
# Oyster restoration: acknowledgement of uncertainty and lessons learned for future decision-making

*Elise Irwin*[1]
*Ayesha Alam*[2]
*Rasika Ramesh*[2]

[1] U.S. Geological Survey, Cooperative Fish and Wildlife Research Unit Program

[2] Alabama Cooperative Fish and Wildlife Research Unit, Auburn University, School of Fisheries and Aquatic Sciences, 203 Swingle Hall, Auburn, AL 36849

Cooperator Science Series # 140-2022

**About the Cooperator Science Series:**

The Cooperator Science Series was initiated in 2013. Its purpose is to facilitate the archiving and retrieval of research project reports resulting primarily from investigations supported by the U.S. Fish and Wildlife Service (FWS), particularly the Wildlife and Sport Fish Restoration Program. The online format was selected to provide immediate access to science reports for FWS, state and tribal management agencies, the conservation community, and the public at large.

All reports in this series have been subjected to a peer review process consistent with the agencies and entities conducting the research. For U.S. Geological Survey authors, the peer review process (http://www.usgs.gov/usgs-manual/500/502-3.html) also includes review by a bureau approving official prior to dissemination. Authors and/or agencies/institutions providing these reports are solely responsible for their content. The FWS does not provide editorial or technical review of these reports. Comments and other correspondence on reports in this series should be directed to the report authors or agencies/institutions. In most cases, reports published in this series are preliminary to publication, in the current or revised format, in peer reviewed scientific literature. Results and interpretation of data contained within reports may be revised following further peer review or availability of additional data and/or analyses prior to publication in the scientific literature.

The Cooperator Science Series is supported and maintained by the FWS, National Conservation Training Center at Shepherdstown, WV. The series is sequentially numbered with the publication year appended for reference and started with Report No. 101-2013. Various other numbering systems have been used by the FWS for similar, but now discontinued report series. Starting with No. 101 for the current series is intended to avoid any confusion with earlier report numbers.



**Contractual References:**

This document (USGS IPDS #: IP-136899) was developed in conjunction with the US Geological Survey and the Alabama Cooperative Fish and Wildlife Research Unit and was supported through a grant to EI from the US Geological Survey in support of Department of Interior RESTORE Council member agencies.

**Recommended citation:**

Irwin, E., A, Alam, and R. Ramesh. 2022. Oyster restoration: acknowledgement of uncertainty and lessons learned for future decision-making. U.S. Department of Interior, Fish and Wildlife Service, Cooperator Science Series FWS/CSS-140-2022, Washington, D. C.
https://doi.org/10.3996/css76278684

**For additional copies or information, contact:**

Elise Irwin
U.S. Geological Survey
Cooperative Fish and Wildlife Research Unit Program
Phone: 334-703-1663
E-mail: eirwin@usgs.gov

# Oyster restoration: acknowledgement of uncertainty and lessons learned for future decision-making

**Prepared for: Ann Hijuelos, Stephanie Romanach, and Greg Steyer**

**U.S. Geological Survey[1]**

**By: Elise Irwin[2], Ayesha Alam[3], and Rasika Ramesh[3]**

**[3]U.S. Geological Survey, Cooperative Fish and Wildlife Research Units**

**[2]Alabama Cooperative Fish and Wildlife Research Unit, Auburn University, School of Fisheries and Aquatic Sciences, 203 Swingle Hall, Auburn, AL 36849**

## Introduction

The northern Gulf of Mexico (GOM) is a nationally significant socioecological system that provides valuable natural resources and services to the coastal regions of five Gulf states in the United States. The GOM is comprised of over 600,000 square miles of complex mesohabitats such as nearshore estuaries and marshes, barrier islands, sand beaches, and offshore water column and marine benthic habitats (DHNRDAT 2016). Beginning in April 2010 the Deepwater Horizon Oil Spill was the largest oil spill in U.S. history causing injury to species, habitats, and ecological function across the GOM geographic region. In response to the disaster, the RESTORE (Resources and Ecosystems Sustainability, Tourist Opportunities, and Revived Economies) Act of 2012 established the RESTORE Council as the administrative body that oversees expenditure of funds towards planning for a regional approach to the "long term health of the valuable natural ecosystems and economy of the Gulf Coast region".

[1] *Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.*

The RESTORE Act's overarching goals of ecosystem restoration, economic recovery, and tourism promotion involve many decisions by the Council with respect to restoration and recovery. The guiding plan (RESTORE Council Comprehensive Plan Update 2016) tasked a workgroup (Council Monitoring and Assessment Work Group; CMAWG) to develop monitoring procedures, standards and an adaptive management (AM) plan to evaluate success of on-the-ground projects and inform future decisions for project implementation. Many decisions by the Council will likely be made in the face of various sources of uncertainty—or knowledge gaps—associated with project selection and/or the potential success of implemented restoration actions.

The definition of uncertainty as it relates to the management of socioecological systems varies; however, it is recognized that the most straightforward description is the lack of knowledge regarding relations among components of the system (Owens 2009). Uncertainty is prevalent in both natural resource system processes themselves and the influence of management on those systems (i.e., the social or policy processes) as restoration actions are selected and implemented (Brugnach et al. 2008; Williams and Brown 2012). Uncertainty related to restoration actions may take many forms. Williams and Brown (2012) cited two main critical uncertainties in adaptive management frameworks: uncertainty related to how system processes work (including environmental drivers) and uncertainty related to how management will impact those processes. Although some uncertainty may be irreducible (i.e., aleatory uncertainty, e.g., climate), at least with technologies and other resources we possess now, incorporating climate uncertainty may lead to better understanding of the risks associated with uncertainty (Hallegatte et al. 2012; Irwin et al. 2016). The Council may benefit from explicit methods to incorporate uncertainty of different types in their decision-making; structured decision-making and adaptive management provide both the framework and methodology to do so.

Adaptive management has been widely recommended to inform management actions along the Gulf of Mexico and AM programs and projects have been framed and implemented (The Water Institute of the Gulf 2013; DHNRDA Trustees 2017; DHOOTIG 2020). However, missed opportunities to learn during restoration monitoring have also been apparent. La Peyre et al.

(2014) demonstrate this using the example of oyster reef restoration and enhancement efforts. They compiled a database of 250 artificial inshore sub-tidal oyster reefs and associated physical aspects (number, location and design of reef restoration attempts) along the northern Gulf of Mexico across five states from Texas to Florida. However, given inconsistencies in data reporting, and lack of reporting, only 17 reefs had information that was adequate enough to include in their data analysis. These authors emphasized the lack of basic information associated with reef restoration management and reported that inadequate data compromised potential learning to inform future reef management. The promise of AM is reduction of uncertainty through application of management alternatives (i.e., restoration actions), assessment of how management impacted the resource (using monitoring data), and consequent learning to improve future management (Murray and Marmorek 2003; Williams and Brown 2012). However, without identification and explicit testing of uncertainties, sound implementation strategies for AM, and coincident well-planned monitoring specifically tied to management outcomes, reduction of uncertainty may not be measurable.

Oyster reef and fishery restoration strategies are commonly implemented in the GOM region with common objectives of increasing fishery production and/or enhancing oyster populations (La Peyre et al. 2014; Shepard et al. 2018; La Peyre et al. 2021). In addition, ecosystem services provided by oysters and their habitats increase the ecological value of successful restoration outcomes; some restoration goals are entirely focused on ecological function versus consumptive harvest (Baggett et al. 2015, and citations within; NAS 2017). Although natural oyster reefs provide both production and ecosystem services, aquaculture of oysters through either off-bottom or reef farming practices also provide some of these services (e.g., nitrogen reduction, Humphries et al. 2016). Aquaculture is a restoration alternative for oysters in several U.S. regions including the GOM (Cohn and Humphries 2017; Jaris et al. 2019; Belgrad et al. 2021).

Restoration actions require post-installation monitoring to determine the consequences of those actions (Murray and Marmorek 2003). Monitoring associated with various phases of restoration (e.g., pre-construction, post-construction, or performance assessment) for multiple restoration objectives have been described by many (see NAS 2017) and identification of project level monitoring protocols and metrics have also been developed. This includes comprehensive lists of universal or core elements that should be included for any restoration action (NAS 2017; Shepard et al. 2018). Monitoring could inform AM frameworks during restoration activities in the GOM by reducing uncertainty associated with how the ecological and economic systems respond to restoration.

The National Academy of Sciences (NAS 2017) report on effective monitoring in the Gulf of Mexico cited a suite of "decision-critical uncertainties" including foremost the lack of a "rigorous and general" conceptual ecological model which would help integrate oyster restoration with respect to the broader scale Gulf of Mexico ecosystem and assist in determining restoration and population specific uncertainties that could be addressed through monitoring and AM actions. Conceptual ecological models are management-centric organizational diagrams that allow stakeholders a way to visualize complex relations among system components (Fischenich 2008; Jacobson et al. 2015).

Conceptual ecological models (CEMs) can illustrate ecological linkages, pathways for species restoration, key uncertainties, and strength of knowledge regarding the components which are major ecological factors, or attributes of the ecosystem (Fischenich 2008). Nature Serve and The Nature Conservancy (TNC) developed an oyster CEM with the following key components: environmental drivers, ecological factors and ecosystem services (Shepard et al. 2018 accessed 15 January 2022 at http://www.natureserve.org/sites/default/files/projects/files/chapter_5_-_oyster_indicators.pdf ). From the CEM, the authors applied existing or developed oyster indicators and core metrics that represented four main ecological factors—abiotic factors, ecosystem structure, ecosystem function, and ecosystem services—for use in monitoring restoration activities. Their paper describes linkages in the ecological model; however, uncertainty was not addressed. Although hypotheses regarding ecological pathways and strength of interactions exist (see La Peyre et al. 2021), the influence of management on these is less well known and not explicitly included in the CEMs that were represented in the literature. Another use of CEMs is to treat them as influence diagrams for further development of models that can predict outcomes of restoration actions. For example, Bayesian Belief

Networks (BBNs) can integrate monitoring data and expert knowledge, quantify uncertainty, and predict outcomes of restoration actions (Pourret et al. 2008).

Bayesian Belief Networks (BBNs) are graphical models of complex systems that are useful in evaluation of natural resource, conservation, and restoration problems (Stewart-Koster et al. 2010; Gieder et al. 2014). Examples of using BBNs for coastal restoration decisions include shrimp aquaculture in Thailand (Schmitt and Brugere 2013), enhancement of estuarine fisheries in eastern Australia (Gilby et al. 2021), marine socio-ecological systems of the nutrient polluted Black Sea (Langmead et al. 2009) and conservation of barrier island fauna and habitats on Dauphin Island, Alabama (Irwin et al. 2020). Bayesian Belief Networks are context specific and constructed from relational influence diagrams; influence diagrams (e.g., CEMs) can be used to construct alpha-level (i.e., initial quantitative probabilistic models) BBNs that can then be revised or updated through integration of additional data or expert opinion.

More specifically, BBNs are directed acyclic graphs comprised of networks of nodes that represent key components of a system connected with one-directional links (arcs) indicating conditional dependencies (Pourret et al. 2008). Influencing factors (parent nodes) are connected to influenced factors (child nodes) and the network is quantified by parameterizing conditional probability tables (CPTs) for nodes in the network. Inputs to the CPTs can be informed by experts or available data and BBNs can be used to evaluate the independent and conditional (interactive) effects of environmental change or variation on the modeled response or state variables (Pourret et al. 2008; Conroy and Peterson 2013). In addition, decision nodes with states that represent possible restoration actions can be added to the network along with costs and benefits of actions. Finally, utility nodes that express the expected value or utility of decisions on the modeled variables can be included to assist with analysis of stakeholder objectives (Conroy and Peterson 2013). For restoration decision makers, parameterized BBNs are predictive models that can incorporate quantitative and qualitative data, provide information regarding consequences of restoration actions on multiple and often competing objectives, and are interactive and visual tools that allow for identification and incorporation of various types of uncertainty. In addition, the different states of the parameters inherently incorporate uncertainty in either the state variables themselves (sampling or natural variation), or in the relations among nodes (process uncertainty).

