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research paper

Advancing ecosystem management strategies for the Gulf of Mexico's fisheries resources: implications for the development of a fishery ecosystem plan

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ABSTRACT.—Recent global improvements to fisheries sustainability have been made through the adoption of more holistic management frameworks, such as the ecosystem approach to fisheries management (EAFM) and ecosystem-based fisheries management (EBFM), and a concurrent transition from a focus on single species or stocks to multispecies and ecosystems. In the US, federal and regional fisheries management encompass multiple layers of comprehensive, ecosystem focused management strategies for living marine resources within its network of large marine ecosystems (LMEs). Here, we provide an overview for the US portion of the Gulf of Mexico large marine ecosystem (GOM-LME) by examining multiple aspects of its fishery management scheme through the lenses of EAFM, EBFM, and the integrated ecosystem assessment (IEA) framework that has been used worldwide to advise, inform, and operationalize ecosystem management. The US-GOM's fishery management and ecosystem community appears to be keeping pace with other US regional efforts. However, more tools like fishery ecosystem plans (FEPs), which are conducive to the effective integration of ecosystem considerations into fishery management processes, are needed to inform and guide the work of regional managers, decision-makers, and stakeholders. Therefore, we propose a structured planning process aimed at advancing the development and implementation of a GOM-FEP, and describe two case studies of EAFM and EBFM applications, respectively, that can help to navigate through our proposed planning process. This work offers strategic guidance and insights to support efforts of regional fishery managers to translate ecosystem management principles, approaches, and objectives into an "action oriented" FEP in the GOM-LME.

Ecosystem management (EM) is a holistic approach for the management of natural resources that considers the integration of human activities and their impacts on the natural environment (Larkin 1996, Yaffee 1999, Berkes 2012). From an operational standpoint, the Ecological Society of America provided one of the first widely agreed-upon definitions of EM, which is "management driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function" (Christensen et al. 1996).

Additionally, conclusions from two separate national commissions, the Pew Ocean Commission (2003) and the US Commission on Ocean Policy (2004), called for more comprehensive EM strategies for US marine resources and habitats, thereby contributing to the advancement of further implementation of integrated management considerations for US marine ecosystems (Granek et al. 2005). These commissions' recommendations have been translated into two management paradigms: the ecosystem approach to management and ecosystem-based management (EBM). When centered on fisheries resources, these paradigms are referred to, respectively, as the ecosystem approach to fisheries management (EAFM) and ecosystem-based fisheries management (EBFM). Although EAFM and EBFM are often used interchangeably (Murawski 2007), they have different trajectories, with respect to their particular foci, along the gradient representing the integration of ecosystem aspects into fishery management (Link 2010, Fogarty 2014). Specifically, the EAFM trajectory proceeds from the single-species (SS, or single-stock) focus toward one including the effects of other fisheries sectors as well as environmental and ecological considerations. Ultimately, EAFM aims for single stock management through the integration of more complex multi-species (MS) community dynamics while considering the broader interactions within the ecosystem (Morishita 2008, Link 2010). Conversely, EBFM takes an ecosystem-level focus at the outset by considering the whole ecosystem, its fish stocks, and any associated fisheries, and then attempts to integrate these components in a holistic fashion to account for MS considerations, species interactions/dynamics, and natural and anthropogenic influences (Link 2010, Belgrano and Fowler 2011, Link and Browman 2014, Biedron and Knuth 2016, Dolan et al. 2016). Table 1 briefly summarizes the aspects pertaining to each level of EM that characterize fishery management, including in the US.

Among managers of the eight US Regional Fishery Management councils (hereafter referred to as the councils), there is a wide recognition that more EM strategies would benefit current management efforts for US regional fisheries resources (PFMC 2014, Marshall et al. 2018). This view is also a reflection of the Ecosystem Principles Advisory Panel (EPAP)'s report to the US Congress, which was conducted in 1999. The report concluded that, within the US fishery management structure, conventional strategies included provisions that could address some, but not all, aspects of EBFM, and that some of the principles and goals of EBFM were not applied comprehensively across councils' jurisdictions (EPAP 1999, deReynier 2014). Hence, the EPAP recommended the need for the introduction of fishery ecosystem plans (FEPs) as new comprehensive management tools to achieve a more systematic implementation of EBFM at the regional council level (EPAP 1999).

Conceptually, an FEP is a formal guidance document that can be developed by the councils to support the integration of ecosystem principles, goals, and policies within their fishery management frameworks. In detail, an FEP provides an understanding of key biological, physical, and socioeconomic aspects of the fishery ecosystem, along with a clear pathway toward incorporating trophic and ecological relationships

Table 1. Levels of ecosystem management approaches and applications for fisheries sectors, with a description of specific aspects for each level (adapted from Link and Browman 2014, Dolan et al. 2016). FM = fisheries management, EAFM = ecosystem approaches to fisheries management, EBFM = ecosystem based fisheries management, SA = stock assessment, ISA = integrated stock assessment, LMR = living marine resources, BRPs = biological reference points, SRPs = systemic reference points, SAMs = stock assessment models, ESAMs = extended stock assessment models, MSMs = multispecies models, MSEs = management strategy evaluations, EMs = ecosystem models, RA = risk analysis, FMP = fishery management plan, FEP = fishery ecosystem plan, RFMC = Regional Fishery Management Council.

Specific aspects	Traditional FM	EAFM	EBFM
Focus of biological hierarchy for management	Single stock/population	Single stock/population	Community/whole ecosystem
Evaluation framework	Single SA	ISA	ISA with focus on fisheries sectors
Main objective of the analysis	Determine stock status	Determine stock status	Address trade-offs across fisheries and other sectors, and LMR
	Determine stock productivity	Determine stock productivity	Determine ecosystem productivity
	Diagnose levels of optimal stock production	Diagnose levels of optimal stock production by integrating ecosystem factors and interactions	Diagnose optimal productivity across multispecies fisheries
	Assess within-stock effects of fishing and implications for management	Assess within-stock effects of multiple fisheries and environmental factors/drivers	Assess within-(fishing) sector cumulative effects across multispecies fisheries
Primary output for scientific advice	BRPs for fishery stock	BRPs for fishery stock	SRPs, including BRPs
Analytic tool for decision-makers	SAMs, MSEs	ESAMs, MSMs, and MSEs	EMs with focus on fisheries, MSMs, MSEs, and RA
Implementation framework	FMP	FMP	FEP
Implementation body (US's jurisdiction)	RFMC	RFMC	RFMC

among marine predators, prey, habitats, and human activities in the development of EM strategies for fisheries resources. As such, an FEP is intended to serve as the primary EBFM instrument to guide managers and decision-makers in achieving sustainable, ecosystem-wide fishery management, by means of a process that can address the incorporation of ecosystem goals and actions into regional EBFM strategies (EPAP 1999, Levin et al. 2018, Marshall et al. 2018). In turn, these strategies can help managers to make more informed decisions, and also within the context of fishery management plans (FMPs).

