Moving Toward an Oyster Modeling Framework for the Gulf of Mexico: Informing Gulf-Wide Oyster Restoration

Final Report from Oyster Modeling Workshop
Gulf of Mexico Conference in Baton Rouge, Louisiana on April 25, 2022

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Executive Summary

Eastern oysters (*Crassostrea virginica; hereafter referred to as 'oysters'*) are an ecologically and economically important species distributed throughout the Gulf of Mexico (GoM). Oysters provide various ecosystem services that benefit the environment and organisms around them. For example, oysters enhance fisheries production by providing structure and habitat, and filter the water and sequester nutrients to improve water quality (Grabowski and Peterson 2007, La Peyre et al. 2019). Oysters are threatened due to human activities, such as overfishing and water pollution, and climate change which can alter where suitable habitat is for oysters and may disproportionately affect the younger larval stages, reducing settlement success (Cole et al. 2016). While oyster populations have been declining for decades, in recent years many populations have collapsed and are currently not harvestable (e.g., Apalachicola Bay, Pensacola Bay, and Mississippi Sound) (Camp et al. 2015, Snabes 2021, Radabaugh et al. 2022). Current efforts to address this decline and regain associated ecosystem services provided by thriving oyster populations involve numerous single-reef restoration efforts across the GoM. However, as understanding of oyster reef connectivity grows, restoration efforts seek to identify ways to restore reef networks that provide increased resiliency and sustainability of oyster populations (DWH NRDA 2017, LDWF 2022). One of the suggested ways to inform these efforts is to use modeling approaches (e.g., habitat suitability indices). A recent study recommended the development of a single platform for these models that would allow for more efficient access to these tools by decision-makers focused on Gulf-wide restoration (La Peyre et al. 2021). However, there is frequently a disconnect related to desired model outputs and ease of model use between scientists and natural resource managers that limits success towards sustainable natural resources (van der Molen et al. 2015, Wiesenburg et al. 2021). Workshops or other formal gatherings are needed to bring both scientists and managers together to better inform resource management. This report presents findings from a virtual workshop, organized by The Pew Charitable Trusts as part of the Gulf of Mexico Conference 2022 in Baton Rouge, LA (April 2022), that brought together restoration practitioners, modelers, resource agency managers, and other invested oyster professionals to discuss how to best maximize modeling efficiencies, reduce the disconnect between how models are developed by scientists and used/accessed by natural resource managers, and advance towards a single modeling framework to guide Gulf-wide oyster habitat restoration.

The April 2022 workshop was sought to build off identified needs and recommendations from La Peyre et al. (2021) and bring interested parties together to discuss availability, application, and priority needs of models across the GoM. Participants were asked to respond to pre-identified polling questions developed by a project team comprised of individuals involved in the development of the La Peyre et al. (2021) modeling report and other experts working in the GoM to advance oyster habitat restoration.

Facilitated discussions were held to gain insight into participant's opinions and thoughts on how oyster modeling in the GoM can begin to move towards a realized modeling framework to restore GoM oyster habitat. Outputs of this workshop highlighted the importance of co-production when developing modeling frameworks that decision-makers will use. For example, when managers identify a clear restoration goal, models can be developed to address those specific objective(s), resulting in more useful and meaningful model outputs. At the same time, participants also indicated that relevant models can often be hard to access or are not easily transferable across systems, and that streamlining model availability would be highly useful to managers.

Ultimately, this 4-hour workshop did not result in a consensus on how to achieve a single platform framework; however, conversations identified information (i.e., data, model validation and calibration, estuary-specific data, developed management questions) needed before a single platform framework can be realized and applied to large-scale restoration. Participants suggested that the next steps should be developing realistic restoration goals (e.g., achievable oyster abundances under a changing climate) and developing an oyster modeling Community of Practice to continue co-production discussion between modelers and managers. A dedicated working group may be ideal to further the discussion and develop strategies to achieve the cross-state collaboration needed to make a Gulf-wide oyster modeling framework a reality.

Workshop Recommendations

- Build models to inform specific restoration objectives (co-production with modelers and natural resource managers)
- Apply lessons learned from other regions including inclusion of future conditions as model drivers to assess potential climate change implications on oyster habitat restoration
- Have a singular organization to coordinate modeling efforts across the GoM, including developing standardized metrics and spatiotemporal scales for data collection
- Develop an open-sourced platform with training opportunities to streamline model availability and usability for natural resource managers

Introduction

Eastern oysters (*Crassostrea virginica; hereafter referred to as 'oysters'*) are an ecologically and economically important species along the U.S. Atlantic and Gulf of Mexico (GoM) coasts. Oysters are widely distributed throughout most estuaries along the GoM (Figure 1; Shepard et al. 2018). Oysters are unique in that they both support a fishery through direct harvest, and also provide habitat for fish and invertebrates (Humphries and La Peyre 2015). Commercial oyster landings in 2020 in the GoM generated $59 million (NOAA Fisheries 2022). Oysters construct complex reef structures that provide nursery and foraging habitat for important fish and invertebrate species, protect and stabilize shorelines from storms and wave action, sequester nutrients, and filter waters (Grabowski and Peterson 2007, La Peyre et al. 2019). These ecosystem services that oysters provide are valued between $5,500-$99,000 per hectare per year (Grabowski et al. 2012). Due to decades of overfishing, poor management, water quality declines, oil spills, and changes in salinity regimes, oysters worldwide are declining (Reece et al. 2018). In fact, wild oyster populations in the GoM have been on a long-term decline since the mid-1990s, and 80-90% of oyster habitat has been lost in the last century (Figure 2; Beck et al. 2011, Tunnell 2017, Murawski et al. 2021, NASEM 2021). In recent years, wild harvest of GoM oysters has declined further as evidenced by the Apalachicola Bay oyster fishery, which used to be the one of most productive oyster fisheries in the GoM, but was closed to all harvest in 2020 (possibly until 2025) to minimize human pressures and give oysters a chance to recover (Radabaugh et al. 2021). Similarly, many of the major oyster harvest areas in Texas were closed to commercial harvest during most of the 2021-22 fishing season and the start of the 2022-23 fishing season due to low abundances (Watkins 2022, TPWD 2022). Thus, there is a need to restore oyster populations to bring back critical ecosystem services lost and enhance the resiliency of coastal areas.