Objectives for this study were to use existing published literature to inform oyster restoration practitioners regarding uncertainties that may impact restoration decisions. Specific objectives were:

1) Conduct a literature search to determine if recommended core parameters are being monitored to reduce uncertainty
2) Develop a draft conceptual ecological model (CEM) for eastern oyster in the Gulf of Mexico region to illustrate uncertainties among linkages
3) Demonstrate how the draft CEM could be used as an influence diagram to develop an alpha-level version of a Bayesian Belief Network

# Methods

## Core monitoring evaluation informed by a literature search

Ecological resilience indicators and metrics for oyster reefs delineated by Shepard et al. (2018, Table 5.17) were used as guidelines for a literature search. We identified publications documenting active and post-oyster reef restoration efforts, and/or promoting oyster recruitment in the Gulf of Mexico and associated estuaries. These were compiled from a number of databases, including Google Scholar, Web of Science and U.S. Geological Survey Publications Warehouse (USGSPW), using various combinations of the keywords "oyster," "reef," "restoration," "Gulf of Mexico" and "*Crassostrea virginica*." Of 747 results on Google Scholar, 54 results on Web of Science, and 4 results on the USGSPW, we condensed the list to 22 publications reporting the most complete datasets which included some multiple-year reef restoration efforts.

For this review, metrics were defined as direct measurements taken in the context of monitoring oyster restoration activities and an indicator was a unit representing the state of the ecological factor of interest (Shepard et al 2018). We also included metrics that might not inform the state of the ecosystem (e.g., latitude and longitude, project cost), but may be useful to stakeholders in a broadscale spatial, temporal, or fiscal assessment. In addition, we recognized that some indicators and/or metrics may represent more than one ecological attribute or factor.

Tables 1 and 2 report the metrics/indicators of interest for reef restoration efforts measured in the studies that we identified from the publications, Table 1 lists location (latitude and longitude), depth (m), reef material/substrate, reef dimensions [area/size ($m^2$)], reef height (m), cost of restoration project (USD), tidal attributes (tidal/subtidal), water temperature (°C), salinity (psu and/or ppt), turbidity (nephelometric turbidity units, NTU), Secchi depth (cm), total suspended solids (TSS; mg/L), chlorophyll a (*chl a*) concentration (mg/L), oyster filtration rate ($m^3$ $g^{-1}$ dry weight (DW) $day^{-1}$) oyster shell height (mm), tidal range (m), cost of the project (USD) and density of live oysters (individuals/$m^2$). Table 2 lists summer salinity (ppu or ppt), dissolved oxygen (DO) content (mg/L), time of day and tidal stage at DO collection, change in percent cover of reef substrate, disease prevalence (weighted prevalence), change in reef area ($m^2$), change in reef height (cm), density of live oysters relative to regional mean (including recruits; %), species richness (number of species/m), biomass of resident species, (wet weight; g/$m^2$), status of macrofaunal populations (density of Naked Goby; individuals/$m^2$), oyster fishery (site harvest status and presence of commercial oyster landings), erosion reduction (shoreline change in m/year across permanent transects, and/or length of affected shoreline), and reported presence/perception of recreational fishery.

We aggregated data on a spreadsheet by individual reef, and percent of reefs reporting data for metrics specified above were graphically compared to reefs that reported metrics recommended for monitoring by Shepard et al. (2018). In addition, we tallied the number and percentage of monitoring programs reporting metrics that attributed the four main ecological factors identified in Shepard et al. (2018)— abiotic factors, ecosystem structure, ecosystem function, and ecosystem services (Table 2). Specifically, we calculated the percentage of GOM programs that monitored at least one attribute for each of the four main ecological factors.

## Use of a conceptual ecological model to illustrate uncertainties

Conceptual ecological models (CEMs) can illustrate ecological linkages, pathways for species restoration, key uncertainties, and strength of knowledge regarding the components. We used the methods outlined in Jacobson et al. (2015) to develop a draft CEM for eastern oyster for the GOM region. We examined published CEMs from USACE (2012) and Shepard et al. (2018), as well as other guiding documents for GOM oyster restoration and modeling (e.g., DHNRDAT 2017; La Peyre et al. 2021). These papers described some broad linkages in ecological models; however, uncertainty was not addressed in the existing CEMs. Hypotheses or inference regarding ecological pathways and strength of interactions exist, however the influence of management on these is less well known and not explicitly included in the CEMs that were represented in the literature. Management alternatives were added to the CEM at various places in the hierarchical model. We categorized the uncertainty and importance of links in our CEM as high, moderate or low, using methods outlined in Jacobson et al. (2015). For uncertainty, links were categorized based on the existence of published studies that allowed for explicit understanding of the causal relations among the conditions and processes. High uncertainty was assigned to links with few or no published studies and low uncertainty was assigned to links with published accounts describing the relation between links on process or species response. Similarly, high importance was assigned to links known to have a strong influence on another process or condition and low importance was assigned to links with small modifying effects. In addition, uncertainty among links in general increases as you move from left to right in the CEM as primary biotic responses are less understood (Jacobson et al. 2015).

## Bayesian Belief Network

The CEM was used as an influence diagram to develop an alpha-level Bayesian Belief Network (see Marcot et al. 2006; BBN). The BBN was constructed using Netica software (version 6.03, Norsys Software Corporation, Vancouver, British Columbia; available at norsys.com) to predict how two common GOM restoration strategies, or decisions, were influenced by state variables associated with oyster populations and ecosystem services. Alpha-level BBNs are usually constructed using causal links identified in an influence diagram (Marcot et al. 2006; Conroy and Peterson 2013). The BBN included many of the causal links identified in the CEM; however, overparameterization of BBNs decreases their predictive capabilities therefore we simplified BBN structure compared to the CEM.

The BBN consisted of decision nodes, nature (or uncertainty) nodes representing state variables obtained directly from the CEM, and utility (value) nodes that model the conditional probabilities related to the influence of decisions (e.g., restoration measures or aquaculture actions and harvest decisions) on discrete system states (nature nodes; representing system states), thereby facilitating predictions of the additive stakeholder utility (value) associated with potential restoration actions. The decision nodes were parameterized with two decisions related to oyster restoration (reef building or off-bottom farming) and one decision related to harvest (yes). In practice, relations among nature nodes can be modeled using probabilistic dependencies derived from empirical data and expert opinion. In the case of this alpha-level version BBN, relations from published literature were used (with the exception of ecosystem services, oyster habitat suitability index [HSI], and storm and sea level rise scenarios) to parameterize the CPTs. For each nature node (i.e., uncertainty node), CPTs were populated with probabilities of causal links among associated nodes or with technical modeling output from the Alabama Barrier Island Restoration Assessment (ALBIRA; Enwright et al. 2020; Irwin et al. 2020). Conditional probabilities for the HSI oyster node varied depending on the restoration models (Model Scenarios) and on four different storm and sea level rise scenarios that impacted island morphology and habitat composition. Utility nodes were parameterized with data derived from expert opinion or data derived from linked nodes and were reflective of values, as costs or benefits, associated with outcomes or decisions. All variables in the CEM were not incorporated in the BBN so that the network model remained relatively simple.

The BBN incorporated an oyster habitat suitability index (HSI) developed for nearshore waters surrounding the ALBIRA. This HSI focused on Dauphin Island, Alabama (i.e., the spatial scale for the alpha-level BBN) and was used to relate multiple integrated physical and water quality parameters included in the CEM to oyster survival (Enwright et al. 2020). The variables included in the HSI were salinity, dissolved oxygen, temperature, turbidity, and depth; the output of the HSI was a score derived using a weighted geometric mean method to integrate the variables (see Enwright et al. 2020, page 64, accessed 15 January 2022 and found at https://pubs.usgs.gov/of/2020/1003/ofr20201003.pdf). We also included the ecosystem services node that was developed for ALBIRA (Irwin et al. 2020) because one primary function of oyster reefs is the provision of ecosystem services. Other key network variables identified in the CEM (but not represented in the integrated HSI) were included in the BBN because they also influence oyster survival and recruitment.

Storm and sea level rise uncertainty was also parameterized during ALBIRA and incorporated into the decision framework for restoration of the island (Irwin et al. 2020). Enwright et al. (2020) predicted how oyster HSI would respond to these storminess and sea level rise scenarios and therefore we maintained these nodes in the alpha-level network. For the alpha-level version, the other nodes in the network were parameterized with relations derived from the literature, or were parameterized with normal or uniform probability distributions (see Appendix B for the full conditional probability tables). The utility values were assigned based on how satisfied a decision maker may be given combined states of the linked uncertainty nodes (i.e., 100 = very satisfied, 0 = not satisfied). For example, the combination of low, acceptable initial cost and low monitoring costs was assigned a utility value of 100 and the combination of unacceptable initial cost and high monitoring costs was assigned a value of 65 (see Appendix B for full tables). The utility nodes were equally-weighted and the optimal decision was the one with the highest sum of the utility values in the network. When the BBN was compiled, utility (or satisfaction) values associated with each strategy were calculated in the BBN as a combination of values associated with different states of ecosystem sustainability, oyster population viability, and cost.

We conducted one-way sensitivity analysis on the BBN to determine which parameters most influenced the utilities, and therefore the decisions, associated with the restoration scenarios (Conroy and Peterson 2013). Tornado diagrams were constructed to visualize the uncertainty of each parameter (i.e., how much each parameter influenced the utility of the decisions) included in the BBN for each restoration alternative. We then compared the top ranked variables, in terms of uncertainty, against commonly monitored variables from the reefs for which we identified monitoring data. This was conducted to gauge if extant monitoring might help reduce uncertainty related to oyster restoration actions.

# Results

## Core-metrics monitoring assessment

Assessment of monitoring for 100 reefs was reported in the 22 published papers we considered (Appendix A). A total of thirty-one metrics were defined (Tables 1 and 2); the frequency by which they were reported for individual reefs was highly variable (Figure 1). Fourteen metrics were considered core-metrics identified by Shepard et al. (2018) and were reported infrequently with the exception of three (reef area/project footprint, dissolved oxygen and species richness) which were reported for > 45% of the 100 reefs (Figure 1). In general, published data were scarce; monitored metrics were case specific and were not consistent among studies. For the 22 published studies, only three studies (13.6%) reported metrics that monitored all four main ecological factors from Shepard et al. (2018). Ecosystem structure metrics were reported the most (100%), followed by abiotic factors (86.1%), then ecosystem function metrics (59.1%). Metrics associated with ecosystem services were only reported in 13.6% of the studies we reviewed.

Some of the monitoring metrics that were reported were not linked to ecological processes; however, they provide context for the projects that may be used in broadscale assessment or inventory (e.g., latitude, tidal range). Others may be of interest to stakeholders, especially costs associated with the projects.

## Conceptual ecological model

A draft CEM was compiled and consisted of independent drivers, primary and secondary ecological factors and primary biotic responses (Figure 2). The potential influence of adaptive management actions on primary and secondary ecological factors was noted in the model. Metrics identified as potential targets for monitoring were also noted. Linkages were identified in the CEM; uncertainty and importance levels were assigned based on published literature defining the links.

Independent drivers were either anthropogenic (e.g., coastal development, hydrologic modification) or natural (e.g., climate, land use). Primary ecological factors were geologic and hydrologic interactions such as estuarine morphology or water quality and more specific hydrology factors that influence oyster ecology (e.g., circulation patterns, freshwater inflows). Secondary ecological factors included specific physical and chemical habitat variables (e.g., salinity, reef height) and reef community composition and dynamics (e.g., predator, oyster, and/or finfish populations). Primary biotic responses were factors related to growth and condition, recruitment and direct mortality. Primary outcomes of the CEM were ecosystem services and oyster survival. Examples of management actions were included in the CEM, as well as factors that might be important variables for monitoring. (Figure 2). Appendix A lists the primary literature that was used to develop the CEM and the strength of uncertainty and importance links.

It was noted that several of the key uncertainties in the CEM were not represented by monitoring indicators or metrics in Shepard et al. 2018. In particular, metrics associated with ecosystem structure (food availability, oyster larvae, and predation) and ecosystem function (oyster filtration rate, condition of adjacent habitat, nitrogen removal) were not identified. In addition, water quality metrics were not identified for the ecosystem services factor.

## Bayesian Belief Network

Using nodes from an extant BBN (from ALBIRA; Irwin et al. 2020) and attributes identified in the CEM, an alpha-level oyster restoration BBN was successfully constructed and produced a network that was compiled to predict the utility of two restoration actions (Figure 3; Tables 3-6). Relations among nodes in the BBN were modeled using probabilistic dependencies derived from empirical data and expert opinion; in the case of this alpha-level version BBN, relations from published literature were used (with the exception of ecosystem services, oyster habitat suitability index [HSI], and storm and sea level rise scenarios) to parameterize the CPTs (see example CPT in Figure 4 and Appendix B). For additional information about BBN construction see Irwin et al. (2020; https://gom.usgs.gov/DauphinIsland/data/ALDecisionAnalysis_AppJ.pdf).

