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ARTICLE

Recommendations on the Use of Ecosystem Modeling for Informing Ecosystem-Based Fisheries Management and Restoration Outcomes in the Gulf of Mexico

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Abstract
Ecosystem-based fisheries management (EBFM) and ecosystem restoration are gaining momentum worldwide, including in U.S. waters of the Gulf of Mexico (GOM). Ecosystem models are valuable tools for informing EBFM and restoration activities. In this paper, we provide guidance and a roadmap for ecosystem modeling in the GOM region, with an emphasis on model development and use of model products to inform EBFM and the increasing investments in restoration. We propose eight "best practices" for ecosystem modeling efforts, including (1) identification of priority management questions, (2) scenarios as simulation experiments, (3) calibration and validation needs, (4) sensitivity and uncertainty analyses, (5) ensuring transparency, (6) improving communication between ecosystem modelers and the various stakeholders, (7) documentation of modeling efforts, and (8) maintaining the ecosystem models and codes. Fisheries management in the USA adheres to a prescriptive set of calculations. Therefore, the use of ecosystem modeling in EBFM for the GOM will likely be incremental, starting with the incorporation of environmental variables into single-species assessments, the provision of background (stage-setting) information on environmental and food web effects (e.g., the impacts of lionfish *Pterois* spp. invasion), and strategic advice through management strategy evaluation. Management questions related to restoration in the GOM (e.g., the impacts of freshwater and sediment diversions as part of coastal restoration, habitat preservation, and rehabilitation; and measures to mitigate nutrient loading and hypoxia) have more flexibility in how they are addressed and thus are primed for immediate use of ecosystem modeling. The questions related to restoration are appropriate for ecosystem modeling, and data collection at the restoration project level can provide critical information for modeling to then scale up to regional responses. Ecosystem modeling efforts need to be initiated and advanced now in order for the tools to be ready in the near future. Addressing resource management issues and questions will benefit greatly from the proper use of ecosystem modeling.

Ecosystem-based fisheries management (EBFM) and ecosystem restoration are increasingly being used worldwide, including in U.S. waters of the Gulf of Mexico (GOM; Bullock et al. 2011; Suding 2011; Karnauskas et al. 2013; Keith et al. 2013). Ecosystem-based fisheries management takes into account the impacts of biotic and abiotic factors on species dynamics and also considers socioeconomic factors in order to formulate fisheries management strategies and actions (Patrick and Link 2015). Ecosystem restoration is the process of assisting the recovery of damaged, degraded, or destroyed ecosystems (Abelson et al. 2016). Ecosystem simulation models—along with other tools, such as spatially explicit population dynamics models, ecosystem indicators, and environmental risk assessments—are valuable assets for influencing and strengthening EBFM and restoration activities (Fogarty 2013; Rose et al. 2015; Lehuta et al. 2016).

The GOM provides an excellent testbed for EFBM and for a discussion of the availability and adaptability of various ecosystem modeling tools. The GOM provides a diverse set of ecosystem services, including commercial and recreational fisheries, energy (oil and gas) exploration and extraction activities, shipping and transportation, storm protection, essential habitat for many organisms (including special-status species), a cultural basis for coastal communities, and tourism opportunities (NAS 2013). The GOM is also subjected to disturbances and stressors, such as loss of wetland habitat, sea level rise, invasive species, mixed-species and bycatch conflicts, watershed-driven eutrophication and resulting hypoxia, unexpected food web responses, and accidental releases of oil and other contaminants (e.g., the Deepwater Horizon oil spill; Diamond 2004; Karnauskas et al. 2013).

The combination of diverse ecosystem services, multiple stressors, and ramping up of state and federal restoration activities creates a situation where fisheries management can benefit from explicitly accounting for these services and factors, which are typically only indirectly or qualitatively dealt with in single-species management. While the specifics may vary, there are many large-scale ecosystems with services and stressors that overlap those seen in the GOM. Despite this situation, which suggests that EBFM would be beneficial, only limited attempts in the GOM and most applications of EBFM worldwide have been for strategic rather than tactical management advice (Heymans et al. 2016; Skern-Mauritzen et al. 2016). The National Oceanic and Atmospheric Administration (NOAA) recently issued a "road map" for widespread implementation of EBFM in U.S. waters (Link 2016), and a path forward that uses the existing management structure to encourage EBFM for both strategic and tactical advice has been proposed (Essington et al. 2016; Marshall et al., in press).

There are a few specific examples of EBFM-like activities and more examples of ecosystem restoration and enhancement activities already underway in the GOM. The EBFM-related actions in the GOM include turtle excluder devices in the shrimp trawl fishery (Raborn et al. 2012), mitigation of the lionfish *Pterois* spp. invasion with a culling program (McCreedy et al. 2012), and use of the output of ecosystem models to specify the impacts of red tides (harmful algal blooms) on natural mortality in single-species stock assessments of the Gag *Mycteroperca microlepis* and Red Grouper *Epinephelus morio* (SEDAR 2014, 2015). As part of the response to the Deepwater Horizon oil spill, multiple large-scale restoration activities related to seagrass, marsh, wetland, and oyster reef habitats are underway in the GOM and are expected to grow over the next decades (CPRA 2012; NAS 2016). Ecosystem restoration and enhancement in the GOM cover a wide range of other measures, including the creation of artificial reefs for providing additional habitat for marine species (GCRRTF 2011) and freshwater and sediment diversions of river waters to restore natural hydrologic flows and provision land-building for wetlands (CPRA 2012).