In this regard, FMPs and FEPs are functionally different in purpose, legal mandate, and scope (Essington et al. 2016). Specifically, FMPs are conceptualized, and statutorily required under the regulatory framework of the US Magnuson-Stevens Fishery Conservation and Management Act (MSA) that provides for the conservation and management of fisheries resources in the US exclusive economic zone, to achieve management goals that are set for SS or single sector fisheries. Conversely, FEPs are developed discretionarily by each council to support the achievement of EBFM objectives for the broader fishery ecosystem within each council's jurisdiction.

Accordingly, the scale of FMPs is more commonly related to the confined spatial focus of a single stock's range, whereas for FEPs the scale is enlarged to the spatial extent of the whole fishery ecosystem (Essington et al. 2016), or to a specific portion of a large marine ecosystem (LME; e.g., the Aleutian Islands FEP managed by the North Pacific Fishery Management Council). In essence, FEPs do not necessarily have similar "management teeth" as FMPs are required to have by the MSA. However, an FEP can work as a compass to direct management plans within and across FMPs, and can help to enhance fishery sustainability and community resilience by addressing issues (e.g., trophic relationships among species and their interactions) that would be more difficult to account for within individual FMPs. Hence, FEPs are commonly more suitable than FMPs for operationalizing and translating EBFM principles into action (Essington et al. 2016).

Over the last decade, nine FEPs have been completed by various councils (the North Pacific, Pacific, Western Pacific, and South Atlantic councils), with another two under development (the New England and Caribbean councils). More recently, the Gulf of Mexico Fishery Management Council (GMFMC) has tasked its staff with initiating the process for the development of an FEP (GMFMC 2018) for the US portion of the Gulf of Mexico (GOM), which is part of one of the 66 LMEs of the world (Turner 1999, UNEP 2016). The GOM-LME is shared by the US, Mexico, and Cuba, and is a key asset for both commercial and recreational fisheries. In 2016, marine resources from this LME contributed to approximately 18% of landings (about 16% in value) for the US commercial fisheries and represented 39% of the total US recreational catch (NMFS 2017). This translated into approximately US$912 million in revenue for commercial landings across the five US gulf states (Texas, Louisiana, Mississippi, Alabama, and Florida), and in more than 19 million trips by recreational fishermen generating billions of US dollars (NMFS 2018). Compared to other US regions, the GOM-LME is characterized by high productivity, biodiversity, fishery landings, and socioeconomic status (Link and Marshak 2019). However, during the last century, this LME has been under increasing natural and anthropogenically-driven pressures that affect the broader ecosystem dynamics and statuses of various fish stocks (Coleman and Koenig 2010, Karnauskas et al. 2013, 2015, 2017, Kilborn et al. 2018). Cognizant of these effects to GOM fisheries resources and trophic interactions (Jacobson et al. 2005, Keyl and Wolff 2008, Kirby et al. 2009, Hidalgo et al. 2011, Ainsworth et al. 2018, Trifonova et al. 2019), the challenge of advancing the GOM-LME toward EBFM may benefit through the development of an FEP.

Therefore, this study provides a thorough overview of the multiple lines of information pertaining to US national and regional fishery management policies and frameworks to support ongoing efforts for the development of a US GOM-FEP. The aims of this paper are to: (1) examine the EM literature with respect to EAFM and EBFM within the GOM-LME, and in relation to best practices for the development of FEPs; (2) synthesize this information into a proposed planning process to support current efforts for developing a US GOM-FEP; and (3) describe two applications of EAFM and EBFM, respectively, as case studies exemplifying potential ways to navigate through the proposed US GOM-FEP planning process. This information is intended to guide regional fishery management decision-makers at an operational level, thereby helping to shape fishery sustainability practices in the GOM-LME through enhanced planning and governance.

Applications of EM to US Fisheries Sectors

Implementation of EM at the US Federal Level.—The National Marine Fisheries Service (NMFS) has taken meaningful steps to advance an ecosystem-based strategy for fishery resources in the US, which is specifically conceptualized in the form of an EBFM Policy based on six guiding principles (NMFS 2016a). To further support and accelerate this strategy, NMFS also released an EBFM Road Map (NMFS 2016b) describing how to operationalize those six principles through a series of core components, and with the goal of making actionable steps for the implementation of EBFM at the federal level. Moreover, as key components of this implementation strategy, nine EBFM regional implementation plans have been developed by NMFS to identify priority actions and milestones for the next five years, and that are meant to complement councils' efforts for the implementation of EBFM at the regional level (https://www.fisheries.noaa.gov/national/ecosystems/ecosystem-based-fishery-management-implementation-plans).

While not a requirement, the integrated ecosystem assessment (IEA) framework is recognized by the US National Oceanic and Atmospheric Administration (NOAA) as the main scientific engine supporting the advancement and implementation of both EBM for marine resources (Levin et al. 2009, Samhouri et al. 2014), and EBFM for fisheries resources (NMFS 2016b). The IEA management framework is broadly based on a five-step iterative loop (*see* figure 1 in Levin et al. 2009, Samhouri et al. 2014, and Harvey et al. 2016).

Implementation of EM at the US Regional Level.—The IEA framework advocated by NOAA has been implemented in five US regions: Alaska, the Northeast Shelf, the Gulf of Mexico, the California Current, and the Pacific Islands (Samhouri et al. 2014). For each of those regions, an ecosystem status report (ESR) was developed containing a full suite of indicators providing critical information about the status and trends of key ecosystem components, including socioeconomic, biological, climatological, and physical-chemical aspects. This information provides ecosystem-wide context for managers and stakeholders regarding the ecosystem's structure and function through a better understanding of environmental, ecological, and socioeconomic conditions (NOAA 2009, Karnauskas et al. 2017, Harvey et al. 2018). Additionally, ESRs contribute to the crucial process of information sharing, tool exchange, data repository, and communication between federal and regional managers to support ecosystem-based decision-making processes and the implementation of place-based EM strategies (Slater et al. 2017).