The expected utility for each restoration option (farm versus reef construction) was essentially the same; 199.118 for the off-bottom farm and 199.086 for reef construction. The units of the final utility values are the sum of the utility node value (i.e., cost, marine resources, and sustainability) that optimizes the decision. Because the utility values were similar, the BBN as it is parameterized, predicted that *either* restoration action would satisfy multiple objectives of restoration put forth in the BBN.

In the case of this example BBN, two types of ecological uncertainty were identified; system and aleatory uncertainty (Irwin et al. 2016). Results of the sensitivity analysis indicated that uncertainty was highest for ecosystem services, HSI and oyster populations for both restoration options (Figures 5 and 6). Variation occurred in the ranks of uncertainty after the top three parameters. For the off-bottom farm option, oyster survival, initial cost, and disease ranked 4, 5 and 6; initial cost and disease had fairly low levels of uncertainty. For the cultch reef, predator populations, oyster survival and initial cost ranked 4, 5 and 6; initial cost and disease also had lower levels of uncertainty. Three of the more uncertain parameters were monitored at the highest rates for the 100 reefs that we identified in this study: the water quality parameters (which, except for TSS, comprise the HSI; monitored in > 91% of the reefs), oyster populations (monitored in 78% of reefs reporting density) and predator populations (i.e., species richness or biomass monitored in 60% and 40%, respectively, of reefs). The other uncertain parameters were monitored at lower rates. They were, oyster survival (0%), ecosystem services (11%), and initial cost (30%)

## Discussion

Although restoration techniques are available and in general well established, specific objectives regarding long-term success associated with restoration of oysters are usually not well defined (Kennedy et al. 2011; La Peyre et al. 2014). This is a general finding among oyster restoration programs and may be a function of inadequate funding for on-going monitoring of restoration actions (Bloomberg et al. 2018). The monitoring analysis, CEM construction, and use of an example BBN to illustrate uncertainties regarding oyster ecosystem restoration were designed to build on existing planning efforts and illustrate tools that could improve decision-making. Adaptive management requires careful planning in the set-up phase, and these tools provide stakeholders with a mechanistic approach to conceptualize, quantify and predict how variation in system attributes may impact restoration decisions. If both the draft CEM and BBN are better informed by expert opinion and existing data, uncertainty can be better quantified.

An example of how the constructed BBN could assist with reduction of the uncertainty illustrated in both the CEM and BBN would be to treat the similarity between the restoration utilities as competing models or hypotheses. Future monitoring data can be incorporated into the BBN to update the probabilities associated with the state variables (Irwin et al. 2019), thereby updating the model predictions and reducing system uncertainty. As monitoring data are collected, a better understanding regarding the impact of aleatory uncertainty on the decisions can also be realized. The availability of monitoring data is a critical aspect of model updating, especially in AM frameworks.

Pre- and post-monitoring of quantifiable metrics associated with the primary outcomes for restoration projects (e.g., increased oyster density, shoreline protection) within an experimental framework (i.e., replication, sample size, adequate temporal scale) could also substantially increase decision-making capabilities and reduce uncertainty in the restoration ecology system (Kennedy et al. 2011; La Peyre et al. 2014; Blomberg et al 2018); these efforts have been supported by the RESTORE council. Ultimately, careful assessment of restoration projects could inform AM of oysters in the Gulf region, yet despite guidance for the implementation of AM (DHOOTIG 2020, Pine et al. 2022), AM for oyster restoration appears to be lacking in the GOM region. The perceived lack of AM programs for oysters in the GOM may be a function of findings being published in outlets other than peer-reviewed publications; however, evidence-based restoration outcomes are routinely reported in the primary literature and these types of papers have increased in the last decade (Wortley et al. 2013).

La Peyre et al. (2014) reported on the "inability to learn from past efforts" despite high levels of reef restoration in the region because information on cost, design, and restoration success was unavailable to make informed decisions about future restoration projects. Our search for published literature presenting monitoring data to estimate uncertainty did not yield adequate results to allow us to quantify parameter uncertainty among the attributes monitored and reported. Although this may be primarily due to inconsistencies among project objectives and measures of outcomes, AM frameworks are not possible without careful monitoring tied explicitly to the restoration action(s).

The discrepancies in reported monitoring on restoration projects that we distinguished in the literature review for this study may not be entirely accurate. Many of the projects that we uncovered were established prior to the Shepard et al. (2018) guidance and restoration practitioners may have been doing their best based on prior knowledge or guidance. Portals that house monitoring data are available for Gulf of Mexico restoration actions (e.g., https://www.restorethegulf.gov/cmap) and increased monitoring of restoration projects in general has been reported. There may be results from restorations where monitoring data are or will soon become available to inform future management actions. Potential outlets for monitoring may be extant with the individual state agencies/institutions that oversee different restoration projects. Monitoring to inform future management could benefit by improving the process of reporting findings. In addition, impediments to monitoring may impair collection of these data (e.g., lack of funding, instrumentation, training, access). Careful established monitoring protocols that can inform AM frameworks are difficult to implement because each of these needed elements are often not accounted for in the set-up phases of adaptive management.

The set-up phase of AM is where careful consideration of stakeholder objectives, alternatives and trade-offs among alternatives are vetted. To accomplish the set-up phase of the AM framework, conceptual models and/or influence diagrams could be drafted as communication tools for AM framework establishment (Conroy and Peterson 2013). This process can be relegated to decision makers or to a broader stakeholder audience; however, it is a critical step in establishment of the AM framework, especially with respect to outlining potential final outcomes and uncertainties. Our CEM and BBN included the broad outcome of ecosystem services that are documented for oyster reef habitats which is often the primary goal of oyster restoration activities (Coen et al. 2007). Irwin et al. (2020) elicited ecosystem services for habitats on a barrier island (Dauphin Island, AL) and the top ranked services were all provided by oyster reefs. New studies are documenting the ecological and economical services associated with oyster restoration and oyster aquaculture (Lai et al. 2020; Petrolia et al. 2020);

these could help to quantify and predict uncertainty related to restoration methods. The sensitivity analysis that we conducted for the BBN indicated that uncertainty regarding the level of ecosystem services and other population level responses provided by restoration actions appears to be high; monitoring and assessment of these parameters requires carefully executed programs. Lindenmayer (2020) advocated for improved integration of monitoring programs and well-thought-out inclusion of ecological theory as it relates to restoration outcomes from actions. The use of CEMs and past literature assists with developing rigorous monitoring plans and helps illustrate where uncertainty might be resolved (Lindenmayer et al. 2010).

Demonstration of advantages of AM as a learning framework to improve restoration management through reduction of uncertainty could be accomplished through communication tools, such the CEM and BBN that we developed for this report. The BBN could be further parameterized with existing knowledge (e.g., expert elicitation), technical model output, or case results from monitoring (Irwin et al. 2020). Communication of uncertainty and how it influences decision making is important but many integrated modeling options are complex and sorting out the decision-relevant uncertainty to a decision maker may be achieved using Bayesian decision analysis (such as BBNs) including stakeholder input during analysis (Ascough et al. 2008). The ability to predict the likelihood of system responses to management under different future sea level and storm scenarios—specifically relevant for oyster restoration—could allow decision makers to assess tradeoffs among restoration options and weigh risks (Irwin et al. 2020).

Using BBNs as a way to quantify a conceptual model is an effective way to communicate uncertainties regarding relations among variables included in a decision analysis (Friis-Hansen 2000; Daylander et al. 2016; Irwin et al. 2020). Alternate hypotheses of system response to management can be parameterized and additional sensitivity analysis that quantifies how individual state variables impact decisions can be quantified. These models differ from systems models because they focus on reducing uncertainty related to management while incorporating other system uncertainty in a predictive sense (e.g., climate, storms, sea level rise). Because the BBN can work in reverse such that preferred outcomes can be selected in the software to illustrate state variables that influence those outcomes, the potential for stakeholder/decision maker interactive queries of the network (or future versions better informed by stakeholder needs) are possible thereby increasing the value of the BBN as a communication and risk assessment tool. BBNs are flexible in that additional state variables of interest can be added and informed using multiple sources of data. This includes extant and future monitoring data that are requisite for learning in any adaptive management framework.

In conclusion, frameworks that illustrate uncertainty in complex socioecological systems are requisite for decision makers and restoration practitioners. Adaptive management and associated monitoring are designed to resolve system uncertainty; the literature search for monitoring data illustrated that metrics related to more uncertain system attributes were often not monitored. Planning for monitoring key attributes after restoration actions is critical for learning the impacts of restoration decisions. The draft conceptual ecological model presented here could be an effective mechanism for opening discussions regarding the need for monitoring primary factors influencing restoration objectives. Engaging experts in the GOM region could further quantify the CEM linkages in terms of uncertainties and their importance to the objectives of managers and restoration practitioners. The alpha-level BBN can be modified for specific contexts, different system attributes (e.g., food availability, metapopulation structure), and additional or different restoration decisions. A fully parameterized BBN (i.e., beta-level) with more existing data and expert opinion could forecast model predictions and uncertainties related to restoration choices. Finally, additional focus on ecosystem services attributes of oyster restoration through adaptive management could assist with better valuation of restoration actions.

## References

Ascough II, J.C., Maier, H.R., Ravalico, J.K., and Strudley, M W. 2008. Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecological modelling *219*(3-4), 383-399.

Belgrad, B.A., Combs, E.M., Walton, W.C., and Smee, D.L. 2021. Use of predator cues to bolster oyster resilience for aquaculture and reef restoration. Aquaculture, *538*, 736553.

Blomberg, B.N., J.B. Pollack, P.A. Montagna and D.W. Yoskowitz. 2018. Evaluating the U.S. Estuary Restoration Act to inform restoration policy implementation: A case study focusing on oyster reef projects. Marine Policy, 91: 161-166.

Brugnach, M., A. Dewulf, C. Pahl-Wostl, and T. Taillieu. 2008. Toward a relational concept of uncertainty: about knowing too little, knowing too differently, and accepting not to know. Ecology and Society 13(2): 30. [online] URL: http://www.ecologyandsociety.org/vol13/iss2/art30/

Coen, L.D., Brumbaugh, R.D., Bushek, D., Grizzle, R., Luckenbach, M.W., Posey, M.H., Powers, S.P. and Tolley, G. 2007. Ecosystem services related to oyster restoration. Marine Ecology Progress Series 341:303-307.

Coen, L.D., and Humphries, A.T. 2017. Oyster-generated marine habitats: their services, enhancement, restoration and monitoring. In Routledge handbook of ecological and environmental restoration (pp. 274-294). Routledge.

Conroy, M.J., and Peterson, J.T. 2013. Decision making in natural resources—A structured, adaptive approach: Oxford, United Kingdom, Wiley-Blackwell, 456 p. Available at [https://doi.org/10.1002/9781118506196.].

Daylander, P.S., Myers M. Mattson B., Steyer G., Godsey E., McDonald J. Byrnes M, and Ford M. 2016. Use of structured decision-making to explicitly incorporate environmental process understanding in management if coastal restoration projects: case study on barrier islands of the Northern Gulf of Mexico. Journal of Environmental Management 183 (2016) 497-509.

Deepwater Horizon Natural Resource Damage Assessment Trustees (DHNRDAT). 2016. Deepwater Horizon oil spill: Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement. Retrieved from http://www.gulfspillrestoration.noaa.gov/restoration-planning/gulf-plan

Deepwater Horizon Natural Resource Damage Assessment Trustees (DHNRDAT). 2017. Deepwater Horizon Oil Spill Natural Resource Damage Assessment: Strategic Framework for Oyster Restoration Activities. June. Available: http://www.gulfspillrestoration.noaa.gov/restoration-planning/gulf-plan.

Deepwater Horizon Open Ocean Trustee Implementation Group (DHOOTIG). 2020. Open Ocean Trustee Implementation Group Monitoring and Adaptive Management Strategy. June. Available: http://www.gulfspillrestoration.noaa.gov/

Enwright, N.M., Wang, H., Dalyander, S.P., and Godsey, E., eds. 2020. Predicting barrier island habitats and oyster and seagrass habitat suitability for various restoration measures and future conditions for Dauphin Island, Alabama: U.S. Geological Survey Open-File Report 2020–1003, 99 p., https://doi.org/10.3133/ofr20201003

Fischenich, J.C. 2008. Application of conceptual models to ecosystem restoration. Retrieved from: https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/4060/1/TN-EMRRP-EBA-01.pdf

Friis-Hansen, A. 2000. Bayesian networks as a decision support tool in marine applications. PhD Dissertation. Department of Naval Architecture and Offshore Engineering, Technical University of Denmark.