There are also many examples of ecosystem models. Usually, these models include multiple species whose dynamics are linked together through food web interactions, and the models explicitly or implicitly account for environmental effects; however, they differ greatly in their biological details (processes included and how they are represented), treatment of spatial variation, and solution time steps and projection length (Plagányi 2007; Espinoza-Tenorio et al. 2012). Some ecosystem models are tailored versions of the same modeling platform (e.g., Ecopath with Ecosim [EwE]; Pauly et al. 2000; Christensen and Walters 2004), while others were uniquely developed for their specific application (e.g., the dynamic model ALFISH for the Florida Everglades; Gaff et al. 2000). Because many of these models include environmental and biological components, they can—with appropriate modifications—be adapted to many specific EBFM and restoration issues. The simplest types of ecosystem model are conceptual (Swannack et al. 2012; Kelble et al. 2013) and qualitative models (e.g., loop analysis; Dambacher et al. 2003; Marzloff et al. 2011), which illustrate qualitative understanding of the linkages between abiotic environmental stressors, ecosystem components, human activities, and management actions. Single-species stock assessment models that explicitly integrate ecosystem considerations (often the effects of other species), also called "extensions of single-species assessment models" (ESAMs), represent the simplest form of quantitative ecosystem models (Hollowed et al. 2000). At the other end of complexity are the highly complex ecosystem models, such as applications of the EwE modeling platform and implementations of the three-dimensional, biogeochemical-based and food web Atlantis modeling framework (Fulton et al. 2007, 2011). Implementations of EwE and Atlantis often represent a very large number of species or functional groups in an attempt to capture the full dynamics of the upper-trophic-level food web. Both modeling frameworks have the capability to simulate changes in both the benthic (e.g., the percentage of marsh) and aquatic (e.g., sea surface temperature and salinity) habitat of marine organisms (Fulton et al. 2007; De Mutsert et al. 2015, 2016b; Lewis et al. 2016).

In this paper, we provide some recommendations to advance the use of ecosystem modeling for informing EBFM and restoration activities, with a specific focus on the GOM. Coastal Louisiana has been the focus of an ongoing large-scale restoration effort (CPRA 2012), and with the funding resulting from the Deepwater Horizon oil spill, restoration activities will accelerate GOM-wide (GCERTF 2011; NRC 2014; NOAA 2015). Our recommendations result from a workshop entitled "Aligning Ecosystem Modeling Efforts with Ecosystem-Based Fisheries Management and Restoration Needs in the Gulf of Mexico," which took place in Tampa, Florida, during August 2016. The workshop included ecosystem modelers, scientists from federal and state resource management agencies, fishing industry representatives, and representatives from nongovernmental organizations. Its purpose was to assess the state of ecosystem modeling in the GOM region and identify opportunities and obstacles for using ecosystem models to help advance EBFM and inform ecosystem restoration. We summarize the resulting recommendations, address the obstacles, and briefly describe pressing questions that would benefit from ecosystem modeling in the GOM. Our recommendations and opportunities likely also apply to many other marine and coastal systems.

Our goal is to provide recommendations and suggestions to ensure effective use of ecosystem models for EBFM and for evaluating restoration in the GOM. The structure, mechanics, and operation of available ecosystem models have been previously reviewed (Plagányi 2007; FAO 2008; Fulton 2010; Espinoza-Tenorio et al. 2012). Here, we first offer several suggestions for the immediate path forward to encourage ecosystem modeling for EBFM and restoration evaluation in the GOM. We then provide eight suggested "best practices" for using ecosystem models that apply to the GOM and elsewhere. Best practices have been previously recommended for using ecological models to assess ecosystem restoration (Rose et al. 2015), complex system models aiming to inform fisheries management in Europe (Lehuta et al. 2016), improving the effectiveness and relevance of ecological modeling in resource management (Addison et al. 2013), selecting models for EBFM (FAO 2008), reviewing end-to-end ecosystem models for management applications (Kaplan and Marshall 2016), documenting ecological modeling efforts (Schmolke et al. 2010), and communicating complex ecological models to users and stakeholders (Cartwright et al. 2016). Our recommendations are based on these earlier descriptions of best practices, with a specific focus on ecosystem modeling for EBFM and restoration in the GOM. After detailing the eight suggested best practices, we identify priority management questions in the GOM region to address with ecosystem models during the coming years. Finally, we describe critical future needs for ecosystem models of the GOM that will repeatedly arise in many situations.

STREAMLINING THE USE OF ECOSYSTEM MODELS

The use of specific ecosystem models for informing EBFM and restoration activities should be dictated by the management question(s) that need to be addressed. This includes how the predictions will be used and interpreted by the end users (e.g., resource managers). The results of ecosystem models can have conceptual, strategic, or tactical roles in resource management (FAO 2008; Collie et al. 2016). Depending on the situation, ecosystem models may be more useful as conceptual models for communication, as strategic analyses to inform resource managers about the broad impacts of management measures (e.g., long-term yields that consider food web interactions; see PFMC and NMFS 2015; Chagaris et al. 2015b; Grüss et al. 2016c), or as a means of delivering tactical advice (e.g., proposing harvest quotas over a 2–3-year window; see examples in Holsman et al. 2016, NPFMC 2016, and Punt et al. 2016b). To date, there have been relatively few examples of ecosystem modeling being used for tactical fisheries management advice or broad-scale ecosystem restoration. Two notable exceptions are the use of multiple, coupled models for evaluating complicated, multi-action restoration in coastal Louisiana (CPRA 2012; De Mutsert et al. 2015) and the Florida Everglades (DeAngelis et al. 1998). Given the wide diversity of ecosystem models and EBFM and restoration questions, we offer several suggestions to focus the immediate path forward in (i.e., streamline) ecosystem modeling for the GOM to encourage its use.