The northern GoM is identified as one of the remaining places where oyster habitat restoration may be successful in bringing back oyster populations because oysters in this region are not functionally extinct (Beck et al. 2011). To effectively restore oyster populations across the GoM, creation of large-scale restoration through a network of reefs across the GoM has been identified as a need (DWH NRDA 2017). Currently, most restoration efforts are individual projects with varying levels of success (Kennedy et al. 2011, Brooke and Alfasso 2022). Pensacola Bay is the first GoM estuary that has an estuary-scale oyster restoration plan that can be used as a model for other Gulf estuaries (Birch et al. 2021). A similar effort is underway in Apalachicola Bay (ABSI COB 2021) and the Mississippi Sound (MDMR 2022). To move towards these larger restoration efforts, restoration planning is imperative to ensure oysters will once again be at harvestable levels and provide their many additional ecosystem services.

Modeling can be a useful tool to inform oyster habitat restoration and site selection. Practitioners along the Atlantic coast have used modeling tools to inform the site selection of an interconnected oyster reef network (Puckett et al. 2018, Theuerkauf et al. 2019). Site selection is a critical component of oyster habitat restoration as reefs are sensitive to environmental factors such as salinity, dissolved oxygen, and water temperature (Coen and Luckenbach 2000), which should be considered during the planning stages of oyster habitat restoration. La Peyre et al. (2021) compiled an inventory of existing models that can be used to guide oyster habitat restoration planning along the GoM and highlighted the need for a single modeling platform (i.e., a model repository that natural resource managers can easily use) that houses existing models to be used for select approaches (i.e., shell budget, fisheries production, filtration services, etc.). This platform would house standardized variables that comprise the models (e.g., environmental data, oyster life cycle data, etc.) and procedures to apply to each individual estuary. However, for a single platform to be useful, estuary-specific oyster and environmental data are needed. Thus, before a single platform can come to fruition, more collaboration, standardized data collection, and validation and calibration of models is needed.

In working towards a single platform, next steps are needed to identify 1) the models that restoration practitioners use to inform site selection and potential restoration success, 2) necessary data that inform these models and their ease of access, and 3) useability and accessibility of these models to restoration practitioners and managers. This report was prepared following a workshop to gather insight into how to make existing models and their associated data more readily usable by managers and restoration practitioners to inform oyster habitat restoration along the GoM. The workshop, attended by natural resource agencies, academia, modelers, and practitioners, was organized by The Pew Charitable Trusts, at the Gulf of Mexico Conference 2022 (Baton Rouge, LA) to seek consensus on or identify what the data needs are to streamline models and associated model outputs for use in restoration approaches by natural resource managers, what the challenges are for filling those data needs, and how to overcome those challenges to maximize modeling efficiencies and possibly move towards developing a single modeling platform for the GoM to inform oyster habitat restoration planning and oyster management.

Oyster Restoration Goals

- Oyster population and harvest enhancement
- Fisheries enhancement (species other than oysters) through habitat creation
- Shoreline protection and stabilization
- Water quality improvements

While specific restoration goals were not stated during the workshop discussion, the above lists common goals associated with oyster restoration and management

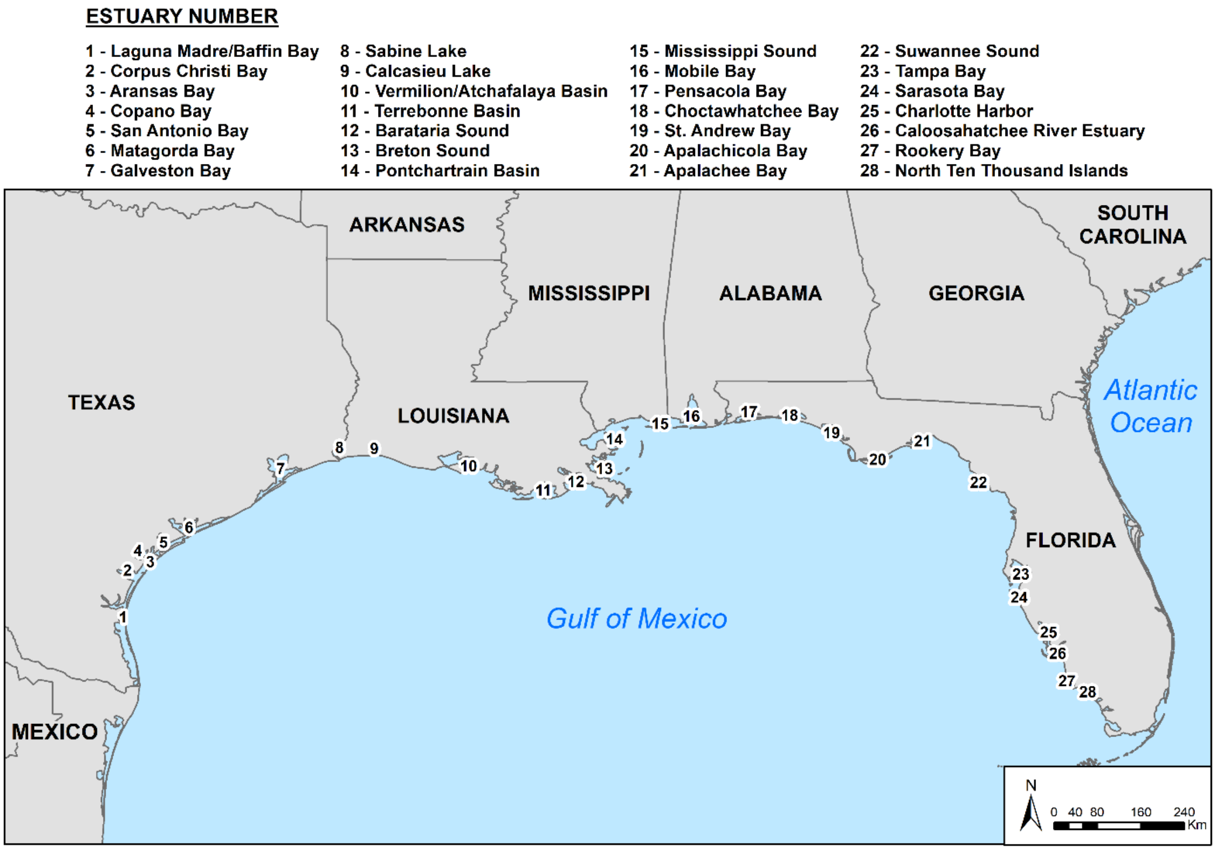

Figure 1. *Estuaries within the northern Gulf of Mexico that have known oyster populations (Gulf of Mexico Open Data Platform, Oyster CoP Map: https://gmod-portal-gomalliance.hub.arcgis.com/)*