Gieder, K.D., Karpanty, S.M., Fraser, J.D., Catlin, D.H, Gutierrez, B.T., Plant, N. G., Turecek, A, M, and Thieler, E.R. 2014. A Bayesian network approach to predicting nest presence of the federally-threatened piping plover (*Charadrius melodus*) using barrier island features. Ecological Modeling 276:38-50.

Gilby, B.L., Olds, A.D., Chapman, S., Goodridge Gaines, L.A., Henderson, C.J., Ortodossi, N.L., ... and Schlacher, T.A. 2021. Attraction versus production in restoration: spatial and habitat effects of shellfish reefs for fish in coastal seascapes. Restoration Ecology, 29(7), e13413.

Grabowski, J.H. and Peterson, C.H. 2007. Restoring oyster reefs to recover ecosystem services. In: Cuddington, K., Byers, J.E., Wilson, W.G., Hastings, A. (eds.) Ecosystem engineers: concepts, theory and applications. Elsevier-Academic Press, Amsterdam, p 281–298.

Hallegatte S., A. Shah, R. Lempert, C. Brown and S. Gill. 2012. Investment decision making under deep uncertainty—application to climate change. Policy Research Working Paper 6193. The World Bank, Washington DC.

Humphries, A. T., Ayvazian, S. G., Carey, J. C., Hancock, B. T., Grabbert, S., Cobb, D., ...and Fulweiler, R. W. 2016. Directly measured denitrification reveals oyster aquaculture and restored oyster reefs remove nitrogen at comparable high rates. Frontiers in Marine Science, *3*, 74.

Irwin B., B. Crawford, T.G. Crawford and C. Moore. 2016. Turning uncertainty into useful information for conservation decisions. Southeast Climate Science Center Fact Sheet 2016-02. https://secasc.ncsu.edu/wp-content/uploads/sites/14/2019/05/SECASC_FactSheet_Turning-Uncertainty-into-Useful-Information-for-Conservation-Decisions.pdf.

Irwin, E.R., M.C. Freeman, J. Peterson, M.C. Lloyd, K.D.M. Kennedy, K. Ouellette and E. Kosnicki. 2019. Adaptive Management of Flows from R.L. Harris Dam, (Tallapoosa River, Alabama): Stakeholder Process and Use of Biological Monitoring Data for Decision Making. Open File Report 2019-1026, 93p. https://doi.org/10.3133/ofr20191026

Irwin, E.R., K.O., Coffman, E. Godsey, N.M. Enwright, M C. Lloyd, K. Joyner, and Q. Lai. 2020. Decision analysis of restoration actions for faunal conservation and other stakeholder values: Dauphin Island, Alabama. Alabama Barrier Island Restoration Assessment. Final Report. Available at [https://gom.usgs.gov/DauphinIsland/Reports.aspx]

Jacobson, R.B., M.J. Parsley, M.L. Annis, M.E. Colvin, T.L. Welker, D.A. James. 2015. Development of conceptual ecological models linking management of the Missouri River to pallid sturgeon population dynamics. Open-File Report 2015-1038, U.S. Geological Survey, Reston, Virginia. DOI: 10.3133/ofr20151038.

Jaris, H., Brown, D.S., and Proestou, D.A. 2019. Assessing the contribution of aquaculture and restoration to wild oyster populations in a Rhode Island coastal lagoon. Conservation Genetics, *20*(3), 503-516.

Kennedy, V., Breitburg, D.L. Christman, M. C., Luckenbach, M.W., Paynter, K., Kramer, J., Sellner, K.G., Baxter, J.D., Keller, C., and Mann, R. 2011. Lessons learned from efforts to restore oyster populations in Maryland and Virginia, 1990 to 2007. Journal of Shellfish Research, 30(3), 719-731.

Lai, Q.T., Irwin, E.R., and Zhang, Y. 2020. Quantifying harvestable fish and crustacean production enhancement and associated economic values from oyster reefs in Mobile Bay, Alabama. Oceans and Coastal Management 187:105104 https://doi.org/10.1016/j.ocecoaman.2020.105104

Langmead, O., McQuatters-Gollop, A., Mee, L. D., Friedrich, J., Gilbert, A. J., Gomoiu, M. T., ... and Todorova, V. 2009. Recovery or decline of the northwestern Black Sea: a societal choice revealed by socio-ecological modelling. Ecological Modelling, 220(21), 2927-2939.

La Peyre, M., J. Furlong, L. Brown. B. Piazza and K. Brown. 2014. Oyster reef restoration in the northern Gulf of Mexico: extent, methods and outcomes. Ocean and Coastal Management, 89: 20-28. DOI 10.1016/j.ocecoaman.2013.12.002

La Peyre, M.K., Marshall, D.A., and Sable, S.E., 2021, Oyster model inventory: Identifying critical data and modeling approaches to support restoration of oyster reefs in coastal U.S. Gulf of Mexico waters: U.S. Geological Survey Open-File Report 2021–1063, 40 p., https://doi.org/10.3133/ofr20211063.

Lindenmayer, D. 2020. Improving restoration programs through greater connection with ecological theory and better monitoring. Frontiers in Ecology and Evolution *8*, 50.

Lindenmayer, D. B., Likens, G. E., Krebs, C. J., and Hobbs, R. J. 2010. Improved probability of detection of ecological “surprises”. Proceedings of the National Academy of Sciences, 107(51), 21957-21962.

Marcot, B.G., Steventon, J.D., Sutherland, G.D., and McCann, R.K. 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation: Canadian Journal of Forest Research 36:3063–3074. [https://doi.org/10.1139/x06-135].

Mickey, R.C., Godsey, E., Dalyander, P.S., Gonzalez, V., Jenkins, R.L., III, Long, J.W., Thompson, D.M., and Plant, N.G. 2020. Application of decadal modeling approach to forecast barrier island evolution, Dauphin Island, Alabama: U.S. Geological Survey Open-File Report 2020–1001, 45 p. https://doi.org/10.3133/ofr20201001

Murray, C. and Marmorek, D. 2003. Adaptive management and ecological restoration. Ecological Restoration of Southwestern Ponderosa Pine Forests, 417-428.

National Academies of Sciences, Engineering, and Medicine (NAS). 2017. Effective Monitoring to Evaluate Ecological Restoration in the Gulf of Mexico. Washington, DC: The National Academies Press. https://doi.org/10.17226/23476.

Owens, N. 2009. Adaptive management frameworks for natural resource management at the landscape scale: Implications and applications for sediment resources. Journal of Soils and Sediments 9(6):578-593. https://doi.org/10.1007/s11368-009-0137-2

Pine III, W.E., Johnson, F.A., Frederick, P.C., and Coggins, L.G. 2022. Adaptive Management in Practice and the Problem of Application at Multiple Scales—Insights from Oyster Reef Restoration on Florida's Gulf Coast. Marine and Coastal Fisheries, 14(1), e10192.

Petrolia, D.R., Nyanzu, F., Cebrian, J., Harri, A., Amato, J., and Walton, and W.C. 2020. Eliciting expert judgment to inform management of diverse oyster resources for multiple ecosystem services. Journal of Environmental Management 268:110676.

Pourret, O., Naim, P. and Marcot, B. 2008. Bayesian networks: a practical guide to applications. John Wiley and Sons, Ltd., West Sussex, England. 428pp.

Schmitt, L. H. M., and Brugere, C. 2013. Capturing ecosystem services, stakeholders' preferences and trade-offs in coastal aquaculture decisions: a Bayesian belief network application. *PloS one*, *8*(10), e75956.

Shepard, C.J., Brenner, K.L. Goodin, and K.W. Ames. 2018. Ecological Resilience Indicators for Oyster Ecosystems. In: Goodin, K.L. et al. (editors), Ecological Resilience Indicators for Five Northern Gulf of Mexico Ecosystems. NatureServe, Arlington, VA. 40 pages.

Stewart-Koster, B., Bunn, S.E., Mackey, N.L., Poff, L., and Naiman, R.J. 2010. The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. Freshwater Biology 55:243-260.

U.S. Army Corps of Engineers, Mobile District, U.S. Geological Survey, State of Alabama, and National Fish and Wildlife Foundation. 2020. Alabama Barrier Island Restoration Assessment. Final Report. Available at [https://gom.usgs.gov/DauphinIsland/Reports.aspx]

The Water Institute of the Gulf. 2013. Adaptive Management Framework for Coastal Louisiana. The Water Institute of the Gulf. Produced for and funded by the Coastal Protection and Restoration Authority under Task Order 9, Contract No. 2503-12-58. Baton Rouge, LA.

Williams, B.K and Brown, E.D. 2012. Adaptive management: the U.S. Department of the Interior applications guide. U.S. Department of the Interior, Washington, DC.

Wortley, L., Hero, J. M., & Howes, M. 2013. Evaluating ecological restoration success: a review of the literature. Restoration Ecology *21*(5), 537-543.

Table 1. Metrics reported in various reference publications (n = 22) and used to monitor conditions associated with oyster restoration in the Gulf of Mexico. The number of reefs, from a total of 100, that were monitored for each metric is reported (Total, n). Units for each metric are also reported. See Appendix A for the list of publications.

| Metric | Units | Total (n) |
|---|---|---|
| **Reference Publications** | | 22 |
| **Total Reefs / locations** | | 100 |
| **Metrics reported for oyster restoration monitoring** | | |
| **Latitude of reef** | | 74 |
| **Depth of reef** | m | 91 |
| **Reef substrate Info / Material** | | 97 |
| **Dimensions of reef (area)** | $m^2$ | 43 |
| **Relief of reef** | m | 54 |
| **Reef tide attributes** | Tidal/subtidal | 79 |
| **Water temperature** | °C | 95 |
| **Salinity** | psu or ppt | 95 |
| **Turbidity (nephelometric turbidity units)** | NTU | 28 |
| **Secchi Depth** | cm | 42 |
| **Total Suspended Solids** | TSS, mg/L | 4 |
| **chlorophyll a (chl A)** | mg/L | 53 |
| **Oyster Filtration Rate** | $m^3\ g^{-1}$ dry weight (DW) $day^{-1}$ | 24 |
| **Oyster Shell Height** | mm | 39 |
| **Tidal Range** | m | 12 |
| **Cost of Project** | USD | 30 |
| **Density of Live Oysters** | Individuals/$m^2$ | 78 |

Table 2. Core metrics defined in Shepard et al. (2018), reported in various reference publications (n = 22) and used to monitor conditions associated with oyster restoration in the Gulf of Mexico. Number of reefs, out of a total of 100, that were monitored for each value is reported (Total, n) and the units reported are also presented. The table is organized by major ecological factors and services including, abiotic factors, ecosystem structure, ecosystem function and ecosystem services. See Appendix A for the list of reference publications.

| | Metric | Units | Total (n) |
|---|---|---|---|
| | **Reference Publications** | | 22 |
| | **Total Reefs / locations** | | 100 |
| **Shepard et al. (2018) Core metrics reported** | | | |
| **ABIOTIC FACTORS** | **Summer Salinity** | Summer Mean--b/w May and August; psu or ppt | 35 |
| | **Dissolved Oxygen (DO)** | mg/L | 94 |
| | **Time of day and tidal stage @ DO collection** | | 41 |
| | **% Cover of Reef Substrate** | % reef footprint covered in hard substrate suitable for oyster settlement | 3 |
| | | | |
| **ECOSYSTEM STRUCTURE** | **Disease Prevalence** | %, weighted prevalence | 9 |
| | **Reef area / Project Footprint** | m | 79 |
| | **Reef Height** | cm | 35 |
| | **Density of Live Oysters relative to Regional Mean, Including Recruits** | [(Individuals/m2) / regional mean density] x 100% | 11 |
| | | | |
| **ECOSYSTEM FUNCTION** | **Species Richness** | # of species/m | 60 |
| | **Biomass of Resident Species** | Wet weight by species, g/m | 40 |
| | | | |
| **ECOSYSTEM SERVICES** | **Status of Macrofaunal Populations** | Density of Naked Goby, Individuals/$m^2$ | 3 |
| | **Oyster Fishery** | Site Harvest Status Y/N; Commercial Oyster Landings Y/N | 3 |
| | **Erosion Reduction** | Shoreline Change in m/yr across permanent transects, and length of affected shoreline | 11 |
| | **Recreational Fishery** | % anglers/site/yr with positive perception of fishing in oyster reefs | 0 |