First, we recommend more formal use of conceptual and qualitative models in the early phase of all ecosystem modeling efforts. The use of conceptual models is relatively common, but these models often lack documentation and usually do not evolve with the ecosystem modeling phases. Conceptual and qualitative models are valuable for their ability to formalize and reconcile the knowledge of scientists, resource managers, and other stakeholders regarding the structure and function of the marine ecosystem and the impacts that stressors and management measures have on these ecosystems. These models can be used directly to influence and strengthen specific EBFM and restoration outcomes; alternatively, they can represent a robust first step toward the design of quantitative ecosystem models for informing resource management (FAO 2008; Swannack et al. 2012; Hyder et al. 2015; Rose et al. 2015; Cartwright et al. 2016). It is recommended that any quantitative ecosystem modeling effort aiming to inform EBFM or restoration should include a scoping workshop with diverse participation to ensure that all views about the knowledge of the system and phrasing of the management questions are represented. Subsequent workshops should be spaced so that major progress in the model development and implementation are demonstrated and vetted with the participants (Addison et al. 2013). Conceptual and qualitative models provide a mechanism for capturing divergent and convergent views of the system and continuity for communicating the development of the model and interpretation of the results.

Second, we recommend that investigations of tactical fisheries management questions be conducted with ecosystem models that can truly generate tactical advice. Most ecosystem models are not yet to a maturity stage where they can be sufficiently validated for the purpose of short-term forecasts of absolute quantities, such as species-specific biomasses. Furthermore, tactical advice often requires that the model output be on a finer resolution than is generated by most ecosystem modeling efforts. For example, participants in some fisheries are greatly affected by the number of days that they are allowed to spend at sea; such detailed temporal resolution is typically beyond the capabilities of ecosystem models that use aggregate outputs, such as total annual fishing effort or identification of target fishing mortality levels.

Highly complex ecosystem models, such as EwE or Atlantis applications, are at present generally better geared toward investigating a wide range of strategic management questions (e.g., the broad impacts of harvest quotas). These models are useful for considering issues that simpler models cannot (fully) address, particularly those issues that involve multiple components of the food web, fishing fleet interactions, environmental interactions, and the effects of biogeochemical (bottom-up) and predation (top-down) drivers. Example applications well suited to these models are investigations on predator–prey dynamics, abiotic environmental drivers of stock productivity, regime shifts, and climate change effects (Plagányi 2007; Espinoza-Tenorio et al. 2012; Arreguín-Sánchez et al. 2015). Highly complex ecosystem models provide a basis for avoiding (or at least anticipating) surprises and unintended consequences of management actions (e.g., by providing insights into how species not intentionally targeted by management efforts will respond to alternative management actions; Walters et al. 2008, 2010) and for ensuring robust designs and implementation of restoration actions.

We agree with other authors (e.g., Trites et al. 1999; Plagányi 2007; Christensen and Walters 2011) who have suggested that highly complex ecosystem models should be used to complement conventional research and management tools (e.g., field surveys and single-species assessment models) rather than being viewed as replacements; that is, ecosystem modeling should be viewed as an evolution rather than as a revolution. When outputs of highly complex ecosystem models are carefully chosen, they can be used to reduce uncertainty in single-species stock assessments. For example, some highly complex ecosystem models are able to deliver strategic insights into the potential impacts of stock rebuilding plans under different ecosystem conditions (i.e., under different futures; e.g., Chagaris et al. 2015b). Some highly complex ecosystem models have been used to provide parameters for single-species assessment models (e.g., estimates of age- and time-varying natural mortality rates; Chagaris and Mahmoudi 2013; Grüss et al. 2015, 2016c; Sagarese et al. 2015b). In the case of evaluating the effects of restoration activities, ecosystem models can deliver insight into determining the combined effects of multiple projects at the population and food web levels, which is helpful to the decision-making process even in the absence of reporting absolute biomasses and abundances (e.g., De Mutsert et al. 2015). At a minimum, ecosystem models can provide valuable information to the ecosystem consideration section of stock assessment reports and fisheries management plans (e.g., SEDAR 2015) and can help to put restoration actions into a broader ecological context.

An area where ecosystem models could be used immediately for resource management is management strategy evaluation (MSE), a framework that is designed to simulate alternative management strategies and to determine (1) how well those strategies balance management objectives and (2) whether the strategies are robust to uncertainties (Smith et al. 1999; Holland 2010; Punt et al. 2016a). An MSE can consider all components of a given ecological–human coupled system, including the biological, monitoring, assessment, management, and implementation aspects (Holland 2010; Bunnefeld et al. 2011). Within an MSE framework, the biological subsystem is simulated by an "operating model," the role of which can be filled by an ecosystem model (Dichmont et al. 2013; Fulton et al. 2014; Grüss et al. 2016b). The MSE approach is gaining increasing traction around the world because of increasingly complex management situations (Holland 2010; Punt et al. 2016a).

Conducting an MSE-like analysis using ESAMs to address strategic or tactical issues is well within reach. The ESAM used should be constructed and parameterized so that several specific issues can be addressed, and it should include stakeholder input prior to and during the modeling efforts. Such analyses would demonstrate the utility of the MSE approach and could provide a soft entrance of the GOM community into ESAMs and their use within an MSE-style approach. Some of the parameters of these ESAMs could be estimated by highly complex ecosystem models (Chagaris and Mahmoudi 2013; Sagarese et al. 2015b).

In the longer term, highly complex ecosystem models (e.g., EwE or Atlantis applications) can serve as operating models within an MSE framework to address a wide range of strategic management questions. Management strategy evaluation frameworks using highly complex ecosystem models have the potential to explore not only the response of a selected few species to management actions but also the more general questions involving the fish community and performance of management actions under anticipated possible future conditions. Such broad analyses can also be used to evaluate the potential value to management (e.g., reduced uncertainty) of initiating new sampling programs or expanding existing sampling programs (Sainsbury et al. 2000; Holland 2010; Harford and Babcock 2016).