Improvements in scientific research and policy implementation over time, including the 1996 Sustainable Fisheries Act (SFA) revision to the MSA, have helped to reduce overfishing and bycatch levels while supporting the rebuilding of many of the depleted US stocks on a regional level (NRC 2014, Marshall et al. 2018). Despite these successes, however, the overall structure of the MSA, and its amendments like the SFA, centers more on conventional SS fisheries management strategies, and does not prevent councils from developing regional policies that are less in line with stated federal EBFM objectives. Consequently, the current segmentation into single sector FMPs may potentially be restricting the effectiveness of the fishery management system to deliver on broader ecosystem goals and to account for trade-offs across multiple fishery sectors, both of which are paramount to advance EBFM strategies

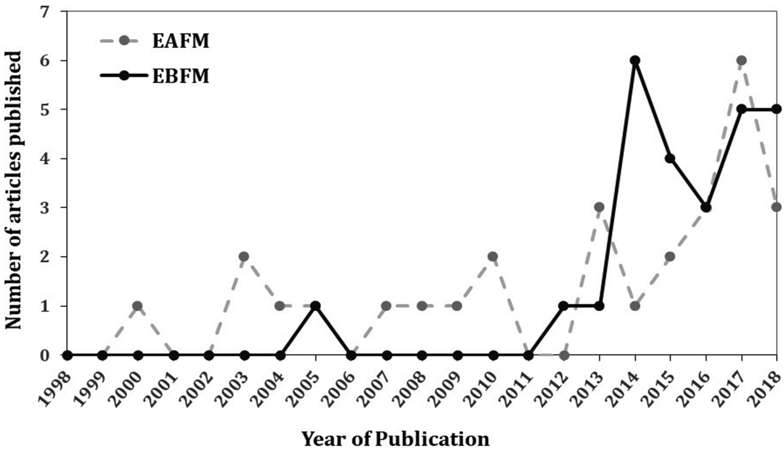

Figure 1. Number of peer-reviewed articles published annually (1998–2018) containing the combined terms "Ecosystem approach to fisheries management AND Gulf of Mexico" (i.e., EAFM) and "Ecosystem-based fisheries management AND Gulf of Mexico" (i.e., EBFM), over time. Data are based on independent keyword searches of the above EAFM and EBFM combined terms, respectively, in the "topic" field of the Web of Science database (drawn from all databases). Database accessed on 27 November, 2018.

(Link 2010, Levin et al. 2018). Therefore, the EPAP's recommendation for councils to develop comprehensive FEPs may be a more effective pathway for enacting EBFM at the regional scale (EPAP 1999, Essington et al. 2016, Levin et al. 2018, Marshall et al. 2018).

The Status of EM for Fishery Resources in the GOM.—Recently, an increased focus on EM approaches to fisheries resources has emerged in the GOM. For example, a bibliometric analysis conducted for the period 1998–2018 resulted in a total of 28 and 26 peer-reviewed papers on EAFM and EBFM, respectively, in the GOM (Fig. 1). However, results suggested a higher level of attention given to EAFM approaches during the first decade, with a change in focus to EBFM around 2013. Specifically, over the last five years of the analysis, 23 papers on EBFM were published, compared to a total of 15 for EAFM. The number of published EAFM papers peaked in 2017 and was largely due to the contribution of articles by Mexican researchers and institutions (50% of the total papers published in 2017).

The recent increase in EBFM-related research is also a reflection of the ongoing efforts of fisheries scientists on the Gulf of Mexico Integrated Ecosystem Assessment (GOM-IEA) team working to advance the implementation of EBFM in the region. Key products resultant from the GOM-IEA team's work include two ESRs specific to the GOM (Karnauskas et al. 2013, 2017) and a GOM-EBFM Implementation Plan (NMFS 2019). At the junction of federal and regional efforts, the GOM-IEA team and the GMFMC have been working together to discuss potential ways to effectively incorporate ecosystem science and research into fisheries management (https://www.integratedecosystemassessment.noaa.gov/regions/gulf-of-mexico/ecosystem-support-fisheries). These efforts add up to ongoing processes and activities of the GMFMC that are focused on conceptualizing, developing, and delivering a regional fishery plan for the GOM (GMFMC 2018).

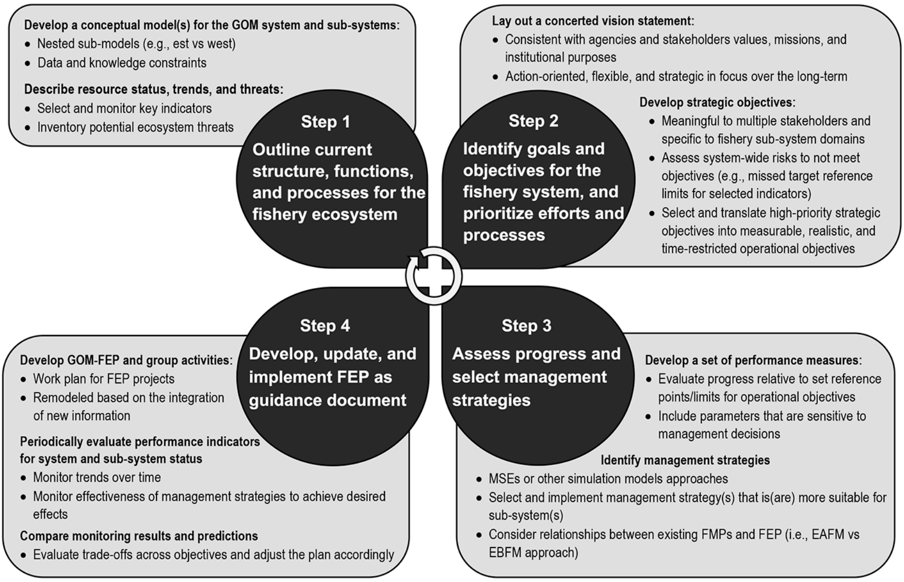

Figure 2. Conceptual diagram of the proposed planning process for guiding the development of a fishery ecosystem plan (FEP) for the US Gulf of Mexico (GOM) fishery ecosystem and sub-systems. The US GOM-FEP planning process is based on an iterative loop of four steps (dark grey polygons) and associated actions (bold text within light grey polygons) and considerations (bullet points; adapted from Essington et al. 2016, Levin et al. 2018). MSE = management strategy evaluations, FMPs = fishery management plans, EAFM = ecosystem approach to fishery management, EBFM = ecosystem-based fishery management.