Table 3. Bayesian Belief Network (BBN) node variables, discretized methods, states and utilities (if applicable). The discretized methods describe how the nodes were parameterized. These particular nodes were parameterized for the Alabama Barrier Island Restoration Assessment (ALBIRA) and reported in Irwin et al. (2020).

| Variable | Discretization Methods | State | Utility |
|---|---|---|---|
| Model Scenarios | Restoration model scenarios described in Enwright et al. (2020). Several of these models impact habitat suitability indices (HSI) for oysters by year 10 in the models. For this model, equal likelihood was assigned to each model scenario. | Eleven restoration scenarios were included in the BBN | n/a |
| Ecosystem Services List | Top five ecosystem services provided for habitats. The list was compiled using importance values elicited from experts for each ecosystem service and habitat and ranked; see Irwin et al. (2020). | Fish Habitat<br>Storm Buffer<br>Biodiversity<br>Sediment/Nutrient Reduction<br>Water Quality Enhancement | n/a<br>n/a<br>n/a<br>n/a<br>n/a |
| Ecosystem Services | Percentiles of scores for ecosystem services that met the criteria for four quartile suitability bins. Calculated by combining values for ecosystem services provided by oysters and HSI oyster for the conceptual ecological model (CEM). This node incorporates the Ecosystem Services provided by oysters listed above and CEM variables from the physical and chemical habitat variables and the reef community dynamics included in the Secondary Ecological Factors of the CEM. | Unsuitable<br>Marginal<br>Suitable<br>Highly Suitable | n/a<br>n/a<br>n/a<br>n/a |
| HSI<br>Oyster | Probability distribution for HSI meeting the state conditions reported in Enwright et al. (2020) for model and probability of storms/ sea level rise (ST/SL) scenarios. They calculated HSI for oysters over the extent of the modeling space for ALBIRA. This node incorporates several individual physical and chemical habitat variables from the CEM including, salinity, dissolved oxygen, temperature, total dissolved solids and depth | Unsuitable (<0.3)<br>Marginal (0.3-0.5)<br>Suitable (0.5-0.7)<br>Highly suitable (>0.7) | 0<br>10<br>15<br>25 |

Table 4. Probabilities associated with the storm and sea level rise scenarios used in the Bayesian Belief Network (BBN) for Alabama Barrier Island Restoration Assessment (ALBIRA) model scenarios [$P_{st}$; Mickey et al (2020), Table 2, page 19.] and sea level rise ($P_{sl}$) probabilities for each scenario. These scenarios were retained in the oyster restoration BBN because they influence breaching in the Mississippi Sound and impact oyster habitat suitability in the model domain. The storm and sea level rise node was parameterized with estimated probabilities of storms (ST) and sea level rise (SL) occurring during the 10 year model horizon used for ALBIRA. Normalized probabilities were computed by multiplying $P_{st}$ and $P_{sl}$ [(estimated for each SL scenario from published National Oceanic and Atmospheric Association (NOAA) curves for an intermediate greenhouse gas model (RCP4.5) for Dauphin Island**; Figures 6 and 7 in Irwin et al. (2020))], summing the products (total probability), and normalizing the data by dividing each scenario's product by the sum and multiplying by 100. See text for more detail. These scenarios address several of the Independent Drivers in the first column of the conceptual ecological model (CEM). Appendix B contains the full conditional probability tables. ST/SL = storms/ sea level rise.

| ST/SL Scenarios | $P_{st}$* | Best fit NOAA sea level curve | $P_{sl}$ RCP4.5** | Total Probability ST/SL | Normalized Probability ST/SL |
|---|---|---|---|---|---|
| ST2SL1H | 0.57 | Intermediate-high | 0.005 | 0.00285 | 0.45 |
| ST2SL1I | 0.57 | Intermediate-low | 0.730 | 0.4161 | 65.83 |
| ST3SL3H | 0.29 | Intermediate-high | 0.005 | 0.00145 | 0.23 |
| ST3SL3I | 0.29 | Intermediate-low | 0.730 | 0.2117 | 33.49 |
| **Total** | - | | - | 0.6321 | 100.00 |

*Mickey et al (2020)
**Sweet et al. (2020)

Table 5. Variables with associated costs relative to restoration measures related to oyster reef or farm size. Methods used to inform states, node states with bin definitions, and utility values for the Bayesian Belief Network (BBN) developed for oyster restoration decisions are reported for initial cost, monitoring cost and reef/farm size. Higher utility values were assigned to higher valued states in each node to inform the minimum cost utility node (not reported on this table). The utility value for all combinations variables and states were summed for the total utility. The maximum utility was 100 which was equal to the summed values of highest valued state (value in bold, see text for more information).

| Variable | Discretization Methods | State | Utility |
|---|---|---|---|
| Initial Cost | Initial cost represents the cost to implement the proposed measure with the given option of acquiring material to restore oyster reef. Cost estimates could include design, management and 10% contingency. This node addresses the independent economic driver in column one of the conceptual ecological model (CEM). Actual costs are not represented in this alpha-level BBN. | Low Acceptable<br>High Acceptable<br>Unacceptable | 40<br>20<br>0 |
| Monitoring Cost | Estimated cost to monitor over a designated period. This node addresses the independent economic driver in column one of the CEM. Actual costs are not represented in this alpha-level BBN. | Low<br>Intermediate<br>High | 30<br>15<br>0 |
| Reef/Farm Size | Size of the constructed reef or off-bottom farm. This variable influences the costs. This node addresses the independent economic driver in column one of the CEM. The node was parameterized using a distribution of the sizes of farms represented in the literature. | Large<br>Medium<br>Small | n/a<br>n/a<br>n/a |

Table 6. Harvest decision (yes, no), oyster restoration strategy decision (off-bottom farm, new reef cultch), monitoring variables and their states (high, moderate, low)and oyster survival states (high, moderate, low) that impact oyster populations are reported. These variables were represented in the Bayesian Belief Network (BBN) for oyster restoration alternatives. The discretized method is described as well as utility values. n/a = not applicable.

| Variable | Discretization Methods | State | Utility |
|---|---|---|---|
| Harvest (decision) | Presence or absence of oyster harvest. For this alpha-level BBN, we only evaluated harvest “yes” scenario | Yes<br>No | n/a<br>n/a |
| Oyster Restoration Strategies | Decision node to implement off bottom farms or build new reefs with cultch | Off-Bottom Farm<br>New Reef Cultch | n/a<br>n/a |
| Currents | Reflects the relation between spat recruitment and water currents in the Mississippi Sound. This node is related to the recruitment variable in the Primary Biotic Response column of the conceptual ecological model (CEM; Figure 2). The probability distribution informing this node was normal pending expert elicitation. | High<br>Moderate<br>Low | n/a<br>n/a<br>n/a |
| Oyster condition | Oyster condition positively relates to spawning success and recruitment. This node is related to the growth and condition variables in column four of the CEM. The probability distribution informing this node was normal pending expert elicitation. | High<br>Moderate<br>Low | n/a<br>n/a<br>n/a |
| Recruitment | Recruitment is critical for sustainable oyster populations. A function of oyster condition and water currents. Probabilities informing the conditional probability table for this node were estimated from the literature. | High<br>Moderate<br>Low | n/a<br>n/a<br>n/a |
| Disease Reservoir | Disease increases natural mortality of oysters. This node quantifies one potential aspect of direct mortality in column five of the CEM. The probability distribution informing this node was normal pending expert elicitation. | High<br>Moderate<br>Low | n/a<br>n/a<br>n/a |
| Predator Populations | Predators increase natural mortality of oysters. A function of habitat suitability index (HSI) for oysters (Enwright et al. 2020). This node quantifies one potential aspect of direct mortality in column five of the CEM. Probabilities informing the conditional probability table for this node were estimated from the literature. | High<br>Moderate<br>Low | n/a<br>n/a<br>n/a |
| Oyster Survival | The inverse of mortality; a function of predators, disease and HSI oysters. In the CEM this node is a primary outcome. Probabilities informing the conditional probability table for this node was estimated from the literature. | High<br>Moderate<br>Low | n/a<br>n/a<br>n/a |
| Oyster Populations | A function of harvest, survival and recruitment. This variable informed the marine resources utility node. This is represented in the reef community composition and dynamics group in column five of the CEM. Probabilities informing the conditional probability table for this node were estimated from the literature. | High<br>Moderate<br>Low | 100<br>50<br>25 |

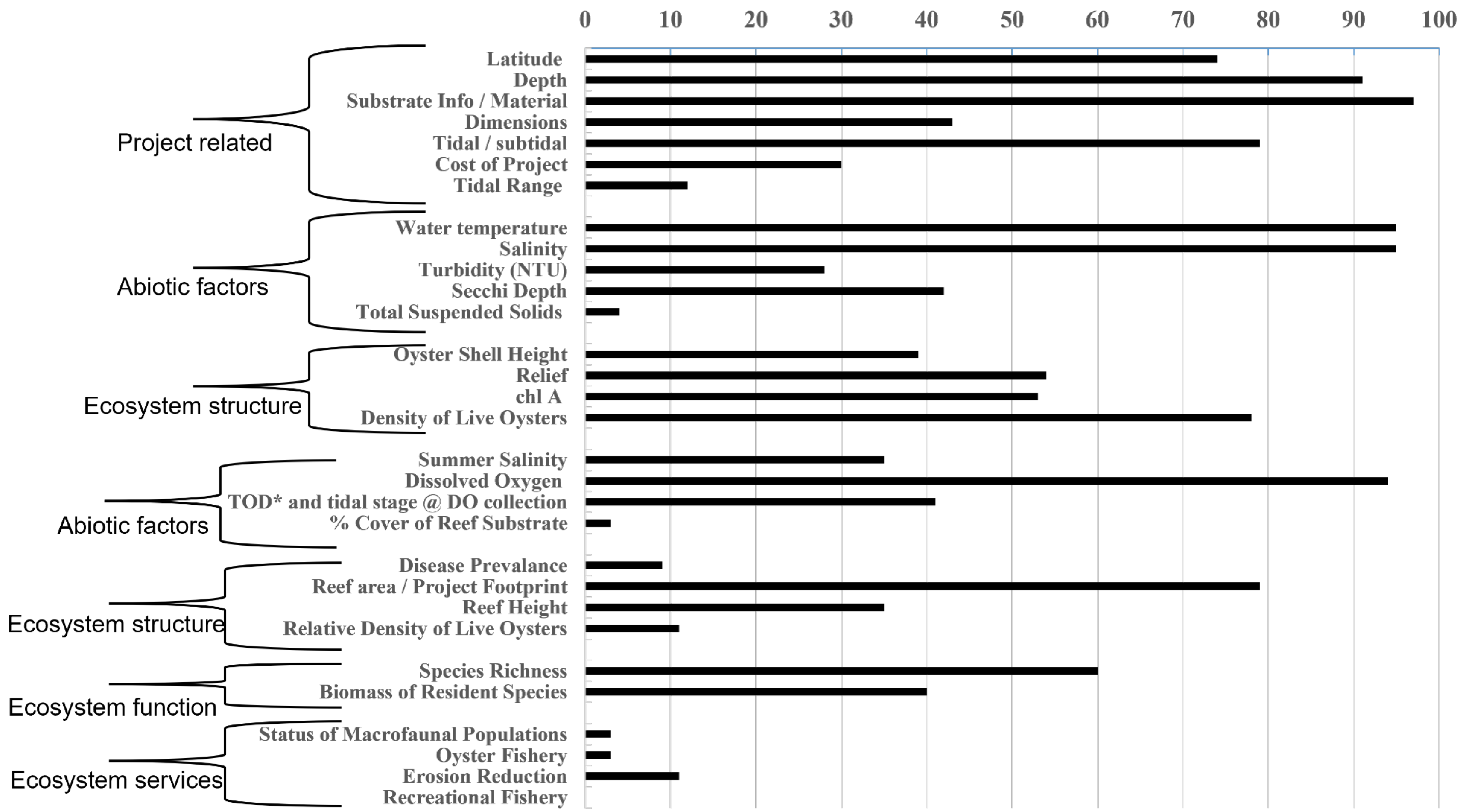



Figure 1. Percent of monitoring data for 31 metrics reported for 100 reefs (see Appendix A) from the Gulf of Mexico region. The metrics in the top three brackets were auxiliary to those described by Shepard et al. (2018) which are represented in the bottom four brackets. Metrics were grouped by five types and included project specific metrics and those that represented abiotic factors, ecosystem structure, ecosystem function and ecosystem services. Data were delineated from 22 published accounts regarding reef restoration in the region (see Appendix A). Chl a = chlorophyll a; NTU = nephelometric turbidity units. * = time of day.

