisheries implemented in these states are at risk of not being able to bring their product to market - either locally or internationally. For some states this is driven by low tourism numbers (i.e., Cuba and Trinidad and Tobago), low imports (i.e., Cuba and the Dominican Republic), and low export potential (i.e., Martinique, Saint Lucia), or a combination of these (i.e., Haiti). Haiti in particular faces numerous challenges with regards to catch marketability, including very limited access to refrigeration (making export challenging) and low tourism numbers (suggesting limited demand) (Vallès, 2015). Despite having very low regulatory strength, Haiti has not experienced the dramatic overproliferation of MFAD fisheries that has occurred in the neighboring Dominican Republic (Wilson et al., 2020). The vessel capability may explain this (typically $\leq$ 7 m long and without outboard engines), as well as the fuel deficit experienced by most vessels fishing MFADs (Vallès, 2015). Given the high social need in Haiti there may be an opportunity to improve MFAD deployment and harvesting strategies in order to help meet food security needs.

In addition to Haiti, several low regulatory strength states with low catch marketability also received high scores for social need (i.e., Grenada, Saint Lucia), and MFADs may provide an opportunity to address this need. In the Indo-Pacific region

MFADs have been associated with increased food security and revenues for fishers, yet these MFADs tend to be deployed in shallower waters (<50 to 450 m, although some were up to 1,500 m), which may make access less challenging (Monintja and Matthews, 1999; Prange et al., 2009; Albert et al., 2014). However, research on Indo-Pacific region MFADs have found that short-term increases in catch after initial MFAD deployment can lead to recruitment overfishing and catch declines over the long term (Monintja and Matthews, 1999; Yusfiandayani, 2013). Addressing social need through MFADs should be done cautiously, considering that the absence of enforcement and regulatory strength could lead to overproliferation.

Data Limitations and Future Research Directions

Our framework establishes a useful tool for assessing the conditions likely to influence MFAD fisheries outcomes. However, its operationalization in the Caribbean and Bermuda is limited by the heterogeneity of and data scarcity within the region. For example, our biophysical suitability and cost assessment would be much improved with fine-scale information on local species abundances and specific oceanographic features. Such information would help gauge whether MFADs would be successful in aggregating target species to a given location, as well as potentially aggregating abundances of target species, which may offset high costs in certain areas. Additionally, regulatory strength was estimated using self-reported data, and is extremely challenging to externally evaluate in small, data-limited states. Regulatory strength was evaluated specifically in the context of MFAD fisheries, while data on management capacity more broadly would likely be more informative in anticipating MFAD management in states without existing MFAD fisheries, where MFAD regulations may not yet have been motivated (e.g., Aruba). Unfortunately, standard metrics such as the World Governance Indicator score are unavailable for many Caribbean states. Incorporating a measure of overall governance capacity of each state, as opposed to only MFAD-specific regulations, could be valuable in inferring management potential in states without active MFAD fisheries where MFAD regulations may have never been motivated (only 57% of states included here have World Governance Indicator data available). Lastly, underreporting of catch, export, and import data limits the utility of our framework.

Despite these limitations, this framework lends insight into the viability of MFADs as a sustainable fisheries management tool and highlights numerous areas for future research efforts. A central knowledge gap that this framework can help address is our understanding of differences in MFAD fisheries among regions. While MFADs have been promoted in the Indo-Pacific, Mediterranean, and Caribbean, differences in the socioecological conditions in which MFAD fisheries are utilized and implications for MFAD fishery effectiveness among regions are poorly understood, hindering our ability to guide MFAD applications in these different regions. Further research is also required to evaluate the effects of various social and ecological drivers on MFAD fishery characteristics and outcomes. While the biophysical, governance, need, and market factors included here likely impact the nature of MFAD fisheries, various additional factors (e.g., historical fishing practices, cultural preferences, alternative livelihood options) may play an influential role. Lastly, while our framework evaluates the potential for MFADs to provide social and economic benefits, additional research is needed to understand whether or not (or under what conditions) these benefits are realized. Dedicated case studies of MFAD fisheries in areas with high social need or catch marketability may help assess the effectiveness of MFADs in attaining these proposed benefits.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://doi.org/10.5061/dryad.3r2280gj3.