There is currently an unprecedented opportunity for using ecosystem modeling in planning and evaluating restoration activities in the GOM. Major restoration activities are being initiated, and quantitative tools, such as ecosystem models, are needed for evaluating the performance of different restoration practices and for assessing cumulative effects (NAS 2016). We suggest initiation of a project in the GOM that will focus on a few case studies involving well-studied areas comprising candidate sites for future restoration. The modeling should start now—and has started in areas such as Louisiana, where new freshwater and sediment diversions and habitat restoration efforts are planned (CPRA 2017)—and pre- and postconstruction data can be obtained that will strengthen the modeling efforts.

BEST PRACTICES

We suggest eight best practices for ecosystem modeling efforts aiming to inform EBFM and restoration activities: (1) identifying priority management questions; (2) scenarios as simulation experiments; (3) enhancing the calibration and validation processes of ecosystem models; (4) conducting sensitivity and uncertainty analyses with ecosystem models; (5) ensuring transparency; (6) improving communication between ecosystem modelers and stock assessment scientists, empiricists, managers, resource users, or other stakeholders; (7) documenting ecosystem modeling efforts; and (8) maintaining ecosystem models and codes. These best practices have been proposed, along with other practices, in various forms before, and we highlight them briefly here. They do not constitute a comprehensive set of best practices, and readers are referred to FAO (2008), Schmolke et al. (2010), Addison et al. (2013), Rose et al. (2015), Cartwright et al. (2016), Kaplan and Marshall (2016), and others for a full set of best practices (Table 1). The eight best practices highlighted

TABLE 1. Publications and reports providing complementary insights into the best practices for ecosystem modeling elaborated in this paper and other best practices.

Best practices	Publications and reports
Identifying priority management questions	Rose et al. 2015
Scenarios as simulation experiments	Peck 2004; Rose et al. 2015
Enhancing calibration and validation	Grimm et al. 2005; FAO 2008; Swannack et al. 2012; Steele et al. 2013; Rose et al. 2015; Lehuta et al. 2016
Conducting sensitivity and uncertainty analyses	Saltelli et al. 2004; Plagányi 2007; Rose et al. 2015
Ensuring transparency	Hyder et al. 2015; Rose et al. 2015; Kaplan and Marshall 2016; Lehuta et al. 2016
Improving communication	Espinoza-Tenorio et al. 2012; Rose 2012; Swannack et al. 2012; Addison et al. 2013; Rose et al. 2015; Cartwright et al. 2016
Documenting ecosystem modeling efforts	Schmolke et al. 2010; Grimm et al. 2014; Rose et al. 2015; Cartwright et al. 2016
Maintaining ecosystem models and codes	Kettenring et al. 2006; Swannack et al. 2012; Rose et al. 2015; Peck et al., in press
Making ecosystem models iterative and adaptive tools	Espinoza-Tenorio et al. 2012; Swannack et al. 2012; Rose et al. 2015; Peck et al., in press
Using a multimodel approach to have more confidence in the predictions of ecosystem models and in supporting specific management measures	Plagányi 2007; FAO 2008; Fulton 2010; Espinoza-Tenorio et al. 2012; Peck et al., in press

here were selected because they are especially pertinent to the current situation (i.e., model availability, questions, and stakeholder skepticisms) in the GOM. We determined that addressing these with special care and diligence is critically important for ecosystem models to be further incorporated into EBFM and restoration assessments in the GOM.

1. Identifying Priority Management Questions

There are many uncertainties and issues related to EBFM and ecosystem restoration; thus, there are many questions that can be addressed. Furthermore, EBFM and restoration are in a relatively immature state in the great majority of the world's marine regions (Pitcher et al. 2009; Suding 2011; Leslie et al. 2015). Therefore, before starting new management-focused ecosystem modeling efforts in a marine region, priority management questions should be identified. These questions can be grouped under general issues, but the questions eventually must attain the level of detail that permits clear testing by using a modeling approach. The more specific the questions, the more likely a model can be selected (or developed) and simulations performed that provide answers to the questions. Vaguely stated questions lead to models and simulations that will not be optimally designed to answer the questions, and they also lead to confusion among the modelers, resource managers, and other stakeholders about how to interpret the model results in light of the management decisions. An example of a poorly stated question is "What are the effects of the restoration action on fish?" This is an overarching topic but not a readily testable or answerable question. A better-stated question is "What is the average change in the long-term (20 years postimplementation) population abundance of species A and B within the area influenced by the project (local) and the entire estuary as a result of adding the 48.6 hectares (120 acres) of new marsh?" As part of framing the questions, modelers should establish direct connections with resource management agencies to ensure that ecosystem modeling products are applicable and delivered in a timely manner for management actions.

2. Scenarios as Simulation Experiments

Once specific questions are defined, the next steps are selecting or developing appropriate models and determining how the inputs to the models can be manipulated to generate the information needed to answer each question. Model selection is a complicated process that involves determining the biological (e.g., population or community), temporal (seasonal, annual, or multigenerational), and spatial (e.g., single box or two-dimensional grid) resolution needed and then assessing how existing models provide starting points or whether new models must be developed. Rose et al. (2015) provide detailed steps and examples for the model selection phase.