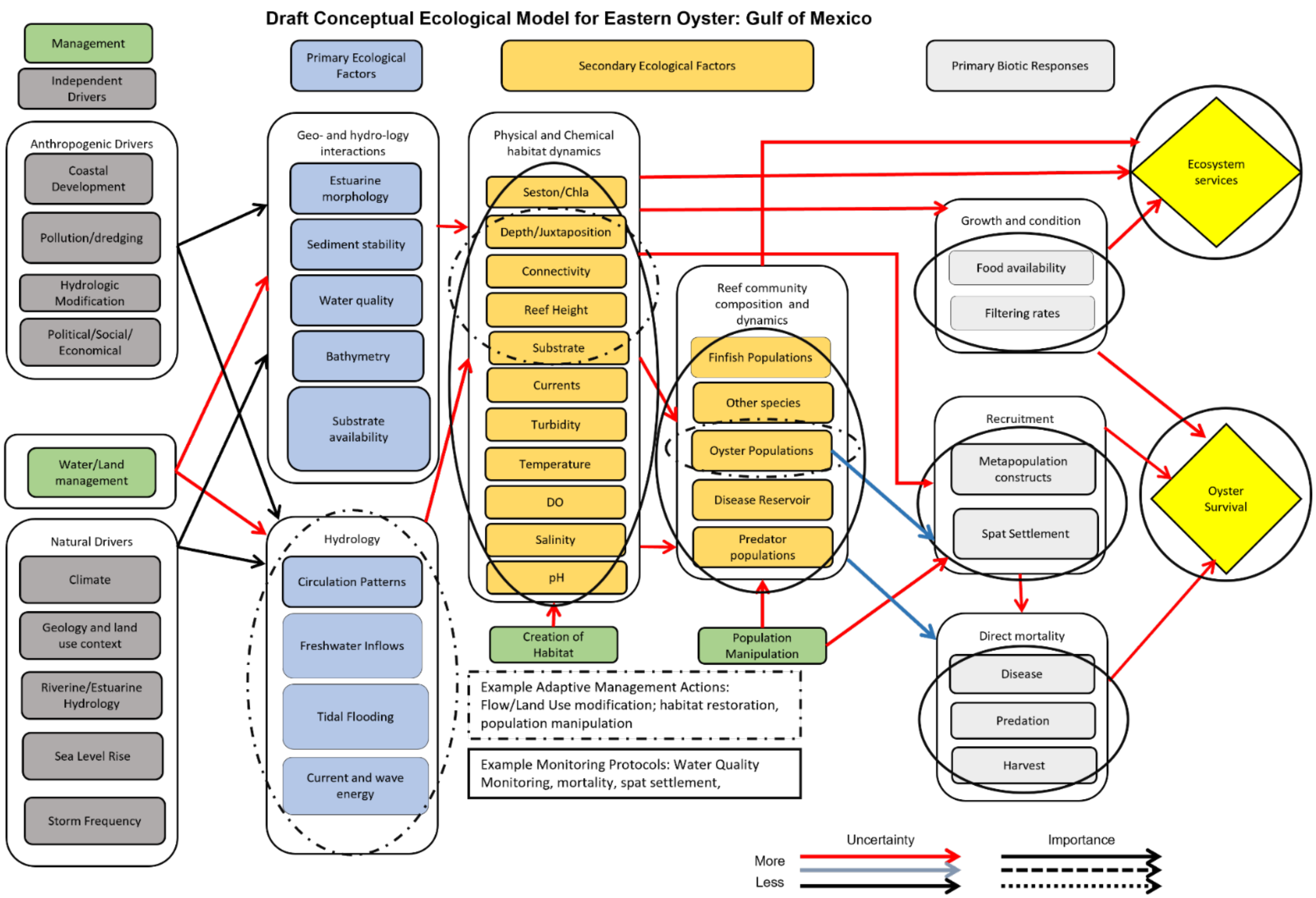



Figure 2.-Draft ecological conceptual model (CEM) for eastern oyster (*Crassostrea virginica*) for the Gulf of Mexico region. Methods described in Jacobson et al. (2015) link independent drivers (dark gray), primary ecological factors (blue), secondary ecological factors (gold), and primary biotic responses (light gray) to oyster survival and condition (outcomes, yellow). Dashed boxes and circles indicate the potential influence of adaptive management actions on certain primary and secondary ecological factors. Metrics identified as potential targets for monitoring are defined by open circles and listed in the black box. Uncertainty between the links is represented by different colored lines. Importance of the relations is not informed in this draft CEM pending expert opinion. DO = dissolved oxygen; Chla = chlorophyll a.

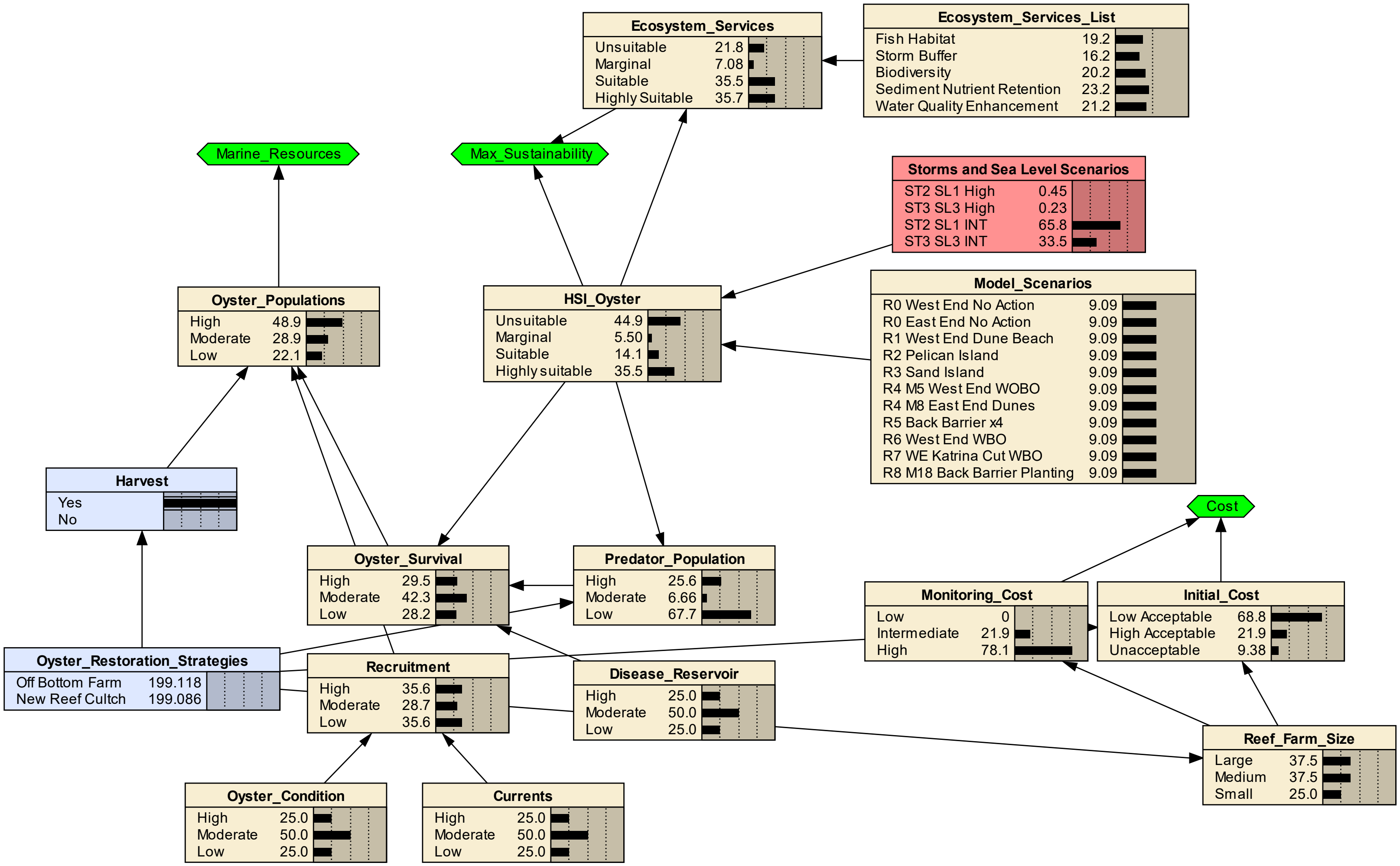
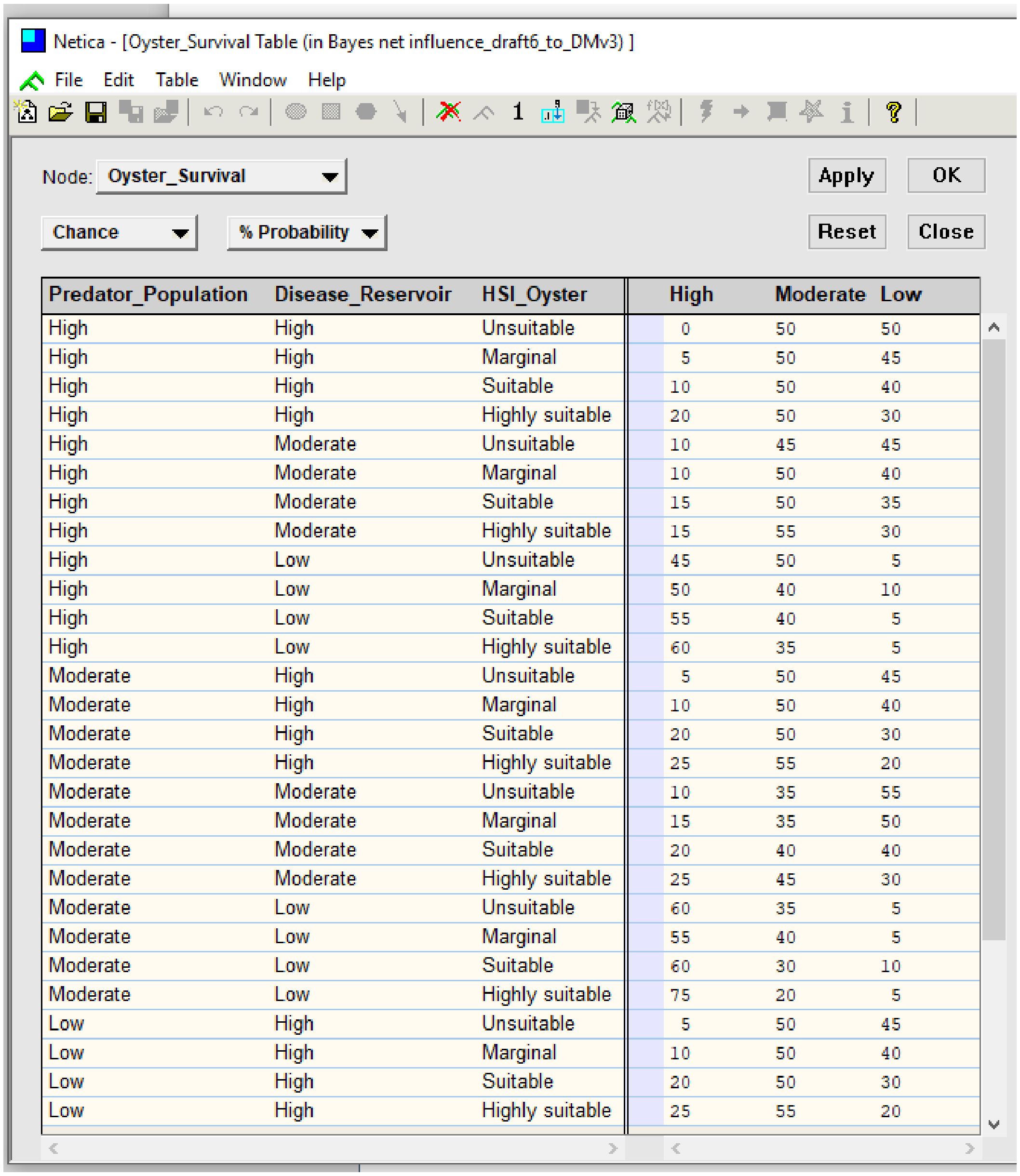