Collectively, this overall picture suggests the presence of a perceived need by regional fishery managers and researchers for EBFM initiatives in the GOM. Thus, the development of an FEP could fulfill this need and enhance progress toward the integration of ecosystem trade-offs (i.e., ecological, economic, and social) and considerations within a more holistic fishery management strategy.

Moving Forward for the Development and Delivery of an FEP in the GOM

To begin with, it would be strategically advantageous for GOM-FEP development efforts to deviate from the focus on SS paradigms, and, instead, cultivate long-term goals that are more in line with the "next generation" vision and concepts of FEPs under the umbrella of EBFM (Essington et al. 2016, Levin et al. 2018, Marshall et al. 2018). Moreover, a preliminary list of initial priorities to achieve this long-term vision has been developed (Chagaris et al. 2019), which could be further refined through open and transparent communication between fishery managers, scientists, and other regional stakeholders. This is key to correctly align objectives for the execution of agreed-upon strategies for EBFM in the GOM.

To support this advancement in the region, we present a four-step iterative planning process for the development of a US GOM-FEP (Fig. 2) that is meant to sketch a structured approach for enhancing regional efforts for developing an ecosystem-plan, policies, and fishery management guidance for the US GOM. This loop, which was conceptualized upon the IEA's adaptive management framework for operationalizing

EBFM (Levin et al. 2018), draws upon the recommendations of the Lenfest Fishery Ecosystem Task Force describing the requirements for "next generation" FEPs in the US (Essington et al. 2016, Levin et al. 2018), the benchmarking analysis of the Pacific Fisheries Management Council's FEP regarding those recommendations (Dawson and Levin 2019), and the conclusions of a recent review of FEPs (Wilkinson and Abrams 2015) with respect to the EPAP's recommendations for councils to guide their FEP development efforts (EPAP 1999).

The proposed planning process is based on four iterative steps defined as follows:

- *Step 1* – Outline the current structure, functions, and processes for the GOM fishery ecosystem;
- *Step 2* – Identify agreed-upon goals and objectives for the fishery system, and prioritize key efforts, focus areas, and processes;
- *Step 3* – Assess progress and select management strategies;
- *Step 4* – Develop, update, and implement the FEP as a management guidance document.

Step 1.—The first step involves developing a conceptual model for the GOM fishery ecosystem as a social-ecological system composed of the various integrated subsystems of the LME. Conceptual models (*see* Levin et al. 2016 for the California Current ecosystem example) are valuable tools for synthesis, integration, and communication of multiple lines of information in ecological and fishery systems that can help us understand the complex structures and functions of these systems by revealing links within and across their components (Ogden et al. 2005, Hunt et al. 2013, Harvey et al. 2016, Levin et al. 2016). For the US GOM fishery ecosystem, these conceptual models could result from collaborative partnerships between the GMFMC, the GOM-IEA program, and/or other stakeholders (e.g., the Gulf State Marine Fisheries Commission) from the region. Additionally, due to the relative paucity of comprehensive data for many of the GOM's subsystems, qualitative, rather than quantitative, conceptual models may be required (e.g., qualitative network models as applied to the California Current ecosystem) to explore socioecological relationships, compare management strategies, and identify trade-offs (Harvey et al. 2016, Wildermuth et al. 2018). Also, due to the nature of the US GOM fishery system, any LME-wide conceptual model would need to be nested, thereby creating a general model for the whole fishery ecosystem along with various submodels accounting for species interactions and relationships among fishery and nonfishery components (e.g., differences between western and eastern basin, climatology changes).

Next, based on the system-wide conceptual model, managers should capture the status and trends of key ecological and social components of the fishery ecosystem through the selection and monitoring of relevant biophysical and socioeconomic indicators. The GOM-ESR (Karnauskas et al. 2013, 2017) is certainly a starting point for identifying indicators from the suite of potential candidates, and would help to maintain continuity with the IEA program's efforts in the region. However, other reliable data sources (e.g., satellite observations, state and academic databases, scientific reports) should be used if available.

As a corollary to this, managers, scientists, and stakeholders should create a list of potential threats that may impact the GOM fishery ecosystem, including terrestrial (e.g., freshwater runoff), climatological (e.g., local and regional weather conditions), coastal (e.g., coastal development, habitat change), and marine (e.g., shipping activity, underwater noise, and physical-chemical conditions) components of the system (Doubleday et al. 2017, Mazaris et al. 2019), along with other human subsystems (e.g., market conditions and exploitation rates). This listing should not be a mere compilation task, and should be a clear accounting of the most relevant threats and their appropriate temporal scales, as these factors will have important implications for the fishery management process and discourse. Arguably, this list of threats should also be subdivided spatially to reflect inherent differences across socioecological subsystems within the widerscale of the LME, and to allow for investigating variability among spatial extents, relative magnitudes, and frequencies of their occurrences (Levin et al. 2018).

Step 2.—Step 2 includes the development of an action-oriented, flexible, and strategic long-term vision statement that is agreed-upon by a diverse set of fishery managers, scientists, and stakeholders. This vision should provide a clear, ambitious identity for common goals, beliefs, and priorities across the system, and offer flexible options for strategies to achieve them. However, this vision also needs to be broad in scope, to avoid giving space to potential fundamental modifications reflecting political changes and institutional turnover within a relatively short time frame (e.g., 10 yrs). Furthermore, this proposed common-vision, while being inclusive of other agencies' and stakeholders' missions, should be largely based upon the GMFMC's guiding ecosystem values and stated institutional purpose, and be consistent through time with the original mission and purpose of the proposed FEP (Levin et al. 2018).

To help prioritize the most realistic and effective management options, the structure and content of this concerted vision needs to be translated into a set of strategic objectives that are meaningful to different stakeholders and centered on specific fisheries subsystems within the US GOM-LME.

Additionally, for each strategic objective developed, there is a need to analyze the risks associated with the scenario in which the objective is not likely to be met. For example, for some objectives, reference limits of key indicators could be set and used as proxies for the desired status of the fishery system (or subsubsystem). In turn, this would allow for simulation studies that quantify the risks associated with surpassing those limits. These risk assessments should be conducted, preferably, in an MS context (Hilborn 2011), and be based on the best scientific information available to integrate across socioeconomic and biophysical components of the fishery ecosystem (Holsman et al. 2017).