AUTHOR CONTRIBUTIONS

MW compiled social need and regulatory strength data, wrote the manuscript with strong inputs from all coauthors, and particular strong contributions from JL on the "Discussion" section. JL and MR-H compiled marketability data. JV-D compiled biophysical suitability and cost data and generated associated maps. MW, JL, MR-H, JV-D, and SG conceived of the manuscript, developed the framework and methodology, contributed to the manuscript, and approved the submitted version.

FUNDING

This work was funded by the H. William Kuni Fellows Research Fund at U.C. Santa Barbara's Bren School of Environmental Science and Management.

ACKNOWLEDGMENTS

We would like to thank Johann Bell, Olivier Guyader, Henri Valles, Lionel Reynal, and Christopher Costello for their feedback throughout the research process. We are extremely grateful for the cooperation of the many Caribbean representatives who shared insights into their local MFAD fisheries, as well as the constructive feedback generated through the Western Central Atlantic Fishery Commission (WECAFC) Moored Fish Aggregating Device Working Group, and the Gulf and Caribbean Fisheries Institute (GCFI).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.827068/full#supplementary-material

Supplementary Figure 1 | Schematic of a moored fish aggregating device (MFAD) using floating and sinking rope.

REFERENCES

Albert, J. A., Beare, D., Schwarz, A. M., Albert, S., Warren, R., Teri, J., et al. (2014). The contribution of nearshore fish aggregating devices (FADs) to food security and livelihoods in Solomon Islands. *PLoS One* 9:e115386. doi: 10.1371/journal.pone.0115386

Basher, Z., Bowden, D. A., and Costello, M. J. (2018). GMED: global Marine Environment Datasets for environment visualisation and species distribution modelling. *Earth Syst. Sci. Data* [preprint], doi: 10.5194/essd-2018-64

Bealey, R., and Moreno, M. P. (2017). *The Caribbean Billfish Management and Conservation Plan*. Rome: FAO.

Bell, J. D., Albert, J., Amos, G., Arthur, C., Blanc, M., Bromhead, D., et al. (2017). Operationalising access to oceanic fisheries resources by small-scale fishers to improve food security in the Pacific Islands. *Mar. Policy* 88:315–322. doi: 10.1016/j.marpol.2017.11.008

Bell, J. D., Albert, J., Andréfouët, S., Andrew, N. L., Blanc, M., Bright, P., et al. (2015). Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands. *Mar. Policy* 56, 98–105. doi: 10.1016/j.marpol.2015.02.010

Beverly, S., Griffiths, D., and Lee, R. (2012). *Anchored Fish Aggregating Devices for Artisanal Fisheries in South and Southeast Asia: Benefits and Risks Anchored Fish Aggregating Devices for Artisanal Fisheries in South and Southeast Asia: Benefits and Risks*. Bangkok: FAO.

Buckley, R. (1986). Fish aggregation device (FAD) enhancement of offshore fisheries in American Samoa. *SPC Fish. Newsl.* 37, 37–42.

Bush, S. R., and Mol, A. P. J. (2015). Governing in a placeless environment: sustainability and fish aggregating devices. *Environ. Sci. Policy* 53, 27–37. doi: 10.1016/j.envsci.2014.07.016

Cabral, R. B., Aliño, P. M., and Lim, M. T. (2014). Modelling the impacts of fish aggregating devices (FADs) and fish enhancing devices (FEDs) and their implications for managing small-scale fishery. *ICES J. Mar. Sci.* 71, 1750–1759. doi: 10.1093/icesjms/fsv214

Caines, L. (2015). *Bermuda 2015 Visitor Arrivals Report*. Hamilton: Bermuda Tourism Authority.

Caribbean Tourism Organization (2015). *Caribbean Tourism Organization Latest Statistics 2015*. Bridgetown: Caribbean Tourism Organization.

Castro, J. J., Santiago, J. A., and Santana-Ortega, A. T. (2001). A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. *Rev. Fish Biol. Fish.* 11, 255–277. doi: 10.1023/A:1020302414472

Central Intelligence Agency (2020). *CIA World Factbook*. Virginia: Central Intelligence Agency.

CRFM (2013). *Report of the CRFM / JICA Fish Aggregating Devices (FAD) Management Workshop for OECS Countries*. Belize: CRFM Secretariat.