Figure 3. Alpha version of a Bayesian Belief Network (BBN) to model the probabilistic relations (black arrows) among nature (uncertainty) nodes (yellow rectangles) consequent to restoration decisions (blue rectangles) for eastern oyster in the vicinity of Dauphin Island, AL. The BBN calculates the expected value of the combined utility nodes (objectives; green hexagons) for each decision. See Tables 3-6for variables in the conceptual ecological model (CEM) that are represented in the BBN. See Appendix B for the parameterized conditional probability tables. HSI = habitat suitability index.




| Predator_Population | Disease_Reservoir | HSI_Oyster | High | Moderate | Low |
|---|---|---|---|---|---|
| High | High | Unsuitable | 0 | 50 | 50 |
| High | High | Marginal | 5 | 50 | 45 |
| High | High | Suitable | 10 | 50 | 40 |
| High | High | Highly suitable | 20 | 50 | 30 |
| High | Moderate | Unsuitable | 10 | 45 | 45 |
| High | Moderate | Marginal | 10 | 50 | 40 |
| High | Moderate | Suitable | 15 | 50 | 35 |
| High | Moderate | Highly suitable | 15 | 55 | 30 |
| High | Low | Unsuitable | 45 | 50 | 5 |
| High | Low | Marginal | 50 | 40 | 10 |
| High | Low | Suitable | 55 | 40 | 5 |
| High | Low | Highly suitable | 60 | 35 | 5 |
| Moderate | High | Unsuitable | 5 | 50 | 45 |
| Moderate | High | Marginal | 10 | 50 | 40 |
| Moderate | High | Suitable | 20 | 50 | 30 |
| Moderate | High | Highly suitable | 25 | 55 | 20 |
| Moderate | Moderate | Unsuitable | 10 | 35 | 55 |
| Moderate | Moderate | Marginal | 15 | 35 | 50 |
| Moderate | Moderate | Suitable | 20 | 40 | 40 |
| Moderate | Moderate | Highly suitable | 25 | 45 | 30 |
| Moderate | Low | Unsuitable | 60 | 35 | 5 |
| Moderate | Low | Marginal | 55 | 40 | 5 |
| Moderate | Low | Suitable | 60 | 30 | 10 |
| Moderate | Low | Highly suitable | 75 | 20 | 5 |
| Low | High | Unsuitable | 5 | 50 | 45 |
| Low | High | Marginal | 10 | 50 | 40 |
| Low | High | Suitable | 20 | 50 | 30 |
| Low | High | Highly suitable | 25 | 55 | 20 |

Figure 4. Portion of a conditional probability table (CPT) for the oyster survival uncertainty node in the Bayesian Belief Network for oyster restoration decisions. States of parent nodes for predator population, disease reservoir and habitat suitability (HSI) oyster are listed in first three columns. The probabilities for oyster survival (child node; high, moderate, low) are parameterized in columns 4-6. Data were based on probable oyster survival in response to the combined states of the parent nodes. See Appendix B for conditional probability data associated with each node in the BBN.

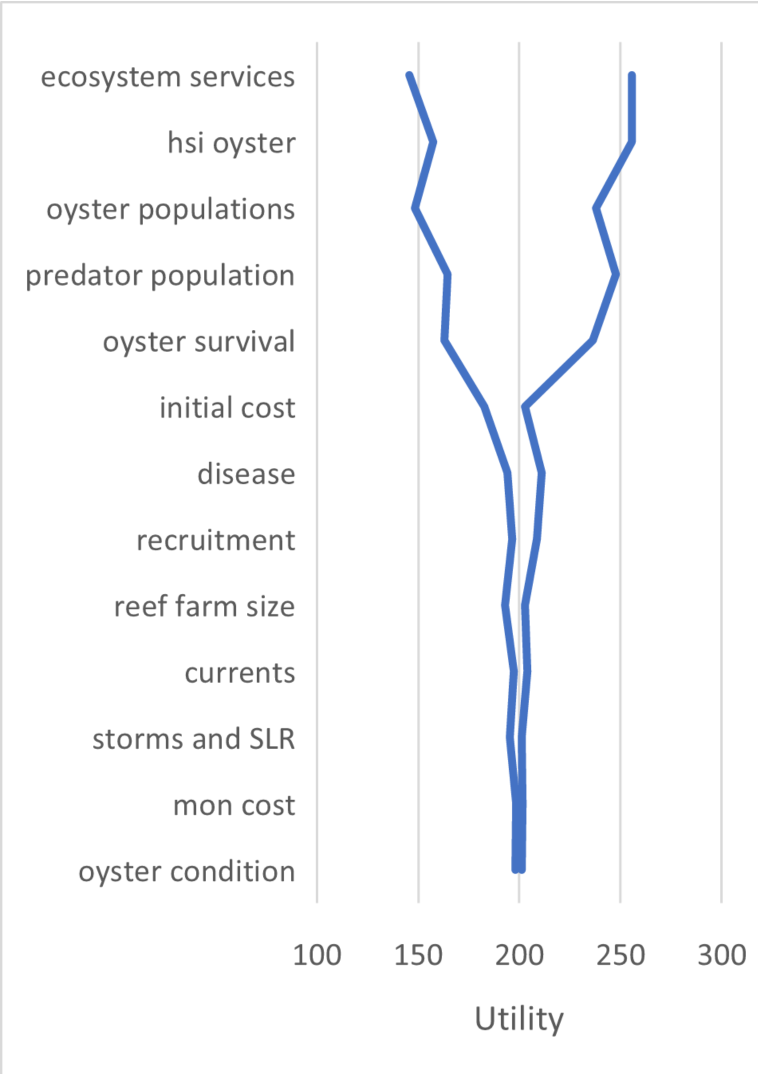



Figure 5- Influence of individual nature or uncertainty nodes on utility of building new oyster reef (cultch). Uncertainty in the parameters is greatest at the top of the tornado diagram and diminishes near the bottom of the graph. hsi = habitat suitability index; mon cost = monetary cost.

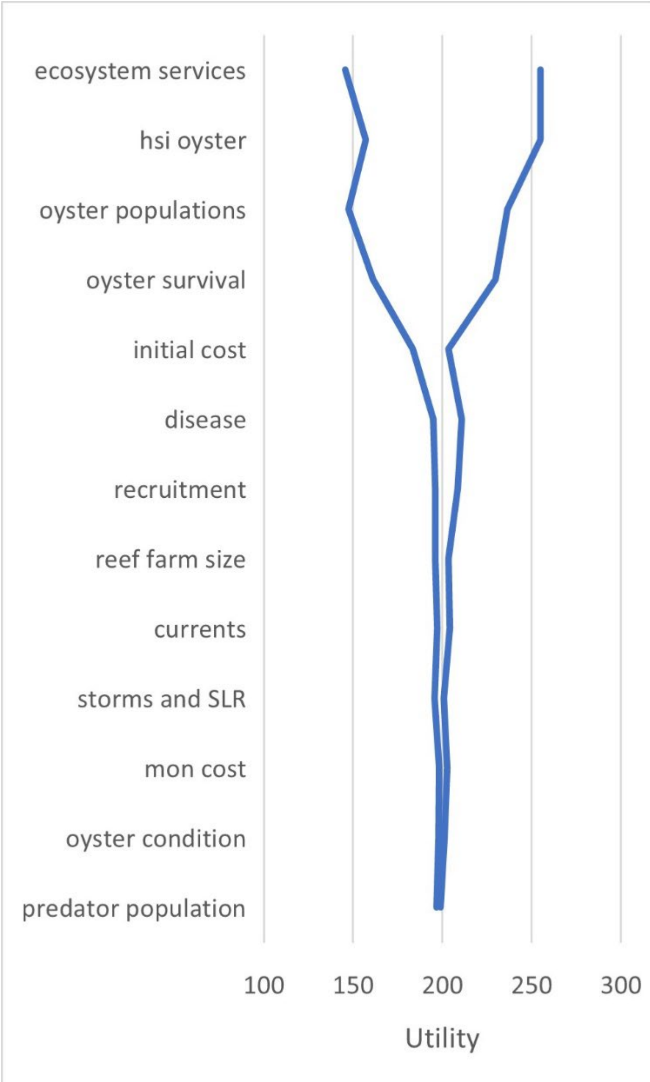



Figure 6-Influence of individual nature or uncertainty nodes on utility of building an off-bottom oyster farm. Uncertainty in the parameters is greatest at the top of the tornado diagram and diminishes near the bottom of the graph. hsi = habitat suitability index; mon cost = monetary cost.

**Appendix A: Literature used to tabulate monitoring metrics and inform the conceptual ecological model and the alpha-level Bayesian belief network**. **The citations in bold type are the 22 studies reporting monitoring data.**

Baggett, L.P., S.P. Powers, R.D. Brumbaugh, L.D. Coen, B.M. DeAngelis, J.K. Greene. B.T. Hancock, S.M. Morlock, B.L. Allen, D.L. Breitburg, D. Bushek, J.H. Grabowski, R.E. Grizzle, E.D. Grosholz, M.K. La Peyre , M.W. Luckenbach, K.A. McGraw, M.F. Piehler, S.R. Westby, P.S.E. zu Ermgassen. 2015. Guidelines for evaluating performance of oyster habitat restoration. Restoration Ecology, 23(6): 737-745. DOI: 10.1111/rec.12262.

Baillie, C.J., J.H. Grabowski. 2019. Factors affecting recruitment, growth and survival of the eastern oyster Crassostrea virginica across an intertidal elevation gradient in southern New England. Marine Ecology Progress Series, 609: 119–132.

Baldera A., D. A. Hanson and B. Kraft. 2018. Selecting indicators to monitor outcomes across projects and multiple restoration programs in the Gulf of Mexico. Ecological Indicators, 89: 559-571. https://doi.org/10.1016/j.ecolind.2018.01.025.

Bible, J.M. and E. Sanford. 2016. Local adaptation in an estuarine foundation species: Implications for restoration. Biological Conservation, 193: 95–102.

Blomberg, B.N., J.B. Pollack, P.A. Montagna and D.W. Yoskowitz. 2018. Evaluating the U.S. Estuary Restoration Act to inform restoration policy implementation: A case study focusing on oyster reef projects. Marine Policy, 91: 161-166.

**Blomberg, B.N., T.A. Palmera, P.A. Montagna, J.B. Pollack. 2018. Habitat assessment of a restored oyster reef in South Texas. Ecological Engineering, 122: 48-61. DOI 10.1016/j.ecoleng.2018.07.012**

**Blomberg, B.N. 2015. Evaluating Success of Oyster Reef Restoration. Dissertation, Ph.D., Texas A&M University, Corpus Christi. http://hdl.handle.net/1969.6/652**

Bortone, S., T. Martin and C. Bundrick. 1994. Factors Affecting Fish Assemblage Development on a Modular Artificial Reef in a Northern Gulf of Mexico Estuary. Bulletin of Marine Science. 55: 319-332.

Boulais, M., J. Vignier, A.N. Loh, F.L.E. Chu, C.R. Lay, J.M.Morris, M.O. Krasnec, A. Volety. 2018. Sublethal effects of oil-contaminated sediment to early life stages of the Eastern oyster, *Crassostrea virginica*. Environmental Pollution, 243(A) : 743-751. DOI: 10.1016/j.envpol.2018.09.017.

Casas, S. M., R. Lavaud, M.K. La Peyre, L.A. Comeau, R. Filgueira, J.F. La Peyre. 2018. Quantifying salinity and season effects on eastern oyster clearance and oxygen consumption rates. Marine Biology, 165: 90. DOI: 10.1007/s00227-018-3351-x.

Coen, LD, RD Brumbaugh, D Bushek, R Grizzle, MW Luckenbach, MH Posey, SP Powers, and G Tolley. 2007. Ecosystem services related to oyster restoration. Marine Ecology Progress Series 341:303-307.

Dillon, K.S., M.S. Peterson, C.A. May. 2015. Functional equivalence of constructed and natural intertidal eastern oyster reef habitats in a northern Gulf of Mexico estuary. Marine Ecology Progress Series, 528: 187–203. DOI: 10.3354/meps11269.

Deepwater Horizon Natural Resource Damage Assessment Trustees (DHNRDAT). 2016. Deepwater Horizon oil spill: Final Programmatic Damage Assessment and Restoration Plan and Final Programmatic Environmental Impact Statement. Retrieved from http://www.gulfspillrestoration.noaa.gov/restoration-planning/gulf-plan

**Drexler, M., M.L. Parker, S.P. Geiger, W.S. Arnold and P. Hallock. 2014. Biological assessment of eastern oysters (Crassostrea virginica ) inhabiting reef, mangrove, seawall, and restoration substrates. Estuaries and Coasts 37:962–972. DOI 10.1007/s12237-013-9727-8.**

**Fleer, V.R. 2017. Effects of Trophic Relationships on Oyster Reef Restoration Success in the Mississippi Sound. M.S. Thesis. Louisiana State University, Baton Rouge, Louisiana.**

Frederick, P., N. Vitale, B. Pine, J. Seavey and L. Sturmer. 2016. Reversing a rapid decline in oyster reefs: effects of durable substrate on oyster populations, elevations, and aquatic bird community composition. Estuaries and Coasts. 37(4): 962–972.