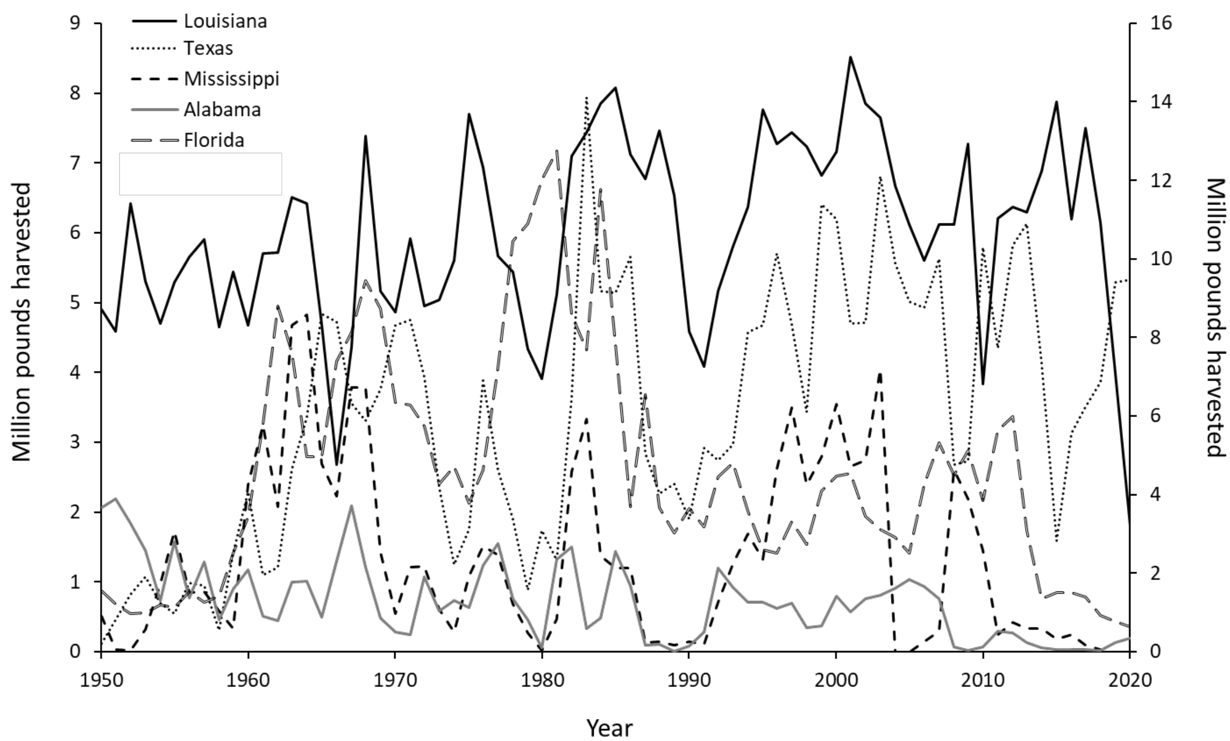

***Figure 2**. Commercial oyster harvests in million pounds of meat harvested per year for each Gulf of Mexico state: Louisiana (solid black line), Texas (dotted black line), Mississippi (dashed black line), Alabama (solid grey line), Florida (longer-dashed black line). Data from NOAA Fisheries 2022.*

Workshop Objectives

- To discuss various modeling uses/needs for enhancing oyster habitat restoration in the GoM.
- To discuss barriers and challenges associated with using and applying those models to enhance oyster habitat restoration in the GoM.
- To discuss options and the feasibility of streamlining model use to inform oyster habitat restoration in the GoM.

Methods

Workshop Format

The 2022 Gulf of Mexico Conference (Baton Rouge, LA) was selected as the venue where modelers, managers, and others working across the GoM could meet to discuss and further these issues. Due to the COVID-19 pandemic, the 4-hour workshop was hosted virtually during the conference. Workshop organizers included Pew staff, the authors of this report, and a small steering committee that included the two primary authors of La Peyre et al. (2021), a modeler, resource manager, and restoration practitioner. Participants were initially selected from the organizing and steering committees' network with the intent of having oyster modelers, researchers, managers, and restoration experts from across the GoM represented. Additional participants were selected based on recommendations from the original invitees. The workshop invite list was limited to 30-40 people with a balanced representation of modelers and practitioners to keep the workshop a manageable size for facilitation of interactive activities and meaningful discussion. Prior to the workshop, participants received the goals, objectives, and general workshop format to prepare for the workshop. Participants were notified prior to and during the workshop that their participation and feedback would be anonymous, and the proceeding would be recorded solely for drafting this report.

MURAL (https://www.mural.co/), an online interactive software program, was used as a virtual whiteboard platform to get workshop participant input on 3 topics related to advancing modeling to inform oyster habitat restoration in the GoM (Appendix 1). Using MURAL enabled participants to add their own 'sticky notes' to relay feedback, vote on those notes, and add other ideas for the group to the board. Voting sessions were held to rank ideas and recommendations, such as next steps. For example, participants voted on what model outputs were most useful to inform restoration and the top 5 outputs were discussed more in depth in the next section. Some sections had pre-filled 'sticky notes' to ensure topics from the La Peyre et al. (2021) report were discussed and to minimize time spent in each section. Participants were able to add notes in addition to the pre-filled 'sticky notes' and group discussions were held where needed to delete pre-filled 'sticky notes' that the group did not find relevant. Some participant 'sticky note' responses from the MURAL board have been reworded for clarity throughout this report. The questions that were asked of the workgroup are listed below:

Questions Asked

Q1) What are the critical data needed to inform oyster habitat restoration in the GoM?