Determining how to conduct the simulations to address the questions should be considered much like performing an experiment (Peck 2004). Stating the factors (treatments) and their levels, the design, and how the predictions will be compared enables the presentation of clear answers. An issue that arises with designing model experiments or scenarios is that all factors of interest do not have to actually appear as parameters or forcing variables in the model in order to be included in the analysis. The changes in factors that are varied as part of scenarios can be represented explicitly or implicitly in the model. Explicit representations typically mean that a variable or factor is named in the model description and that its effects within the model appear in model equations. One simply changes the values as part of the model experiments. However, factors to be varied can also be incorporated using implicit representations. Implicit representations occur when the effect of a factor is imbedded within the formulation of the model, and the factor may not appear on any list of variables or parameters or even anywhere in the model equations. For example, a question may require that fish growth rates be varied in response to the restoration of marsh habitat, but growth is only a function of temperature in the model. Restored habitat is expected to enable enhanced food availability and reduced predation risk, leading to more time for foraging. One can then assume or estimate how the growth rate (and perhaps the mortality rate due to reduced predation) will change for those individuals in the restored habitat and impose these changes in the simulated growth and mortality rates directly. In fact, if done correctly, explicit and implicit representations will confer the same results. Explicit representations are also not as obvious as they appear because the realism of changes depends on how and the range of values over which the representation in the model is considered valid (i.e., just because the variable is named does not mean that all changes to it are valid). Implicit representations do not preclude assessing the effects of a factor that is not explicitly represented, but they require external information on how to change the inputs that are represented in the model.

Ecosystem model predictions can be divided into two types based on how their predictions are viewed. Some questions require predictions in native units, such as annual population abundance, while many other questions can be better addressed with relative predictions. With relative predictions, the model predictions are compared to a simulated baseline condition, and results are expressed as changes from the simulated baseline. These relative predictions are very useful with long-term simulations (future conditions become increasingly uncertain) because the assumptions of future conditions are maintained in both the baseline and scenario simulations; therefore, the differences can still be attributed to the treatment (e.g., restored or not restored). Although absolute predictions are very tempting because they directly relate to what happens in nature and because the model output is labeled with native units, we generally have much more confidence in relative (model-to-model) predictions. However, determining the baseline requires careful consideration of historical conditions combined with likely future conditions (Higgs et al. 2014).

3. Enhancing Calibration and Validation

The calibration and validation processes of ecosystem models are critical for assessing the appropriate level of confidence to associate with the model predictions (FAO 2008; Swannack et al. 2012; Rose et al. 2015). To facilitate their consideration in resource management, ecosystem models should ideally be calibrated to time series data and show that their predictions are in phase with observations (Christensen and Walters 2011). Additionally, to truly enhance the calibration process of ecosystem models, performance metrics that are specific to ecosystem models should be developed and agreed upon so that the goodness of fit of predictions to the observations can be objectively quantified.

Validation is a necessary next step after calibration (Steele et al. 2013; Rose et al. 2015). The most straightforward approach to validation is the comparison of trends or patterns predicted by the ecosystem model to independent data that are not employed for calibration (Latour et al. 2003; Grimm et al. 2005; Rose et al. 2015; Lehuta et al. 2016). Such predicted versus observed comparisons should be augmented with the reporting of diagnostics. Typically, diagnostic checking involves checking whether biomasses, productivity, spatial distributions of key variables, and metrics of system-level energetics are consistent with theoretical expectations (e.g., the PREBAL diagnostics of Link 2010 for network models such as Ecopath) and with general values reported for the system of interest and from other comparable systems.

The calibration and validation results need to be assessed to determine the domain of applicability of the model. Ecosystem models have many assumptions, some of which are not obvious without detailed examination of model equations. A major hidden assumption is about the range of input values over which certain process relationships are valid. The range of conditions encompassed by information used to define the model (e.g., conditions represented in the data used for calibration and validation) defines the model's domain of applicability. The domain of applicability is the range over which the conditions in the model can be changed (e.g., driving variables and parameter values) while still permitting the user to remain confident of the model's realism. The conditions entailed in simulations performed as part of scenarios and model experiments should be assessed as to how well they fall within the model's domain of applicability.

4. Conducting Sensitivity and Uncertainty Analyses

Ideally, the calibration and validation processes of ecosystem models should be complemented by sensitivity and uncertainty analyses to obtain a thorough understanding of the behavior and uncertainties of the model. Sensitivity analyses consist of varying selected input parameters by a small value to evaluate the response of the model within a small region in the parameter spaces centered on the calibration and validation conditions (Saltelli et al. 2004). The idea is to gain knowledge about which inputs (often process parameters) cause large responses in the model (Collie et al. 2016; Peck et al., in press). Sensitivity analyses allow one to determine whether the ecosystem model under consideration produces robust results. In uncertainty analysis, the small changes in inputs are replaced with realistic variability in the inputs; model predictions are then viewed as—and often interpreted as—demonstrating the variability the predictions would show in nature (Saltelli et al. 2008; Saltelli and Annoni 2010; Rose et al. 2015). Proper implementation of uncertainty analysis requires specification of realistic uncertainty (reflecting ignorance) and stochasticity (natural variability; Ferson and Ginzburg 1996). Saltelli et al. (2004) noted that it is rare for an uncertainty analysis to correctly generate realistic variability comparable to that of the observational data, yet we often interpret the variability of predictions as what is expected in nature. When uncertainty analysis is performed, the manner in which the variability in predictions was generated should be clearly documented so that model results can be properly interpreted.

5. Ensuring Transparency

The transparency of ecosystem models should be increased to allow stock assessment scientists, empiricists, other modelers, and stakeholders to properly understand the models and to be well aware of the models' strengths and limitations (Hyder et al. 2015; Rose et al. 2015). Mechanisms encouraging documentation of ecosystem models should be developed (Kaplan and Marshall 2016; Lehuta et al. 2016). For example, a process called Southeast Data, Assessment, and Review (SEDAR) ensures the transparency of single-species stock assessment models for the GOM region. Many years and stock assessments were required before the methods and interpretation of results for single-species assessment became sufficiently standardized and effectively communicated. Ecosystem models will need a similar process, which becomes even more important because there is no standard ecosystem modeling assessment and review process. Without a sufficient understanding of the ecosystem modeling, such modeling analyses are often viewed with healthy skepticism that can evolve into distrust. A thorough review process of ecosystem models by stock assessment scientists, empiricists, and stakeholders should be supplemented with a more rigorous peer review process for the ecosystem models themselves.