As an ensuing effort, managers would need to streamline the list of strategic objectives into a more practical set of high-priority, actionable objectives through a selection process that is inclusive of various stakeholders' perspectives and is transparent throughout its duration. Doing so translates the aspirational aspects of an FEP into more feasible, agreed-upon objectives that reflect current urgencies for the GOM's fishery ecosystem and those who depend on it. As an example, a preliminary list of objectives could be drawn from results of previous investigations, like those of Chagaris et al. (2019), although this would require further engagement with additional regional stakeholders to be more reflective of a wide-scale consensus of current high-priority objectives for the US GOM-LME.

Lastly, based on this set of more practical objectives, managers should strive to develop specific operational objectives that are measurable, realistic, and time-restricted (Levin et al. 2014), and that should include target goals that are capable of capturing, preferably quantitatively, the desired status of the GOM fishery system and its components. Thus, it is important to select relevant operational objectives for each key fishery subsystem (i.e., ecological, socioeconomic, cultural, institutional) of the US GOM-LME (Sainsbury et al. 2000).

Step 3.—Step 3 involves selecting a set of performance indicators that include parameters of interest (e.g., fishery revenue, stock abundance, habitat suitability, social well-being) that are sensitive to management actions (Levin et al. 2018), and which will help to assess whether operational objectives have been met. These performance indicators are different from the ecosystem indicators described in Step 1, which are meant to provide general information on the status and trends of key ecological and socioeconomic components of the fishery ecosystem, and are not directly linked to specific operational objectives within the planning process. Subsequently, managers should set reference points as target levels for evaluating performance indicators of, and progress toward, specific operational objectives. In this regard, several studies can provide examples and guidance pertaining to the selection of operational objectives (Tam et al. 2017) or indicators (Kleisner et al. 2015), and the process of developing criteria for measuring performance of EBFM processes (Juan-Jordá et al. 2018).

These reference points should be based on scientific information and be set to meet specific policy outcomes, while bearing in mind that historical indicators, and particularly so for ecological indicators, should not be used as reference points to represent baseline conditions of the fishery system (Levin et al. 2018). Since humans are considered an integral component of the system in an EBFM context, the status of performance indicators should be considered relative to any fishery system that is impacted by anthropogenic activities and pressures, as this can effectively help to evaluate progress toward achieving operational objectives (Levin et al. 2018).

Concluding Step 3 requires the evaluation of alternative management strategies, preferably through a formal management strategy evaluation (MSE) or other simulation-based modeling approach (Harford et al. 2018). The purpose of this step is to evaluate strengths and weaknesses of different options in a way that is robust and transparent, and which supports the trade-off evaluation of different fishery management strategies within the context of the FEP planning effort. The final results will help managers to select a strategy for implementation, which, depending on the case and subsystem at hand, could be a modification of an existing FMP (an EAFM-type approach) or part of the development of a larger EBFM (i.e., FEP-type) adaptive planning strategy.

Step 4.—In Step 4, the overall work from the previous steps is translated into a structured US GOM-FEP with specific groups of activities (i.e., FEP "projects" as defined by Levin et al. 2018) that can be used to achieve the operational objectives related to the most highly-prioritized efforts and processes (identified in Step 2). In turn, these objectives should be reshaped into a work plan for FEP projects, and these projects should be regularly refined by the integration of new information from recursive iterations of the whole process. Thus, required actions include the continuous monitoring and evaluation of performance indicators and management strategies to determine the status of the GOM fishery system and its subsystems, and the efficacy of the US GOM-FEP. To deliver an effective FEP, a key ingredient throughout this entire process is the systematic consideration of trade-offs and adjusting the plan and goals, along with their specific operational objectives, as part of an adaptive management framework (Essington et al. 2016).

Integration of EM Strategies into the GOM Fishery Management Regulatory Framework

Implications for the Development of a US GOM-FEP within Current Fishery Management Schemes.—When considering the development of a US GOM-FEP, though the GMFMC should take the lead to spearhead and complete this process, it is also worth noting that the framework, goals, and initiatives of this planning effort should be consistent with, both in its broader vision and in practical terms, the current national strategies reflected by the IEA program approach that is specifically conceptualized under the EBFM framework.

Since the primary scope of the IEA's framework, programs, applications, and tools is to support the scientific process of creating informed EBFM at the regional level (Levin et al. 2009, Foley et al. 2013, Harvey et al. 2017), it should be reiterated that pertinent IEA objectives are best defined relative to the needs and concerns of the particular ecosystem and its stakeholders, along with its management focus. This implies that, on a case-by-case basis, IEA efforts could also supplement more traditional SS approaches (Levin et al. 2009), and that any EM strategy should inherently consider the multi-scale "real world" characteristics of the fishery resources within the management unit. To develop a pragmatic FEP that is reflective of the specific fisheries issues for the GOM-LME, managers should also consider the realities of those issues at the appropriate spatiotemporal scale. Hence, for some issues, EAFM approaches might be considered more practical in supporting single FMP objectives, whereas EBFM approaches would be more effective at the larger ecosystem-wide scale.

To clarify this important distinction, here we present two specific cases that illustrate approaches, or tools, which can help decision-makers decide how to effectively integrate EM considerations into current fishery management processes within the GOM. These two cases represent applications of EAFM and EBFM frameworks, respectively, that can inform the development of an FEP, or support the modification of existing FMPs in the US GOM-LME.

Case #1: Integrating "Red Tide"-Induced Mortality into Fishery Management Strategies.—This case illustrates the benefits of an EAFM approach, as developed in Harford et al. (2018). In their study, the authors conducted an MSE pertaining to the ongoing fishery and ecosystem management concerns regarding episodic natural mortality events in the GOM that mainly occur in the form of harmful algal blooms (HABs) of the dinoflagellate *Karenia brevis* [also called "red tide" events (RTEs)]. These RTEs represent key ecosystem stressors that may cause mass fish mortality events (known as "fish kills") that can occur from the acute exposure and bioaccumulation of the neurotoxin brevetoxin, or by asphyxiation from associated areas of hypoxic water (Landsberg et al. 2009, Flaherty and Landsberg 2011, Walter III et al. 2015).