A) What model outputs are the most important to inform oyster habitat restoration in the GoM?

B) What models exist for the desired model outputs and how accessible are those models to managers?

Q2) What are the barriers or challenges to achieve the model outputs needed to inform oyster habitat restoration in the GoM?

A) What are some recommendations on how to overcome these barriers or challenges to achieve the model outputs needed to inform oyster habitat restoration in the GoM?

B) What aspects of modeling approaches need to be streamlined or consolidated to inform oyster habitat restoration objectives in the GoM?

C) How can models be more readily accessible to managers?

Q3) What are the key recommendations and needed next steps to advance modeling to inform oyster habitat restoration in the GoM?

Results and Discussion

Participant Distribution

The workshop was attended by 33 participants. Most attendees were government, mainly state and federal. Other attendees had academic, non-governmental organization (NGO), or other (e.g., consulting) affiliations (Figure 3). This workshop report represents the opinions and views of a subset of researchers, government, NGOs, and managers working on oyster habitat restoration across the GoM. While it is hoped that this broadly captures the consensus of these groups across the GoM, this smaller subset of input may not be fully comprehensive.

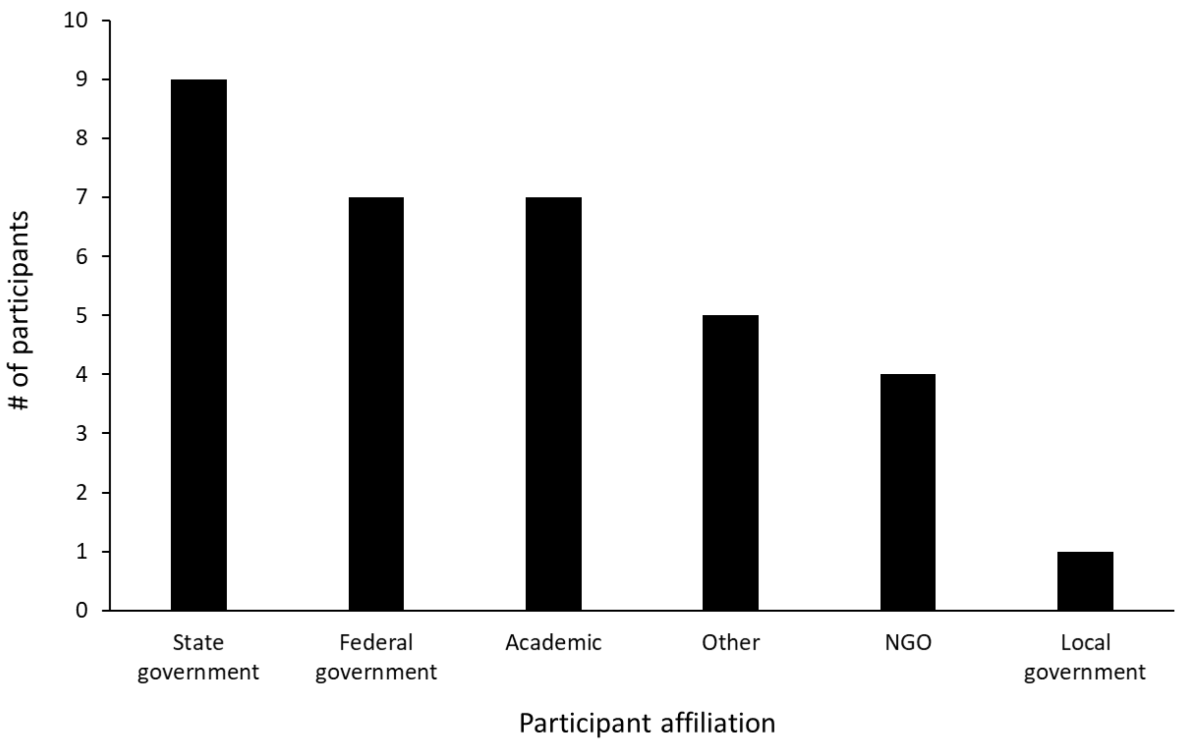

Figure 3 *Distribution of workshop attendees. NGO = nongovernmental organization. Other = consulting firms, private industry, and agencies.*

Participant Responses

The following section highlights the questions asked during the workshop and a summary of participant discussion on those issues.

Q1. What are the critical data needed to inform oyster habitat restoration in the GoM?

Q1 – part a: What model outputs are the most important to inform oyster habitat restoration in the GoM?

Model outputs will vary in applicability to managers and those implementing restoration efforts across the GoM due to variations in model scope, scale, timeline, and/or location. Participants noted models that provide outputs relative to larval settlement success (fraction of larvae settled), demographic rates (i.e., growth, mortality, and survival), and information about suitable oyster habitat (e.g., suitable salinity and substrate) as outputs are most important for informing oyster habitat restoration (Figure 4). An output that was deemed desirable but less available to managers in the GoM is the inclusion of how future environmental predictions will influence oyster populations. In particular, outputs that predict how oysters respond to future salinity conditions influenced by climate change (sea level rise, flooding events, prolonged droughts, intensified storm events, freshwater diversions) will be needed to assess the success of long-term oyster habitat restoration (Lipcius et al. 2015, Wang et al. 2017). Additionally, models do not include long-term climate patterns such as the El Niño Southern Oscillation and Pacific Decadal Oscillation, which may be needed to understand how a restoration project will persist under such conditions.

Q1, part b: What models exist for the desired model outputs and how accessible are those models to managers?

As identified by participants, various existing models can produce the needed model outputs to inform oyster habitat restoration (Table 1; model outputs with top 5 vote count shown). Greater than 15 models were identified by participants; most of the models were identified as being somewhat or readily available to managers, while a few were not available to managers (Figure 5). It was pointed out during discussion that while many of these models are available to managers, they are not in open-access software, or they are not necessarily easy for managers to use without proper training. To make models more accessible and usable for managers, participants wanted to see open-source software options with training and/or workshop opportunities available.