6. Improving Communication

A key component to transparency is effective communication. With the rising demands for EBFM and the initiation of large-scale ecosystem restoration efforts, the time is ripe for a concerted effort to increase the use of ecosystem modeling. Ecosystem modelers should be encouraged to be included in resource management and restoration planning meetings and to present their work during these meetings. For instance, ecosystem modelers in the GOM region should increase their participation in the Gulf of Mexico Fishery Management Council's (GMFMC) meetings, in GMFMC Scientific and Statistical Committee meetings, and in the restoration planning that is underway by federal and state agencies. Management strategy evaluation analyses and incorporation of ecosystem considerations into single-species assessment should be initiated that involve modelers, other scientists, resource managers, and other stakeholders to ensure that the objectives and performance metrics of the process are appropriately defined, implemented, and interpreted (Holland 2010; Plagányi et al. 2014; Punt et al. 2016a). Louisiana uses ecosystem models for its Comprehensive Master Plan for a Sustainable Coast (CPRA 2012, 2017). Ecosystem modeling should—and likely will—play a role in restoration planning and assessment throughout the GOM. The use of conceptual and qualitative models (e.g., conceptual diagrams and loop analysis) as well as the creation of dedicated user-friendly web applications can facilitate the communication of ecosystem modeling efforts from the very beginning of these efforts (Espinoza-Tenorio et al. 2012; Swannack et al. 2012; Colléter et al. 2015; Rose et al. 2015; Cartwright et al. 2016).

Conceptual and qualitative models can serve to integrate the knowledge of stakeholders about how the ecosystem functions and perceptions about the effects of stressors and management actions on these ecosystems. Therefore, the development of quantitative ecosystem models based on conceptual and qualitative models ensures that the quantitative ecosystem models will capture the important features of the ecosystem of interest while also being effectively communicated to stakeholders (Swannack et al. 2012; Rose et al. 2015). User-friendly web applications are web services that allow stakeholders to visualize and interact with models, thereby providing them with a more concrete understanding of the functioning, strengths, limitations, and potential utility of the models (Cartwright et al. 2016).

7. Documenting Ecosystem Modeling Efforts

Proper documentation of ecosystem models is critical to facilitating the review and communication of the modeling as well as to inform future ecosystem modeling endeavors. In particular, there is a need to compile a comprehensive inventory of the assumptions, parameters, functional relationships, and data sets used by ecosystem models and to clearly define their domain of applicability so that the different ecosystem models can be evaluated for new, specific questions and the investment into existing models can be leveraged (Grimm et al. 2014; Rose et al. 2015). Documentation of data inputs should include descriptions of any data processes, cleaning, or summarization that was conducted to develop the model inputs. Documentation of model assumptions should include the changes to inputs made in the calibration phase and any settings in the model software that influence model dynamics. The model's domain of applicability should be described, and the uncertainties around ecosystem modeling predictions (quantified, for example, through uncertainty analyses) should also be properly documented (Cartwright et al. 2016). Schemes for model documentation have been proposed (e.g., Schmolke et al. 2010), and a modeling community effort is needed to standardize documentation across modeling efforts.

8. Maintaining Ecosystem Models and Codes

The construction, parameterization, calibration, validation, and testing of ecosystem models require considerable effort. Ecosystem models are designed to tackle specific research or management questions, but they also represent a large investment; therefore, future application to other issues is likely and should be anticipated as much as possible. It is critical to (1) maintain ecosystem models and codes in a manner that ensures availability to others and (2) use an archival-retrieval system that allows for regular updates (Swannack et al. 2012; Rose et al. 2015; Peck et al., in press). Approaches for archiving and sharing models and codes have been discussed (Kettenring et al. 2006), and examples of the implementation of model archives outside of ecosystem modeling are available (e.g., Nativi et al. 2013; Rollins et al. 2014).

PRIORITY MANAGEMENT QUESTIONS TO ADDRESS WITH ECOSYSTEM MODELS IN THE GULF OF MEXICO

Here, we provide a brief list of areas that appear ripe for ecosystem modeling and that can contribute to EBFM and restoration activities in the GOM. This list is not comprehensive but rather illustrates the many topics for which the questions would benefit from ecosystem modeling and for which the data are minimally sufficient. Examples of topics include EBFM issues, such as the effects of habitat and environmental influences on fish recruitment, strategic MSE-integrating ecosystem considerations, and efforts to mitigate the lionfish invasion.

A question ready to be addressed with ecosystem models is how restoring the seagrass beds of the West Florida Shelf would improve the status of the Gag stock in the GOM. The Gag is a species of high economic importance; it forms large, transient spawning aggregations on the edge of the West Florida Shelf, and its larvae primarily settle in seagrass beds of the region (Coleman et al. 1996; Koenig and Coleman 2012; Switzer et al. 2015). The Gag stock of the GOM has been overfished until very recently, and its reproductive population is still at a low level (NOAA Fisheries 2016). Modeling can provide information on how additional seagrass habitat within the West Florida Shelf can lead to more settlement habitat for Gag larvae, which would improve Gag recruitment. Important questions include the responses to feasible improvements in seagrass habitats compared to other measures that are designed to increase reproductive success (e.g., spawning-aggregation-based marine protected areas).