While HABs are known to occur throughout the GOM, RTEs occur more regularly along the West Florida Shelf (WFS) and nearby coastal waters (Weisberg et al. 2016). A severe event in 2005, for example, killed an estimated 11,000 metric tons (mt) of red grouper (*Epinephelus morio*); a value that reflected a three-fold increase over the stock's average natural mortality rate (Steidinger 2009, SEDAR 2015). Increased awareness of RTEs since 2005 has led to advancements in the estimation of red tide severity, stock assessment applications, and modeling of trophic interactions (Walter et al. 2013, SEDAR 2015, Grüss et al. 2016). The need for more informed decision-making also became clear in 2014, as another RTE led the GMFMC to temporarily postpone setting catch limits for gag grouper (*Mycteroperca microlepis*) while waiting for additional results of scientific analyses (GMFMC 2015, Driggers et al. 2016). Furthermore, in response to another severe RTE in the fall of 2017 and growing concerns among fishers about the state of the red grouper stock, the GMFMC opted to set catch limits that were lower than the catch advice from the most recent stock assessment conducted in 2015 (SEDAR 2015, GMFMC 2018).

Using the GOM red grouper stock, Harford et al. (2018) performed MSE simulation testing to asses candidate decision-making approaches for modifying catch limits that encompassed the: (1) measurement of red tide severity, (2) analytical assessment of the stock, and (3) subsequent use of stock assessment results in a harvest control rule to adjust catch limits according to prevailing conditions. The MSE approach used in Harford et al. (2018) evaluated the likely effects of different management strategies on a fishery and associated fish stock in achieving pre-agreed upon management objectives (Butterworth and Punt 1999, Smith et al. 1999, Sainsbury et al. 2000, Punt et al. 2016). Hence, this approach aligns with an EAFM strategy in the sense that SS management (i.e., setting catch limits for a single stock) was extended to explicitly consider a key environmental effect on the red grouper's stock and its assessment as well as the effect on any subsequent management decisions.

Case #2: Identifying Relevant Ecosystem-Level Fishery Management Indicators in the GOM.—This case describes a new multivariate-statistical protocol, called the "ecosystem-level management-indicator selection tool" (EL-MIST), which was developed by Kilborn et al. (2018) to explore complex LMEs like the GOM. The EL-MIST approach relies on a constrained analysis to highlight relevant fishery ecosystem dynamics and trade-offs among indicators, and is based on paired data tables that are organized to support the management objectives determined during a focused scoping process (ideally conducted between managers and stakeholders). This approach, which can be considered within the EBFM framework, allows for direct hypothesis testing for any underlying relationships between functional sets of response and predictor indicators used to characterize the fishery ecosystem.

Kilborn et al. (2018) examined the period of 1980–2011 using a total of 79 time series management-indicators drawn from the 2013 GOM-ESR (Karnauskas et al. 2013). Of those, 49 were classified as responses (Y matrix; Online Supplementary Table S1) representing: (1) population status for important upper and lower trophic level species; (2) commercial fishery revenue values; and (3) indices of stock structure and function for (a) fisheries independent monitoring catches, (b) fisheries dependent catches (commercial and recreational), and (c) individual species from various taxa. The remaining 30 indicators were designated as predictors (X matrix; Online Supplementary Table S2), and were selected for their capacity to describe: (1) the local, regional, and basin-scale climatology; (2) total commercial and recreational fisheries extractions; (3) fishing effort for all sectors; (4) the physical-chemical marine environment; and (5) oil industry activity. This data configuration allowed for hypothesis testing for effects of predictors (X) on system-wide responses (Y), and for explaining how X influenced the multivariate organization of Y over time (Kilborn et al. 2018). In plain terms, the GOM-EL-MIST example was designed to support the inquiry of whether the natural physical-chemical environment, changing climatology, and variable anthropogenic exploitation patterns in the GOM fishery ecosystem had any effect on the multispecies organization, health, structure, and function of the LME's resources and related commercial revenue values over time.

The outputs from the GOM-EL-MIST by Kilborn et al. (2018), among other high-level management results, were used to identify five numerically distinct dynamic fisheries regimes in the GOM-LME over the 31-yr study period with respect to the organization of underlying responses. To identify the subset of predictors best suited to describe the variability among the dynamic regime states, the list of 30 predictors was ultimately reduced to the 14 most influential to the GOM fishery resources' organization (Online Supplementary Table S3).

Based on the results, a historical narrative for the LME's dynamic regime trajectory was created from the model. The authors noted a major shift in the system's resource organization between the two stable periods 1987–1994 and 1995–2001 that was punctuated by two intermediate shifts on either side of that major shift between 1994 and 1995 (one between 1986 and 1987, and another between 2002 and 2003; Online Supplementary Table S4). By examining the optimal subset of indicators retained by EL-MIST from X and their relative influences to the model (Online Supplementary Table S3), it was determined that the primary drivers of fisheries resource reorganization in the GOM-LME were very strongly related to total fisheries extractions and efforts across all sectors, along with changes in basin- and regional-scale climatological conditions, and the teleconnected environmental processes associated with them (Kilborn et al. 2018).

Discussion

To our knowledge, this study is the first attempt to synthesize, through the lenses of the EAFM, EBFM, and IEA frameworks, the multifaceted aspects of current EM strategies for fishery resources in the GOM-LME to support ongoing efforts for the delivery of a practical US GOM-FEP that aligns with existing FEPs developed for other US regions.

Historically, the US has performed better than the majority of other countries in terms of EBFM (Pitcher et al. 2009), although the levels of EBFM implementation across US marine fishery regions remains heterogeneous, and particularly so when considering ecosystem trade-offs. Specifically, recent studies suggested that US regions performing better in terms of fishery management success were those for which trade-offs among different fish species, fisheries, and other nonfishing sectors were directly considered (Link and Marshak 2019). This further exposes the existence of systematic inadequacies in the integration of these trade-offs, and linked ecosystem considerations, into management strategies among US marine ecosystems (Link and Marshak 2019).

Given that the assessment of ecosystem trade-offs is critical to the development of an effective FEP (Marshall et al. 2018), their identification should, arguably, be conducted through an open and transparent decision-making process. This process should also allow for quantitative integration and evaluation of multiple ecosystem objectives within the fishery management system, going beyond the traditional SS focus (Hilborn 2011, Vert-pre et al. 2013, Fulton et al. 2014) that emphasizes decision criteria like single-stock reference points and fishery performance measures (Fulton et al. 2005, Chagaris et al. 2019, Link 2018). Appropriate ecosystem-level objectives should include, among other things, the assessment of long-term sustainability for various fisheries, impacts to coastal communities through evaluations based on social indicators for vulnerability and resilience (Jacob et al. 2013, Colburn et al. 2016, Stephenson et al. 2018), and the integration of other pertinent ecosystem processes and links (Brown et al. 2012, Skern-Mauritzen et al. 2016, Fu et al. 2019). Within the US GOM-LME, it will be essential to avoid disconnects between fishery scientists and managers regarding the order and importance of key priorities for advancing EBFM in the region (Chagaris et al. 2019).