Participants determined that the most readily available models for managers to use are habitat suitability index (HSI) models (Table 1). HSI models are diverse, simplified approaches that relate the oyster life cycle with environmental variables to define areas within an estuary that are suitable for oysters. While HSI models are also the most widely used modeling approach for planning oyster habitat restoration in the GoM (La Peyre et al. 2021), some were considered to be outdated by participants (Table 1). Furthermore, discussion indicated that data on future conditions of environmental variables (e.g., salinity, temperature, dissolved oxygen) under a changing climate are not available for the region to input into HSI models to assess the effects of climate change on oyster habitat restoration. Thus, while HSI models were indicated to be the most readily accessible model for managers, participants indicated that other modeling approaches, if made readily available and usable, would be valuable to include in oyster habitat restoration planning. These other modeling approaches include coupled biophysical oyster larval models, dynamic energy budget models, surface-area recruitment models, and others (Table 1).

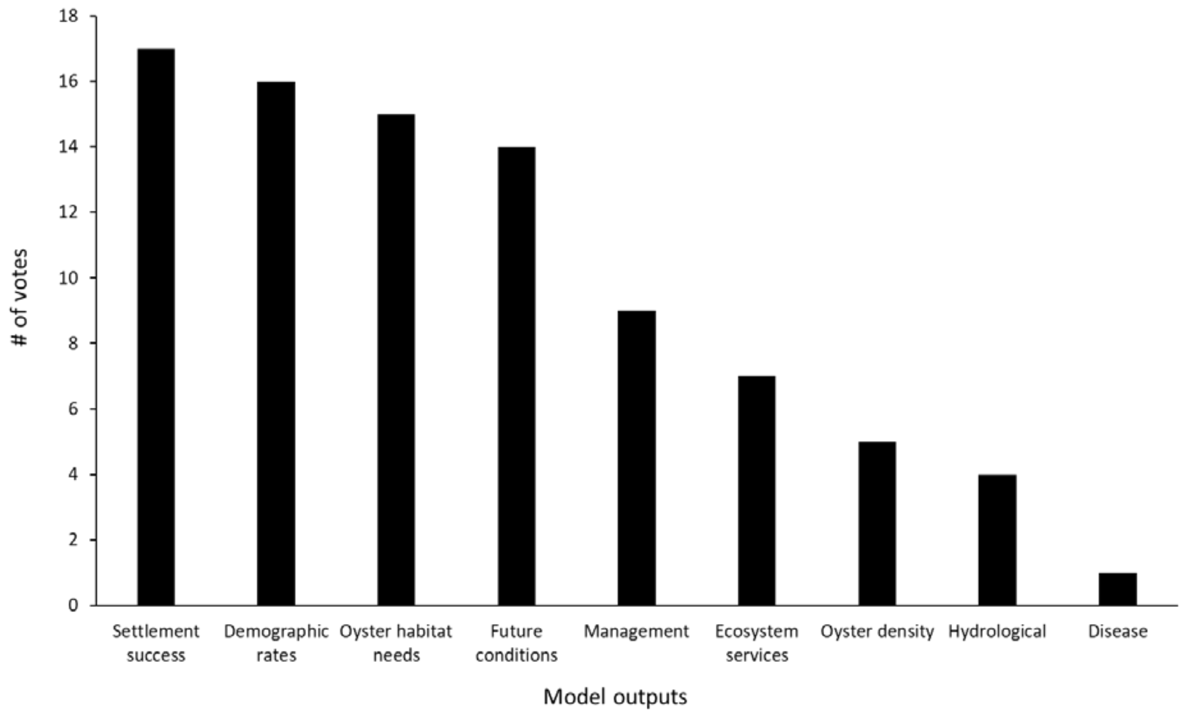

***Figure 4**. Workshop participants were asked to identify and vote on what outputs from models are needed to inform oyster habitat restoration in the Gulf of Mexico. Settlement success = understanding what fraction of larvae settle to an area; Demographic rates = growth, mortality, survival, fecundity metrics; Oyster habitat needs = includes information on environmental conditions needed to support oyster populations; Future conditions = understanding how climate change will affect oyster populations; Management = effect of harvesting on oyster populations; Ecosystem services = the economic and environmental benefits that oysters provide; Oyster density = density of oysters in an area; Hydrological = fine-scale hydrological trends, including changes in freshwater patterns, and circulation patterns affecting larval dispersal; Disease = disease prevalence and intensity on oyster populations.*

Table 1*. For the top 5 voted on most important model outputs needed to inform oyster habitat restoration, workshop participants were asked to identify specific models or types of models that can provide those outputs. * = participants considered these models to be outdated. Maxent = maximum entropy modeling; US EPA = U.S. Environmental Protection Agency.*

Model output	Type of models that can provide the model output
Settlement success	Coupled hydrodynamic oyster larval models
	Dekshenieks larval model (Dekshenieks et al. 1993, 1996, 1997)
	Maxent models
Demographic rates	Dynamic energy budget models
	Metapopulation models
	Surface-area recruitment model (Hemeon et al. 2020)
	US EPA AQUATOX 3.2
Oyster habitat needs	Geometric mean models
	Presence/absence models
	Individual based model
	Dekshenieks et al. 1993, 1996, 1997/Hofmann et al. 1992, 1994/Powell et al. 1992, 1996, 1997 models*
Future conditions	Habitat suitability indices
	Dynamic energy budget model/Reef individual based model
Management	Reef/population model coupling dynamic energy budget model, hydrodynamics, and population structure (Yurek et al. 2021)
	Surface-area recruitment-based reference point model (Solinger et al. 2022)
	Shell budget models (Soniat et al. 2012, 2014)
	US EPA AQUATOX 3.2