Fanning, L., Mahon, R., and McConney, P. (2013). Applying the large marine ecosystem (LME) governance framework in the Wider Caribbean Region. *Mar. Policy* 42, 99–110. doi: 10.1016/j.marpol.2013.02.008

FAO (2017). *Global Fish Trade and Processed Products Statistics Database*. Available Online at: https://www.fao.org/fishery/statistics/global-commodities-production/en. [accessed on Jan 22, 2022]

FAO (2020). *FAOSTAT Statistical Database*. Rome: FAO.

Guyader, O., Bauer, R., and Reynal, L. (2017). Assessing the number of moored fishing aggregating devices through aerial surveys: a case study from Guadeloupe. *Fish. Res.* 185, 73–82. doi: 10.1016/j.fishres.2016.10.003

Guyader, O., Frangoudes, K., and Kleiber, D. (2018). Existing Territories and Formalization of Territorial Use Rights for Moored Fish Aggregating Devices: the Case of Small-Scale Fisheries in the La Désirade Island (France). *Soc. Nat. Resour.* 31, 822–836. doi: 10.1080/08941920.2018.1443235

Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., et al. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nat. Commun.* 6:7615. doi: 10.1038/ncomms8615

Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., et al. (2020). Effective fisheries management instrumental in improving fish stock status. *Proc. Natl. Acad. Sci. U.S.A.* 117, 2218–2224.

Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., et al. (2003). Climate Change, Human Impacts, and the Resilience of Coral Reefs. *Science* 301, 929–933. doi: 10.1126/science.1085046

ICCAT (2018). *Report of the 2018 ICCAT Blue Marlin Stock Assessment Meeting*. Miami, Florida: ICCAT.

ICCAT (2019). *Report of the 2019 ICCAT White Marlin Stock Assessment Meeting*. Miami, Florida: ICCAT.

Jackson, E. J., Donovan, M., Cramer, K., and Lam, V. (2014). *Status and Trends of Caribbean Coral Reefs: 1970-2012*. Gland, Switzerland: Global Coral Reef Monitoring Network, IUCN.

Kascher, K., Kesner-Reyes, K., Garilao, C., Segschneider, J., Rius-Barile, J., Rees, T., et al. (2010). *AquaMaps: Predicted Range Maps for Aquatic Species*. Available Online at: www.aquamaps.com. [accessed on Feb 10, 2015]

Kindsvater, H. K., Reynolds, J. D., de Mitcheson, Y. S., and Mangel, M. (2017). Selectivity matters: rules of thumb for management of plate-sized, sex-changing fish in the live reef food fish trade. *Fish Fish.* 18, 821–836. doi: 10.1111/faf.12208

Liu, O. R., and Molina, R. (2021). The Persistent Transboundary Problem in Marine Natural Resource Management. *Front. Mar. Sci.* 8:1292. doi: 10.3389/fmars.2021.656023

Mathieu, H., Reynal, L., Magloire, A., and Guyader, O. (2014). "Does FAD Deployment Have a Real Effect on Fishing Redeployment Towards Offshore Resources?," in *Proceedings of the 66th Gulf and Carribean Fisheries Institute*, (Texas: ICRS), 512–517.

Monintja, D., and Matthews, C. (1999). "The skipjack fishery in Eastern Indonesia: distinguishing the effects of increasing effort and deploying rumpon FADs on the stock," in *Pêche Thonière et Dispositifs de Concentration de Poissons, Caribbean (Martinique)*, (France: Archimer).

Mosquera, M., Evans, E., Walters, L., and Spreen, T. (2013). The US Food Safety Modernization Act: implications for Caribbean Exporters. *Soc. Econ. Stud.* 62, 151–176.

Nguyen, G. V., and Jolly, C. M. (2010). "Seafood Import Demand in the Caribbean Region," in *2010 Annual Meeting*, (Orlando: Southern Agricultural Economics Association).

NOAA (2021). *Foreign Fishery Trade Data*. Available online at: https://www.fisheries.noaa.gov/national/sustainable-fisheries/foreign-fishery-trade-data (accessed January 27, 2022).

Pinnegar, J. K., Engelhard, G. H., Norris, N. J., Theophille, D., and Sebastien, R. D. (2019). Assessing vulnerability and adaptive capacity of the fisheries sector in Dominica: long-term climate change and catastrophic hurricanes. *ICES J. Mar. Sci.* 76, 1353–1367. doi: 10.1093/icesjms/fsz052

Pittman, J., Tam, J. C., Epstein, G., Chan, C., and Armitage, D. (2020). Governing offshore fish aggregating devices in the Eastern Caribbean: exploring trade-offs using a qualitative network model. *Ambio* 49, 2038–2051. doi: 10.1007/s13280-020-01327-7

Prange, J., Oengpepa, C., and Rhodes, K. (2009). Nearshore fish aggregating devices: a means of habitat protection and food security in post-disaster Solomon Islands. *SPC Fish. Newsl.* 2009, 19–20.