Consideration of environmental influences on fish recruitment to improve stock assessments and derive management recommendations is a priority EBFM issue in the GOM. Although not incorporated within the base model and instead tested as a sensitivity analysis, recent stock assessments for the Gag, Red Grouper, and Red Snapper *Lutjanus campechanus* considered the inclusion of an index of recruitment anomalies due to oceanographic conditions to reduce uncertainty in recent recruitment estimates (SEDAR 2013, 2014, 2015; Sagarese et al. 2015a). For example, the index of recruitment anomalies due to oceanographic factors incorporated into the stock assessment model for the Gag explained around 33% of the variation in the stock–recruitment deviates from the stock assessment model (Grüss et al. 2014). The management of many GOM stocks would benefit from the consideration of environmental influences on their recruitment. A good example is the floating sargassum (*Sargassum* spp.) habitat that affects early life stage survival of Gray Triggerfish *Balistes capriscus* (Wells and Rooker 2004). The Gray Triggerfish is currently overfished (NOAA Fisheries 2016), while sargassum biomass is believed to have decreased in recent years (Powers et al. 2013).

As mentioned earlier, MSE is increasing in popularity in the GOM region. The NOAA Fisheries recently released a large GOM Regional Action Plan (GMRAP) following the approach presented in the NOAA Fisheries Climate Science Strategy (Link et al. 2015), which defines actions to meet climate science needs for the GOM (Lovett et al. 2016). The GMRAP will call for, among other things, MSE studies to assess the effectiveness of harvest control rules during anticipated future conditions under climate change. The ecosystem models employed for such MSE studies could be (1) ESAMs representing the effects of climate changes on the natural mortality rates of specific species and/or (2) highly complex ecosystem models if one assumes that climatic changes have an impact on vital rates other than natural mortality rates (i.e., growth, reproduction, or movement rates).

The mitigation of the lionfish invasion is another priority EBFM issue in the GOM that is ready for ecosystem modeling. Efforts to mitigate the invasion of lionfish in the GOM include a culling program, small-scale derbies throughout the GOM, and an “Eat Lionfish Campaign” encouraging the consumption of lionfish as environmentally friendly seafood (McCreedy et al. 2012; Johnston et al. 2015). To date, only one ecosystem model has addressed the issue of lionfish invasion in the GOM (Chagaris et al. 2015a). That model, which uses the EwE modeling platform, focuses on the potential impacts of actions to mitigate lionfish invasion on the West Florida Shelf. An ecosystem model investigating the effects of measures to tackle the issue of lionfish invasion is under development for the north-central GOM; however, additional work is needed in other areas of the GOM (e.g., the western GOM and the Florida Keys).

The topics for restoration are less well defined than EBFM topics because fewer examples of large-scale restoration exist and many details of the restoration efforts (outside of coastal Louisiana) are not yet specified. Candidate topics include the impacts of freshwater and sediment diversions, following up on the current applications of Ecospace (De Mutsert et al. 2016a) and CASM (Dynamic Solutions 2016), and the many projects that target restoration of natural (e.g., seagrass, oyster reef, marsh, and wetland) habitats. Numerous restoration projects in the GOM are ongoing or planned (e.g., GCERTF 2011; Walker et al. 2012; NRC 2014), and ecosystem models have the potential to provide valuable information for many of these projects. Modeling can be used to better understand the reasons for success (and failure) of specific restoration actions and as a way to combine the effects of multiple restoration actions into broader-scale (e.g., regional) responses. For example, modeling can be used to estimate the role of adding new marsh in affecting local abundances and then combine the local effects of multiple restoration actions into how the suite of local changes can influence regional dynamics, which are also influenced by other environmental factors.

FUTURE ECOSYSTEM MODELING NEEDS IN THE GULF OF MEXICO

Many of the EBFM and restoration questions overlap to some degree and share some common features that can be addressed via enhanced ecosystem models of the GOM. While any model would need to be evaluated in light of the specific questions to address, we perceive that these features will repeatedly arise as needs in many situations; the details would then be tailored to the specific situation. The features are (1) better accounting of forage fish; (2) explicit representation of habitat effects; (3) the capability of capturing future conditions under climate change; (4) the ability to simulate the cumulative impacts of multiple management measures; and (5) the capacity to include or inform socioeconomic considerations.

Better Accounting of Forage Fish

Forage fish (namely small pelagic fishes of the family Clupeidae and Carangidae) constitute a critical component in many coastal systems because they transfer energy from plankton to commercially and recreationally important upper-trophic-level species and, in some cases, are also harvested themselves (Pikitch et al. 2014). Forage fish are also the primary source of food for many fish species, seabirds, and marine mammals (Ahrenholz 1991). However, the precise role of forage fish in GOM ecosystems and how management measures that are focused on forage fish and their predators combine to affect forage fish community composition and ecosystem dynamics have often not been adequately represented in ecosystem modeling studies (but see De Mutsert et al. 2015; Robinson et al. 2015; Geers et al. 2016). The environmental and biological controls on forage fish dynamics are complicated by their position in the middle of the food web (Engelhard et al. 2014). Ecosystem models that permit the emergence of bottom-up, top-down, and wasp-waist controls (Cury et al. 2000; Bakun 2006; Field et al. 2006) and that include realistic age structure and density dependence of predator populations (Walters et al. 2016) are vital for accurate projections of forage fish dynamics (Cury et al. 2008). Therefore, future ecosystem modeling efforts for the GOM should pay more attention to the trophic interactions involving forage fish, the influence of the abiotic environment on forage fish population dynamics, and the impacts of fishing and EBFM and restoration measures on forage fish.