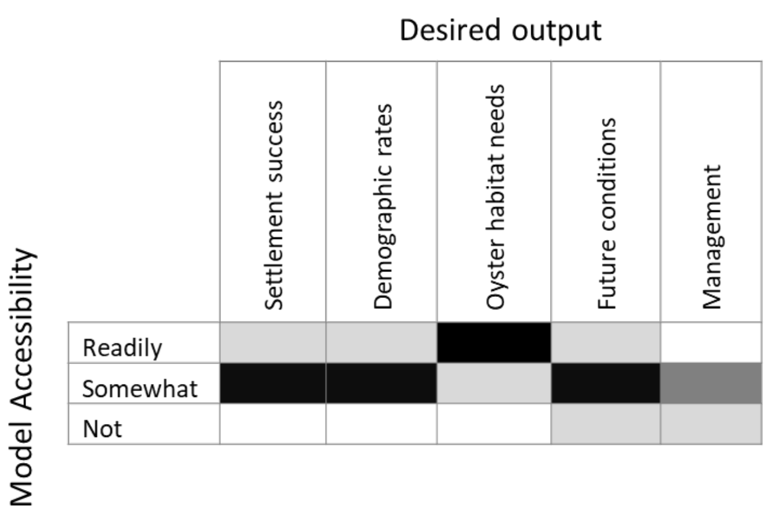

Figure 5. *Participants were asked how readily available and/or accessible the types of models (Table 1) are that achieve the top 5 desired model outputs to inform oyster habitat restoration for managers and restoration practitioners to utilize. Color gradient indicates how many votes each group of models received on their accessibility: white = 0; light grey = 1-5 votes; dark grey = 6-10 votes; black = 11-15 votes.*

Q2. What are the barriers or challenges to achieve the model outputs needed to inform oyster habitat restoration in the GoM?

To improve the use and applicability of models to inform oyster habitat restoration, workshop participants were asked to identify common challenges and barriers when using models and the associated outputs the models provide. For the top five desired model outputs, participants were asked to identify challenges associated with achieving those outputs (Figure 6).

Q2, part a: What are some recommendations on how to overcome these barriers or challenges to achieve the model outputs needed to inform oyster habitat restoration in the GoM?

Data availability consistently ranked as one of the greatest barriers to achieving high quality, management-relevant model outputs. Recommendations to overcome lack of available data were to allocate more funding to projects and monitoring programs across the GoM (Table 2). Participants noted that there is a need for more studies at individual estuary scales because each GoM estuary is vastly different (Bianchi et al. 1998), and more data is needed over longer time periods and larger spatial scales to better capture spatiotemporal variation in these systems. For example, each GoM state handles long-term monitoring differently, with varying spatiotemporal scales measured (La Peyre et al. 2014, Baggett et al. 2015). Most monitoring programs have funding to monitor once annually, which participants noted was not an adequate timeframe to sample oyster populations. Enhanced monitoring efforts and projects were discussed as ways to gather more baseline data (e.g., larval abundance, settlement, recruitment, growth, etc.) that are missing for many of the estuaries and are critical for use in these models.

Model validation was identified as another top barrier in using models to inform restoration. Participants noted the need for funding opportunities to support field validation of model results and acquiring better data is needed to improve overall model outputs. Discussion also centered around the need to include forward-predicting models in the GoM to account for the effects of climate change. It was viewed that models used in the GoM do not incorporate climate change information, which is a disservice for restoration efforts in the Gulf that will likely experience the effects of climate change during the proposed lifetime of a restoration project. It was noted that the Gulf region needs to take lessons learned, models, and frameworks from the mid-Atlantic (particularly Delaware Bay studies; :https://hsrl.rutgers.edu/OysterMonitoring/index.htm) and apply those to the Gulf.

Model complexity was another barrier identified to effectively use models to inform habitat restoration. Participants agreed that a solution to this is to provide trainings, workshops, and/or better metadata associated with the models to make them more usable and less complex for managers to use. A note was added by participants to "combine model approaches to limit the complexity of one approach" (Table 2), with the suggestion that combing model types will make it easier for resource managers to use the model and associated outputs to inform restoration. This raised the concern of the other participants that combining approaches may make the model outputs less accurate and thus less useful for informing restoration objectives. Thus, a better solution identified by participants was more model-manager training to ensure that these models are used.