In recognition of the multiple anthropogenic (e.g., overfishing, coastal development, habitat loss, accidental oil spills) and natural (e.g., climate change, variability of oceanographic processes) stressors that affect the GOM's coastal and marine ecosystems (Schirripa et al. 2012, Ward and Tunnell 2017), initial steps have been taken to achieve a more holistic understanding of this LME. Furthermore, when compared to other US ecosystems, the GOM still needs better characterizations of its ecosystem processes and functions, and the dynamic interactions between natural and human influences on them within the context of the GOM-LME as a social ecological system (Karnauskas et al. 2015).

Among the various management instruments for advancing EM strategies for fishery resources, MSE, ecosystem assessment, and ESRs are viewed as fundamental scientific tools to deliver IEA processes and products to inform EBFM (Levin et al. 2009, deReynier et al. 2010, Harvey et al. 2017). From this perspective, the IEA framework may also be used to supplement existing SS approaches to expose the presence of conflicting ocean use sectors (Levin et al. 2009, Foley et al., 2013), thereby informing more comprehensive decision-making processes and allowing the delivery of more robust, system-wide ecological outcomes.

Our proposed planning process for the development of a US GOM-FEP further supports the advancement of EM strategies for the GOM-LME's fishery resources in a strategic and flexible way. This process is conceptualized to better represent the reality of federal and regional fishery management needs, but is not prescriptive, given that proper FEP implementation needs to account for the complexity of the multiple stakeholders' missions and goals while prioritizing the needs determined by the GMFMC (Levin et al. 2018). Furthermore, the structure of our proposed US GOM-FEP planning process provides an "action oriented" focus throughout all its steps, as this was recently noted as a necessary facet of an FEP's success (Essington et al. 2016, Levin et al. 2018), and as one of the major deficiencies present in various FEPs developed across the US (Wilkinson and Abrams 2015). Thus, the two case studies presented here include "food for thought" regarding the GOM-FEP's provision of direct links to management actions, and focus on process-oriented objectives to address specific regional needs of the fishery ecosystem.

Contributions to the US GOM-FEP Planning Process from the Two Case Studies Presented.—The EAFM approach of Harford et al. (2018) explored management strategies for an SS stock (i.e., red grouper, currently managed under the Reef Fish FMP by the GMFMC), and contained many of the "ingredients", or actions, described in our proposed US GOM-FEP planning process. Specifically, their approach provided several insights related to appropriately integrating ecosystem considerations for a fishery management issue that, although potentially perceived as localized within the US GOM-LME (i.e., RTE-driven mortality along the WFS and coastal Florida), was also prioritized as an urgent research area for EBFM in general (Chagaris et al. 2019).

Given the likely influence of severe RTEs to reduce the abundance statuses for many economically important species, such as the GOM grouper complex (Karnauskas et al. 2017, Harford et al. 2018), red tide occurrences should be considered potential candidates for inclusion in the list of prominent spatial threats to the GOM fishery ecosystem (Step 1). Additionally, as an indicator carrying information with both biophysical (e.g., by favoring the spreading of hypoxic water conditions and higher mortalities among marine natural resources) and socioeconomic (e.g., by impacting humans health, and fishery and tourism revenues) relevance, the occurrence of RTEs appears to be a strong candidate for further attention from regional scientists and managers as part of their strategic discussions, including their efforts to develop the agreed-upon vision statement for the US GOM-LME (Step 2). Moreover, including RTE considerations could translate management goals into "real" actions by explicitly incorporating them into tactical decision-making for a specific GOM fishery subsystem or management domains (i.e., the WFS, the Reef Fish FMP).

Within this context, the MSE approach by Harford et al. (2018) was able to reveal a key trade-off by comparing a management strategy for red grouper where decision-making dynamically reacts, following severe RTEs, against alternatives based on static decision-making intervals (independent of event occurrences) and the reliance on precautionary catch buffers. This trade-off involved balancing modest gains in catches that could be achieved through reactive catch limit adjustments against the practical impediments to implementing such demanding strategies (e.g., timeliness of red tide detection, accurate observation of severity as a trigger for management intervention, and availability of fiscal resources necessary to conduct stock assessments or other comprehensive analyses). Also, several reef fishes appear susceptible to RTEs, posing an additional management challenge regarding whether affected stocks should be episodically prioritized for assessment at the expense of non-affected stocks (Sagarese et al. 2017).

While Harford et al. (2018) provides a strategic view for moving toward EAFM, their analysis stops short of delivering tactical advice (Step 3). For instance, if a static precautionary catch buffer were identified as a preferable management option as, say, a strategy for the implementation of existing management measures for red grouper within the Reef Fish FMP, it would be necessary to further explore the acceptable range for such a buffer. This would also require examining trade-offs between maintaining low probabilities of falling below biomass thresholds while achieving the highest possible catches.

Alternatively, if the preferred strategy is to be responsive in updating red grouper stock assessments, as a means to measure and adjust to red tide effects on stock status, then strategies could be further defined accordingly, such as implementing a catch buffer that is relative to RTE severity (e.g., magnitude, spatial extent, intensity, and duration), which could be seen as responsive to future RTEs. As a different option, monitoring empirical trends in red tide severity and adjusting catch limits during interim periods between stock assessments could serve as a responsive management strategy that seeks to limit conducting assessments too frequently (e.g., red grouper and gag grouper stock assessments have taken place every 3–6 yrs). Benchmarks for RTE severity could be based on previous events (e.g., 2005's RTE), which could provide some approximation of mortality risk. As a different option, where steadier but less responsive solutions are sought, static buffering of catch limits could work to maintain higher average stock biomasses and, therefore, weather fluctuations in stock size. Accordingly, such an approach would require less frequent interventions by decision-makers. Regardless, there remains other tactical options to consider when responding to the aforementioned issue of RTEs (e.g., adjustments to annual catch limits, temporary spatial closures of areas where red tide observations occurred, reductions in bag limits). Lastly, the effectiveness of any of these approaches in achieving the desired outcomes should be monitored (Step 4) and could be further evaluated using a similar MSE approach to that of Harford et al. (2018).