Ritz, D. A., Hobday, A. J., Montgomery, J. C., and Ward, A. J. W. (2011). "Social Aggregation in the Pelagic Zone with Special Reference to Fish and Invertebrates," in *Advances in Marine Biology*, ed. L. Michael (Amsterdam: Elsevier), 161–227. doi: 10.1016/B978-0-12-385529-9.00004-4

Sadusky, H., Chaibongsai, P., Die, D. J., and Shivlani, M. (2018). Management of moored fish aggregating devices (FADs) in the Caribbean. *Collect. Vol. Sci. Pap. ICCAT* 74, 2230–2242.

Samples, K. C., and Sproul, J. T. (1985). Fish Aggregating Devices and Open-Access Commercial Fisheries: a Theoretical Inquiry. *Bull. Mar. Sci.* 37:13.

Sharp, M. (2011). The Benefits of Fish Aggregating Devices in the Pacific. *SPC Fish. Newsl.* 135, 28–36. doi: 10.1139/f89-004

Sidman, C., Lorenzen, K., Sebastien, R., Magloire, A., Cruickshank-Howard, J., Hazell, J., et al. (2014). *Toward a Sustainable Caribbean FAD Fishery: an Analysis of Use, Profitability and Shared Governance*. Belize: CRFM.

Siegel, K. J., Cabral, R. B., McHenry, J., Ojea, E., Owashi, B., and Lester, S. E. (2019). Sovereign states in the Caribbean have lower social-ecological vulnerability to coral bleaching than overseas territories. *Proc. Royal Soc. B Biol. Sci.* 286, 20182365–20182365. doi: 10.1098/rspb.2018.2365

Sinopoli, M., Cillari, T., Andaloro, F., Berti, C., Consoli, P., Galgani, F., et al. (2020). Are FADs a significant source of marine litter? Assessment of released debris and mitigation strategy in the Mediterranean sea. *J. Environ. Manag.* 253, 109749–109749. doi: 10.1016/J.JENVMAN.2019.109749

Tamura, M., Ishida, M., Sidman, C., Montes, M., and Lorenzen, K. (2018). *Facilitating Co-Managed Fisheries in the Caribbean Region: Good Practices and Guidance from the CARIFICO Experience*. Gainesville: CARIFCO.

Taquet, M. (2013). Fish aggregating devices (FADs): good or bad fishing tools? A question of scale and knowledge. *Aquat. Living Resour.* 26, 25–35. doi: 10.1051/alr/2013043

Vallès, H. (2015). "A Snapshot View of the Moored Fish Aggregating Device (FAD) Fishery in South Haiti," in *Proceedings of the 68th Gulf and Caribbean Fisheries Institute*, (Panama: ICRI).

WECAFC (2002). *First meeting of the WECAFC ad HOC Working Group on the Development of Sustainable Moored Fish Aggregating Device Fishing in the Lesser Antilles: National reports*. Rome: Food and Agriculture Organization of the United Nations, 229–235. FAO fisheries Report No. 683.

Wilson, M. (2021). *Bermuda Fish Aggregating Device Pilot Monitoring Plan*. Santa Barbara, CA: Environmental Market Solutions Lab.

Wilson, M. W., Lawson, J. M., Rivera-Hechem, M. I., Villaseñor-Derbez, J. C., and Gaines, S. D. (2020). Status and trends of moored fish aggregating device (MFAD) fisheries in the Caribbean and Bermuda. *Mar. Policy* 121:104148. doi: 10.1016/j.marpol.2020.104148

Yadav, S., Fisam, A., Dacks, R., Madin, J. S., and Mawyer, A. (2021). Shifting fish consumption preferences can impact coral reef resilience in the Maldives: a case study. *Mar. Policy* 134:104773. doi: 10.1016/j.marpol.2021.104773

Yusfiandayani, R. (2013). Fish aggregating devices in Indonesia: past and present status on sustainable capture fisheries. *Galaxea* 15, 260–268. doi: 10.3755/galaxea.15.260

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.