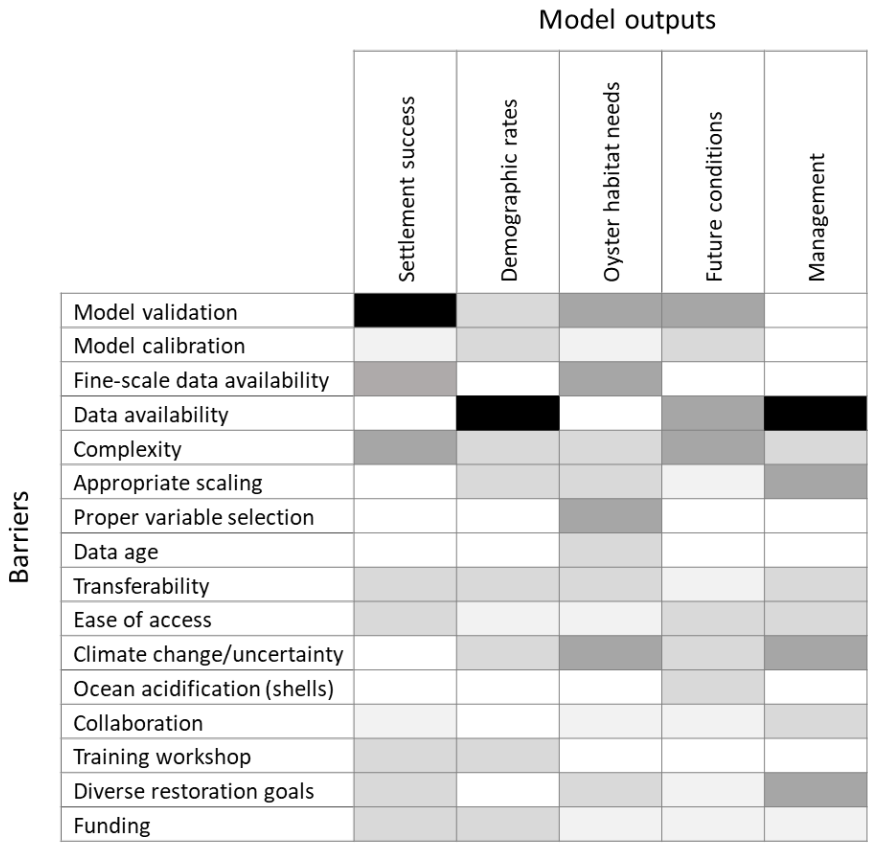

Figure 6*. Results of participant votes on what they viewed as challenges or barriers in achieving the model outputs needed to inform oyster habitat restoration in the Gulf of Mexico. The top five voted on model outputs (settlement success, demographic rates, oyster habitat needs, future conditions, and management) from Figure 4 that were considered necessary to inform habitat restoration were discussed in terms of the challenges associated with developing the model outputs. Color gradient indicates how many votes each barrier received: white = not voted on; light grey = 0 votes; medium grey = 1-5 votes; dark grey = 6-10 votes; black = 11-15 votes. Model validation = validation of results in situ; Model calibration = are the data going into the models adequate enough to provide real-world results; Fine-scale data availability = data availability for fine spatial and temporal scales; data availability = broad data availability; Complexity = are the models too complex for managers to use; Appropriate scaling = are available data on the scale needed to address restoration; Proper variable selection = variables selected to be put into the models need to appropriate for the restoration question; Data age = there is a need for updated data; Transferability = how transferable are the data and outputs to other estuaries in the Gulf of Mexico; Ease of access = how easy it is for managers to access the data; Climate change/uncertainty = data are needed for future scenarios; Ocean acidification = need data for the effects of ocean acidification on oysters in the Gulf of Mexico; Collaboration = organizations and individuals working across the Gulf of Mexico to develop better model outputs; Training workshop = need for trainings for managers to use models themselves; Diverse restoration goals = need for model to address multiple aspects of restoration; Funding = funding needed to achieve accurate model outputs.*

Table 2*. Recommendations provided by workshop participants on how to address challenges and barriers associated with developing the needed model outputs to inform oyster habitat restoration in the Gulf of Mexico. Three barriers were chosen to discuss recommendations.*

Model barrier	**Recommendation**
Data availability	Funding Monthly, instead of yearly, monitoring programs for recruitment/mortality Target data poor metrics (shell loss, surface-area recruitment, etc.)
Model calibration/validation	Funding Need foreword-predicting model to look at conditions under different climate change scenarios (Alexander et al. 2020 mid-Atlantic example) Metapopulation models to assess source-sink relationships
Complexity	Training Good metadata to describe how to use the model Training, instructions, and open-sourced software Combine model approaches to limit complexity of one approach

Q2, part b: What aspects of modeling approaches need to be streamlined or consolidated to inform oyster habitat restoration objectives in the GoM?

A major disconnect between the reason why a model is developed and how/why a model is used by managers was identified, and participants noted the need to start building models with a management restoration objective in mind to address this disconnect (Table 3). Participants also noted that defining specific objectives can be ambiguous because many times the resource manager does not have clear restoration objectives at the project level. There is a need for resource managers to develop clear restoration goals and objectives that they are trying to achieve in their system and communicate that need to the modelers. Many models are currently developed for research use with specific research questions in mind that may or may not be directly applicable to restoration activities in a specific location. Moving towards a co-production framework between managers and modelers was highlighted as a need to bridge this gap to result in a better model end-product for managers to use (Wiesenburg et al. 2021).

According to the participants, the GoM has had less data collected than other regions (e.g., oyster population and environmental data are deficient in many estuaries) and would benefit from more frequent and finer spatial scale data collection and a standardized way of collecting the data in order to make models more comparable across the region. A challenge that the GoM faces is the disparate methods and metrics of data collection used across the state agencies (La Peyre et al. 2021). Having a standardized way that metrics are selected, and data are collected, is essential. Not only will this make the data comparable, but this could also help standardize the models that are used as well to track broader regional successes. It was also highlighted that not every estuary along the GoM has the same amount or type of data that are collected, and some estuaries are more well-studied than others. If the goal is to see large-scale oyster restoration implemented across the GoM, then more data is needed for these data-poor systems. Additionally, the need for future climate prediction data, such as rainfall and other factors controlling salinity distribution in estuaries, to be used in GoM models was seen as needed to best inform restoration efforts across the Gulf. The full list of suggestions provided by workshop participants as ways to achieve best modelling approaches is in Table 3.

Table 3. *Participant responses to three questions asked (in bold) to determine how to achieve modeling approaches that will be used by managers in oyster habitat restoration planning in the Gulf of Mexico. Notes have been paraphrased with the intent to keep the author's original thought. Notes are in no particular order. * indicates notes liked by other participants, emphasizing group consensus of the need for that particular note. GSMFC = Gulf States Marine Fisheries Commission; NOAA = National Oceanic and Atmospheric Administration; VIMS = Virginia Institute of Marine Science.*

What aspects of modeling approaches need to be streamlined or consolidated to inform habitat restoration objectives?
Combine models for metapopulation approach; not all models can be combined
Not possible to consolidate without degrading model outputs → rather training and making models easier to use is better
Need to determine status of current oyster reefs within a system
Practitioners need to be able to access and use the models
Need gene-based metapopulation model to inform marine protected area (MPA) development (Munroe et al. 2012, 2014 - Delaware Bay)
Need to standardize data collection and reporting across states (lowers uncertainty)
*Model outputs don't always match management frameworks: need to start with the management questions to inform management
How can models be more readily accessible to managers?
Make multiple pre-calibrated models available
*Simplified user interface
Model details need to be easily searchable/found
List of modelers that managers could contact
Scale prediction to match scale of management
Co-production (use examples from Pamlico Sound, NC)
Managers need better computing power to run models on their own
*Open-sourced toolbox housed by one organization (GSMFC, NOAA Fisheries) → downloadable models with user manuals and trainings
Secure Data Management (SDM) workshops
Ecological tools need to be compatible with the ecological modeling
What critical data are needed to achieve a streamlined approach to apply models to restoration efforts?
Need better stock assessment methodologies (examples listed below)
VIMS survey of the James River
Rutgers survey of Delaware Bay: https://hsrl.rutgers.edu/OysterMonitoring/index.htm
VIMS sampling sufficiency tool: https://cmap2.vims.edu/OysterInfoToolVa/
Readily downloadable hydrodynamic data (historical, forward-predicting, and real-time) (mid-Atlantic does this)
Need good and available hydrodynamic models for each estuary
Need food input data (chlorophyll *a*, nutrient data, etc.)
Data needs to be in the appropriate format to be input into models → standardization of data
Represent management objectives in models

Q2, part c: How can models be more readily accessible to managers?