Over the extent of the whole GOM-LME, the EL-MIST statistical protocol by Kilborn et al. (2018) represents a powerful application within the EBFM framework that can inform multiple actions within the four steps of the proposed US GOM-FEP development process, while also providing key operational support to the IEA framework (Levin et al. 2009) and the EBFM Policy (NMFS 2016a) and Road Map (NMFS 2016b) promoted by NOAA-NMFS. Specifically, the EL-MIST approach provided detailed information about the specific response indicators that best described notable state changes in the organization of the GOM-LME's fishery resources. The work also corroborated findings from the GOM-ESR (Karnauskas et al. 2013) and other GOM-wide studies (Karnauskas et al. 2015) when selecting key ecosystem indicators accounting for the GOM-LME's organizational state changes (Step 1). However, as pointed out by Kilborn et al. (2018), it is worth noting that within the GOM-ESRs, indicators are classified into independent subsets based on the drivers, pressures, states, ecosystem services/impacts, and responses (DPSER) conceptual model (Kelble et al. 2013). This artificial segmentation raises a potential issue where the assumptions of the DPSER framework overlay an inherent hierarchical structure among categories that may not actually exist in the GOM-LME. This hierarchy creates a scenario-analysis based on a simplistic unidirectional chain that is not conducive to sufficiently describing all complex interrelationships across indicators, and among their underlying ecological processes (Niemeijer and De Groot 2008, Tscherning et al. 2012, Gari et al. 2015, Kilborn et al. 2018). The GOM-EL-MIST approach moves beyond these potential shortcomings of the DPSER model by relying on constrained analyses between paired sets of response and predictor indicators. This provides greater flexibility for exploring the broad scope of management priorities, while also allowing for the additional benefit of direct hypothesis testing for relationships between these two sets of relevant ecosystem indicators (Kilborn et al. 2018).

Both conceptually and practically, the EL-MIST approach has other potential benefits that could contribute to the advancement of a GOM-FEP via our proposed planning process. For example, results of the GOM-EL-MIST indicated that, overall, the trajectory of dynamic fisheries regimes states followed a relatively orderly path through time (Online Supplementary Table S4), and comparisons of temporally adjacent pairs of states throughout the study period resulted in quantitative estimates of the direction and magnitude of incremental, qualitative changes to the organization of the GOM-LME. In turn, this information can help to identify key threats to the GOM, or, based on customized iterations of the model, to identify spatial threats for specific fishery subsystems, thereby supporting the development of strategic objectives for these subsystems (Step 2).

Additionally, by virtue of the flexibility of the underlying statistical algorithms, it would be conceivable for the EL-MIST protocol to help in evaluating progress made by specific operational objectives (Step 3) through direct hypothesis testing of a set of performance indicators (i.e., responses) against a set of indicators characterizing changes in management decisions (i.e., predictors). In turn, these alternative configurations of EL-MIST models could support the development of more strategic objectives capable of capturing underlying views of multiple stakeholders and the overall vision of the US GOM-FEP (Step 2). This flexibility makes the EL-MIST approach an ideal instrument for efficiently distilling large amounts of ecosystem-level information into a more digestible format that managers and stakeholders can consider during strategy selection (Step 3) and decision making (Kilborn et al. 2018). Lastly, the EL-MIST approach can be used to support the iterative aspects of implementing and monitoring an FEP in the GOM-LME by describing performance-indicator trends over time (Step 4), and detecting significant reorganizations in the states of specific biophysical and socioeconomic components of GOM subsystems (Step 1).

The EL-MIST approach used in the GOM-LME (Kilborn et al. 2018) is consistent with the recommendation to translate EBFM principles into actions, rather than into a mere system description, and can be used as a guide highlighting direct links to management actions and FEP effectiveness (Wilkinson and Abrams 2015, Essington et al. 2016). Specifically, managers and stakeholders hoping to assimilate the information learned from an EL-MIST model for the GOM management system can begin by choosing the resolution of detail that they wish to consider from the software outputs. Recall that the primary organization of any EL-MIST model is as response and predictor data tables representing the aspects that managers and stakeholders are "interested in" (i.e., responses), and those factors that are hypothesized to affect those "interesting" aspects (i.e., predictors). Therefore, EL-MIST investigates an ecosystem by assessing the following questions, in order of increasing resolution: (1) is there any statistical effect of the predictors on the responses; (2) are there any dynamic regime states with respect to the underlying responses over the study timeframe; (3) how is the LME's state trajectory affected by the set of predictors over time; (4) which response indicators characterize the most notable differences between any two dynamic regime states (and how do the predictors affect that); and (5) for any notable response indicators, how does the direction and magnitude of incremental change differ between relative regime shifts (and compared to any overall study period trends)? Based on the priorities of the management inquiry set during a focused management scoping process, any of the levels described here may be appropriate, but in an EBFM context it would be best to consider no less than the first three.

Lastly, the flexibility of EL-MIST is not restricted to EBFM-related research. Ecosystem-level results could be used to inform single species EAFM efforts by identifying the key covariates that should be considered for model parameterizations, both biotic and abiotic, as well as the relative dynamics between them. In turn, this information can be used to support the implementation of existing FMPs or future FEPs in the US GOM-LME.

Concluding Remarks.—In this study, we provided a multi-level analysis and narrative supporting the integration of ecosystem science and considerations into fisheries management processes and regulatory frameworks within the US GOM-LME. These analyses culminated in a synthesis of ongoing efforts and guidance toward the development of a US GOM-FEP planning process, and they contribute to the discussion regarding a future management plan for fishery resources in the GOM. Although we recognize that the case studies highlighted here are only two among the many potential examples of applications that can help decision makers understand how to achieve specific steps of the proposed planning process, we considered these two cases sufficiently compelling to help navigate through the process within the sphere of EAFM and EBFM frameworks. To overcome the many challenges associated with integrating the EM paradigm into GOM fishery management, continued emphasis on, and refinement of, partnerships between federal and regional managers, fisheries scientists, and key stakeholders are needed. These collaborations will help to serve local needs by providing an informed decision-making process that is transparent and inclusive, and that will support the identification of crucial trade-offs for the fishery ecosystem and its various subsystems. Therefore, it is our hope that the information provided here can contribute to guiding and strengthening those partnerships, thus leading to the advancement of regional efforts to develop an actionable FEP-type management vehicle for the GOM-LME's diverse fisheries resources.

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