Explicit Representation of Habitat Effects

Environmental variation greatly influences fish recruitment (Pitchford et al. 2005; Houde 2008), and many of the proposed restoration actions are focused on improving habitat (NAS 2016). Although habitat effects are reflected in many models via how growth, mortality, and reproduction are represented, the effects of habitat are often implicit in these representations. Moving the effects of habitat from implicit to explicit representations will facilitate the use of ecosystem models to assess questions that involve habitat changes. Such representations of habitat effects remain challenging because of data limitations that link specific attributes of habitats with process rates (e.g., Johnson et al. 2013). Future ecosystem models aiming to inform habitat restoration projects should be able to simulate changes in the location, quality, and effects of pelagic and benthic habitats through time with sufficient detail to allow for comparison of alternative combinations of habitat changes. Roth et al. (2008) used an individual-based model to simulate how fine-scale variation in marsh habitat would affect production of brown shrimp *Farfantepenaeus aztecus* in the northwestern GOM. At a larger scale, Ecospace was modified to include a “habitat capacity submodel” to explicitly represent how vegetative (wetland) habitat would affect food web dynamics in the Louisiana coastal zone and in Barataria Bay, Louisiana (De Mutsert et al. 2015, 2016a; Lewis et al. 2016). Further development of habitat effects within ecosystem models of the GOM is needed.

The inclusion of water quality (pelagic) aspects of habitat changes into ecosystem models is also an area ripe for advancement. The effects of red tides on natural mortality were taken into consideration in recent stock assessment models of the Gag and Red Grouper, and they improved the fits of the stock assessment models to the data (SEDAR 2014, 2015). Ecosystem models have been used to assess whether and how changes in salinity due to large-scale river diversions (i.e., as part of restoration of wetlands) would affect fish and shellfish (CPRA 2012; De Mutsert et al. 2012, 2015, 2016a). Plans to limit nutrient loadings from the Mississippi River watershed to reduce hypoxia in the coastal zone (Mississippi River/GOM Watershed Nutrient Task Force 2015) call for the production of quantitative relationships between nutrients, hypoxia, and fish responses (De Mutsert et al. 2016b). Some basic development and testing of how to accurately couple ecosystem models to the hydrodynamic and biogeochemical models that are already available for the GOM (e.g., de Rada et al. 2009; Fennel et al. 2011; Zheng and Weisberg 2012; Justić and Wang 2014; Le Hénaff and Kourafalou 2016) are required to address many of the questions related to pelagic habitat effects on fish and fisheries.

Capability to Capture Future Conditions under Climate Change

Climate change is an overarching factor that has not yet been addressed by most ecosystem models of the GOM. As mentioned earlier, NOAA Fisheries recently released the GMRAP, which calls for the consideration of climate change impacts in ecosystem models and for MSE studies to assess the effectiveness of harvest control rules during anticipated future conditions under climate change. Therefore, ecosystem model development that can capture likely changes in future conditions should begin now. Such changes might include changes in species vital rates, shifts in species distribution patterns, changes to primary productivity, and habitat degradation. Most of the EBFM and restoration actions involve model projections decades into the future; thus, scenarios will need to include a range of possible future conditions (e.g., Intergovernmental Panel on Climate Change scenarios; IPCC et al. 2014) as part of analyses.

Ability to Simulate Cumulative Impacts

The definition of EBFM provided by Patrick and Link (2015) states that EBFM aims to "specifically address competing objectives and cumulative impacts to optimize the yields of all fisheries in an ecosystem." Similarly, a major role of ecosystem modeling in restoration applications is to determine the combined effects of multiple actions (NAS 2016). Future ecosystem modeling efforts for the GOM will need to have the capability to deal with multiple management actions singularly and simultaneously, and the features needed for such capabilities should be considered at the onset of model development.

Capacity to Include or Inform Socioeconomic Considerations

Ecosystem modelers are being increasingly asked to include socioeconomic drivers in their models and to devise models that generate outputs relating to socioeconomic outcomes (Thébaud et al. 2014). Examples include submodels of fishing fleet dynamics (e.g., Ward and Sutinen 1994; Saul and Die 2016) and the use of model outputs to inform ecosystem-service-related variables as part of integrated ecosystem assessments (Levin et al. 2009; Schirripa et al. 2012). The modeling community must become coordinated to ensure a coherent response to the increasing calls for socioeconomic considerations in ecosystem modeling.

CONCLUSION

We have provided advice and a roadmap for ecosystem modeling into the future for the GOM, with an emphasis on model development and the use of model products to inform EBFM and the increasing investments in restoration. We proposed eight best practices for ecosystem modeling efforts, including identification of priority management questions, calibration and validation needs, and how the scenarios can be evaluated and the results communicated. Fisheries management in practice adheres to a prescriptive set of calculations; therefore, the use of ecosystem modeling in EBFM will likely be incremental, starting with the incorporation of environmental variables into single-species assessments, the provision of background (stage-setting) information on environmental and food web effects (e.g., lionfish invasion), and strategic advice through MSE analyses. Management questions related to restoration, such as the impacts of freshwater and sediment diversions, habitat restoration, and measures to mitigate nutrient loading and hypoxia, have more flexibility in how they are addressed and thus are primed for immediate use of ecosystem modeling. The questions related to restoration are appropriate for ecosystem modeling, and the initiation of data collection at the restoration project level as projects are implemented can provide critical information.

It is important to emphasize that ecosystem models rely heavily on various types of data for their formulation, calibration, validation, and use in scenario analyses. Therefore, the quality of the predictions made by ecosystem models depends largely on the quality of the available data. For this reason, improving the collection and compilation of critical data for ecosystem models, such as diet compositions and distribution maps, is critical to ensure that the predictions provided by ecosystem modelers to resource managers are sufficiently reliable to inform decision-making (Grüss et al. 2016a; Tarnecki et al. 2016).

We hope that the recommendations and discussion in this paper provide useful guidance to ecosystem modeling efforts aiming to inform EBFM and restoration projects in the GOM and in other marine and coastal regions. Ecosystem modeling efforts need to be initiated and advanced now so that the tools will be ready in the near future. Addressing the issues and questions will benefit greatly from the proper use of ecosystem modeling.

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