To use modeling to inform oyster habitat restoration, participants discussed ways to make data and models more accessible to managers. Suggestions centered around an open-source toolkit (R-programming preferred) that would be housed and upkept by a single organization such as the Gulf States Marine Fisheries Commission or the National Oceanic and Atmospheric Administration (NOAA) Fisheries (Table 3). Models should be downloadable, manuals should be provided, and trainings (in-person workshops, videos, etc.) should be offered to managers. This would provide a simplified user interface that organizations and individuals could use to be able to readily use models to inform their restoration efforts.

Q3 What are the key recommendations and needed next steps to advance modeling to inform oyster habitat restoration in the GoM?

The top recommendations for ways to advance modeling for oyster habitat restoration were 1) improve validation and calibration of data, 2) increase collaboration across state lines, and 3) use of case studies from other regions to demonstrate how models led to successful restoration outcomes (Table 4). Throughout the workshop, participants emphasized the need for validation and calibration of data and increased collaboration. The use of case studies to promote modeling efforts was a new recommendation brought up during this discussion. It was previously discussed to assess models developed from other areas of the United States and adapt or develop similar models to apply to the GoM. Demonstrating that models have been successful in informing oyster habitat restoration elsewhere was seen as a way to increase managers interest in utilizing models to assess and plan for restoration projects. Furthermore, drawing examples from other areas could help optimize model drivers and outputs for better and more reliable results.

An identified priority was to develop realistic restoration goals (Table 5). Doing research, such as modeling in the restoration planning stage to identify optimal location and methods will likely increase the likelihood that the restoration project will be successful (Brooke and Alfasso 2022). Another point raised by participants was that realistic metrics of success (e.g., amount of oyster restored or amount of fish produced in an area) are difficult for organizations to identify because baseline oyster information is unknown for some systems, which reiterates the issue of a lack of data in the GoM estuaries. Yet, realistic restoration targets are needed for models to be used effectively to inform oyster habitat restoration. Thus, more resources and funding are needed for data collection and monitoring to fill these data gaps and inform restoration targets. Other next steps identified were developing a working group or joining in with Gulf of Mexico Alliance's (GOMA) Oyster Management Community of Practice to keep this discussion going to make models more useful across the GoM (Table 5).

Table 4. *Participant provided recommendations for how to advance modeling to enhance oyster habitat restoration in the Gulf of Mexico. Recommendations are ordered from most to least voted on recommendations, with the recommendation at the top having the highest consensus among participants. Notes have been paraphrased with the intent to keep the author's original thought.*

Recommendation	# of votes
Need validation/calibration of data and adaptive management	12
Increase collaboration (especially across state lines)	12
Case studies demonstrating how models led to successful restoration outcomes	11
Find out the management guidelines to inform modeling questions; share outcomes with state managers	9
Co-production of science (modelers and managers in the same room)	8
Identify existing tools that address management needs and adapt and apply to the Gulf of Mexico	7
Account for climate change (models need to make long-term predictions)	4
Single platform	3
Provide trainings or YouTube instruction videos	3
Get stakeholders involved early	3
Modeling workshop based on regional needs	2
Compare short/long-term objectives	0

***Table 5**. Next steps that participants thought should follow this workshop and report. Next steps are ordered from most to least voted on next steps, with the step at the top having the highest consensus among participants. Where needed, next steps have been paraphrased with the intent to keep the author's original thought.*

Next steps	# of votes
Develop realistic goals	8
Oyster modeling Community of Practice	7
Follow up working group	6
Develop an oyster restoration "blueprint" for the region (model-focused)	5
Data sharing	3
Regular communication with state agencies and managers	1
Another workshop	1
Make science and modeling useful for oyster management decisions	1
Work within existing groups rather than create new ones	0
Single platform	0

Workshop Recommendations and Next Steps

The outputs of this workshop resulted in a few key points on how to advance the use of modeling to guide oyster habitat restoration in the GoM. Broadly, participants suggested that more standardized collection of more data are needed to model realistic oyster conditions in order to effectively use models to inform oyster habitat restoration and have a single platform for managers and restoration practitioners to use. Standardized data collection cannot be done without collaboration across the Gulf states to ensure the required data are gathered to generate comparable metrics. Furthermore, participants suggested that looking to other regions within the United States as examples, would benefit the creation of a single modeling platform that can be used for multiple estuaries across the GoM. Listed below are key recommendations that the workshop participants decided was important for future efforts build upon:

- *Build models to inform specific restoration objectives*
    - Identify managers' restoration questions and identify specific restoration targets that a model(s) should inform. Many models are developed as academic exercises and are not always applicable to the restoration question. Participants recommended starting with fully formed restoration questions and build models to inform that question.
- *Use lessons learned from other regions (Delaware Bay, Pamlico Sound)*
    - The Atlantic Coast has used models to inform the site selection of reef networks as a method for oyster habitat restoration (see Theuerkauf et al. 2019) and has developed predictive models that incorporate climate change drivers (see Alexander et al. 2020, Wang et al. 2022). Incorporation of climate change data and information on how a changing climate influences oyster habitat ranges and life-stages was seen as a data need for the GoM. Participants recommended identifying these strategies and models from the Atlantic and applying those to the GoM.

- *Have a singular organization coordinate modeling efforts across the GoM*
    - State resource management agencies across the Gulf typically have different methods of data collection, different oyster and environmental metrics monitored, and different frequencies and spatial scales sampled (La Peyre et al. 2014, Baggett et al. 2015). Consistent, comparable, and standardized data are needed to move toward a single platform for GoM models. While it is often a challenge to standardize sampling protocols across state lines, a coordinating agency can help facilitate the conversation and eventual movement towards standardized methods. This could perhaps best be facilitated through a Community of Practice (see MS-AL Sea Grant Consortium factsheet MASGP-22-035) with representation from the oyster habitat restoration 'sectors' participating in this workshop from all geographies across the Gulf.
- *Develop an open-source platform equipped with training opportunities housed by one entity*
    - Group consensus identified that models could be more accessible and usable to managers and restoration practitioners if there was a single platform that used open-source software (R-programming) to overcome agency firewalls. Open-source software would make models readily available to managers, while trainings (metadata, a PDF manual, or YouTube training videos) would make models more usable by managers. A dedicated organization or agency was suggested to ensure that one group is responsible for the data management and updating the models and code used.

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