**Furlong, J.N. 2012. Artificial oyster reefs in the northern Gulf of Mexico: management, material, and faunal effects. M.S. Thesis. Louisiana State University, Baton Rouge, Louisiana.**

**George, L.M., K.D. Santiago, T.A. Palmer and J.B. Pollack. 2015. Oyster reef restoration: effect of alternative substrates on oyster recruitment and nekton habitats. Journal of Coastal Conservation, 19 (1); 13–22. DOI 10.1007/s11852-014-0351-y**

Grizzle, R.E., A. Rasmussen, A.J. Martignette, K. Warda and L.D. Coen. 2018. Mapping seston depletion over an intertidal eastern oyster (*Crassostrea virginica*) reef: Implications for restoration of multiple habitats. Estuarine, Coastal and Shelf Science 212: 265-272. DOI: 10.1016/j.ecss.2018.07.013

Goodin, KL, D Faber-Langendoen, J Brenner, ST Allen, RH Day, VM Congdon, C Shepard, KE Cummings, CL Stagg, CA Gabler, M Osland, KH Dunton, RR Ruzicka, K Semon-Lunz, D Reed, M Love. 2018. Ecological Resilience Indicators for Five Northern Gulf of Mexico Ecosystems. NatureServe, Arlington VA.

Grabowski JH, Peterson CH. 2007. Restoring oyster reefs to recover ecosystem services. In: Cuddington K, Byers JE, Wilson WG, Hastings A (eds.) Ecosystem engineers: concepts, theory and applications. Elsevier-Academic Press, Amsterdam, p 281–298.

**Graham, P.M., T.A. Palmer, J.B. Pollack. 2017. Oyster reef restoration: substrate suitability may depend on specific restoration goals. Restoration Ecology, 25 (3): 459–470. DOI 10.1111/rec.12449**

**Gregalis, K.C., M.W. Johnson and S.P. Powers. 2009. Restored oyster reef location and design affect responses of resident and transient fish, crab, and shellfish species in Mobile Bay, Alabama. Transactions of the American Fisheries Society 138: 314-327. DOI 10.1577/T08-041.1**

**Gregalis, K.C., S.P. Powers and K.L. Heck Jr. 2008. Restoration of oyster reefs along a biophysical gradient in Mobile Bay, Alabama. Journal of Shellfish Research 27 (5): 1163-1169.**

Grizzle, R.E., A. Rasmussen, A.J. Martignette, K. Warda and L.D. Coen. 2018. Mapping seston depletion over an intertidal eastern oyster (Crassostrea virginica) reef: Implications for restoration of multiple habitats. Estuarine, Coastal and Shelf Science, 212: 265-272. DOI 10.1016/j.ecss.2018.07.013

Gilby, B.L., A.D. Olds, C.H. Peterson, R.M. Connolly, C.M. Voss, M.J. Bishop, M. Elliott, J.H. Grabowski N.L., Ortodossi and T.A. Schlacher. 2018. Maximizing the benefits of oyster reef restoration for finfish and their fisheries. Fish and Fisheries. 19(5): 931-947.

Hallegatte S, A Shah, R Lempert, C Brown and S Gill. 2012. Investment decision making under deep uncertainty—application to climate change. Policy Research Working Paper 6193. The World Bank, Washington DC.

Hernández, A.B., R.D. Brumbaugh, P. Frederick, R. Grizzle, M.W. Luckenbach, C.H. Peterson and C. Angelini. 2018. Restoring the eastern oyster: how much progress has been made in 53 years? Frontiers in Ecology and the Environment, 16(8): 463–471. DOI: 10.1002/fee.1935.

**Humphries, A. T., and La Peyre, M. K. 2015. Oyster reef restoration supports increased nekton biomass and potential commercial fishery value. PeerJ 3: e1111.**

Irwin B, B Crawford, TG Crawford and C Moore. 2016. Turning uncertainty into useful information for conservation decisions. Southeast Climate Science Center Fact Sheet 2016-02. https://secasc.ncsu.edu/wp-content/uploads/sites/14/2019/05/SECASC_FactSheet_Turning-Uncertainty-into-Useful-Information-for-Conservation-Decisions.pdf.

Jacobson RB, MJ Parsley, ML Annis, ME Colvin, TL Welker, DA James. 2015. Development of conceptual ecological models linking management of the Missouri River to pallid sturgeon population dynamics. Open-File Report 2015-1038, U.S. Geological Survey, Reston, Virginia. DOI: 10.3133/ofr20151038.

La Peyre, M.K., D.A. Marshall, L.S. Miller and A.T. Humphries. 2019. Oyster Reefs in Northern Gulf of Mexico Estuaries Harbor Diverse Fish and Decapod Crustacean Assemblages: A Meta-Synthesis. Frontiers in Marine Science, 6: 666. DOI: 10.3389/fmars.2019.00666.

La Peyre, M.K., J. Geaghan, G. Decossas and J.F. La Peyre. 2016. Analysis of Environmental Factors Influencing Salinity Patterns, Oyster Growth, and Mortality in Lower Breton Sound Estuary, Louisiana, Using 20 Years of Data. Journal of Coastal Research, 32(3): 519-530. DOI: 10.2112/JCOASTRES-D-15-00146.1

**La Peyre, M. K., K.T. Serra, T. A. Joyner and A.T. Humphries. 2015. Assessing shoreline exposure and oyster habitat suitability maximizes potential success for restored oyster reefs. Peer J. 3:1317. DOI: 10.7717/peerj.1317**

**La Peyre, M., J. Furlong, L. Brown. B. Piazza and K. Brown. 2014. Oyster reef restoration in the northern Gulf of Mexico: extent, methods and outcomes. Ocean and Coastal Management, 89: 20-28. DOI 10.1016/j.ocecoaman.2013.12.002**

La Peyre, M.K., B.S. Eberline, T.M. Soniat and J.F. La Peyre. 2013. Differences in extreme low salinity timing and duration differentially affect eastern oyster (Crassostrea virginica) size class growth and mortality in Breton Sound, LA. Estuarine, Coastal and Shelf Science, 135 : 146-157 DOI: 10.1016/j.ecss.2013.10.001.

Le, D., W. Huang, and E. Johnson. 2019. Neural network modeling of monthly salinity variations in oyster reef in Apalachicola Bay in response to freshwater inflow and winds. Neural Computing and Applications, 31(10): 6249–6259. DOI: 10.1007/s00521-018-3436-y.

Lemoine, H.R., A.B. Paxton, S.C. Anisfeld, R.C. Rosemond, C.H. Peterson. 2019. Selecting the optimal artificial reefs to achieve fish habitat enhancement goals. Biological Conservation, 238: 108200. DOI: 10.1016/j.biocon.2019.108200.

Linhoss, A.C., R. Camacho and S. Ashby. 2016. Oyster Habitat Suitability in the Northern Gulf of Mexico. Journal of Shellfish Research, 35(4): 841-849. DOI: 10.2983/035.035.0412.

Lowe, M.R., T. Sehlinger, T.M. Soniat and M.K. La Peyre. 2017. Interactive Effects of Water Temperature and Salinity on Growth and Mortality of Eastern Oysters, Crassostrea virginica: A Meta-Analysis Using 40 Years of Monitoring Data. Journal of Shellfish Research, 36(3): 683-697. DOI: 10.2983/035.036.0318.

Marshall, D.A.., B. Lebreton, T. Palmer, K.D. Santiago, J.B. Pollack. 2019. Salinity disturbance affects faunal community composition and organic matter on a restored *Crassostrea* *virginica* oyster reef. Estuarine, Coastal and Shelf Science, 226. DOI: 10.1016/j.ecss.2019.106267.

McCoy, E., S.R. Borrett, M.K. LaPeyre, B.J. Peterson. 2017. Estimating the impact of oyster restoration scenarios on transient fish production. 25(5): 798-809. DOI: 10.1111/rec.12498.

Metz, J.L., E.W. Stoner, D.A. Arrington. 2015. Comparison of Substrates for Eastern Oyster (*Crassostrea virginica*) Spat Settlement in the Loxahatchee River Estuary, Florida. Journal of Shellfish Research, 34(3): 861-865. DOI: 10.2983/035.034.0315.

**Milbrandt, E.C., R.D. Bartleson, A.J. Martignette, J. Siwicke and M. Thompson. 2016. Evaluating light attenuation and low salinity in the lower Caloosahatchee Estuary with the River, Estuary, and Coastal Observing Network (RECON). Florida Scientist, 79 (2/3): 109-124.**

**Milbrandt, E.C., M. Thompson, L.D. Coen, R.E. Grizzle and K. Ward. 2015. A multiple habitat restoration strategy in a semi-enclosed Florida embayment, combining hydrologic restoration, mangrove propagule plantings and oyster substrate additions. Ecological Engineering, 83: 394-404. DOI 10.1016/j.ecoleng.2015.06.043**

Miller, L.S., J. La Peyre, M.K. La Peyre. 2017. Suitability of Oyster Restoration Sites Along the Louisiana Coast: Examining Site and Stock × Site Interaction. Journal of Shellfish Research, 36(2) : 341-351. DOI: 10.2983/035.036.0206.

Morris, R.L., D.M. Bilkovic, M.K. Boswell, D. Bushek, J. Cebrian, J. Goff, K.M. Kibler, M.K. La Peyre, G. McClenachan, J. Moody, P. Sacks, J.P. Shinn, E.L. Sparks, N.A. Temple, L.J. Walters, B.M. Webb, S.E. Swearer. 2019. The application of oyster reefs in shoreline protection: Are we over-engineering for an ecosystem engineer? Journal of Applied Ecology. 56: 1703–1711. DOI: 10.1111/1365-2664.

Murray, C. and D. Marmorek. 2003. Adaptive Management: A Science-Based Approach to Managing Ecosystems in The Face of Uncertainty. Prepared for presentation at the *Fifth*

*International Conference on Science and Management of Protected Areas: Making Ecosystem Based Management Work*, Victoria, British Columbia, May 11- 16, 2003.

Parker, M.L. W.S. Arnold, S.P. Geiger, P. Gorman and E.H. Leone. 2013. Impacts of Freshwater Management Activities on Eastern Oyster (Crassostrea virginica) Density and Recruitment: Recovery and Long-Term Stability in Seven Florida Estuaries. Journal of Shellfish Research, 32(3): 695-708. DOI: 10.2983/035.032.0311.

**Piazza, B.P., P.D. Banks and M.K. La Peyre. 2005. The Potential for Created Oyster Shell Reefs as a Sustainable Shoreline Protection Strategy in Louisiana. Restoration Ecology. 13(3); 499-506. https://doi.org/10.1111/j.1526-100X.2005.00062.x.**

Pierson, K.J. and D.B. Eggleston. 2014. Response of Estuarine Fish to Large-Scale Oyster Reef Restoration. Transactions of the American Fisheries Society. 143:1, 273-288. DOI: 10.1080/00028487.2013.847863.

**Pollack J.B., D. Yoskowitz, H-C. Kim, P.A. Montagna. 2013. Role and Value of Nitrogen Regulation Provided by Oysters (Crassostrea virginica) in the Mission-Aransas Estuary, Texas, USA. PLoS ONE 8(6): e65314. DOI: 10.1371/journal.pone.0065314**

**Pollack, J.B., A. Cleveland, T.A. Palmer, A.S. Reisinger, and P.A. Montagna. 2012. A Restoration Suitability Index Model for the Eastern Oyster (Crassostrea virginica) in the Mission-Aransas Estuary, TX, USA. PLoS ONE 7 (7): e40839. DOI: 0.1371/journal.pone.0040839**

**Pollack, J.B., H-C. Kim, E.K. Morgan, and P.A. Montagna. 2011. Role of Flood Disturbance in Natural Oyster (Crassostrea virginica) Population Maintenance in an Estuary in South Texas, USA. Estuaries and Coasts, 34: 187–197. DOI: 10.1007/s12237-010-9338-6.**

**Rezek, R.J., B. Lebreton, E.B. Roark, T. A. Palmer and J.B. Pollack. 2017. How does a restored oyster reef develop? An assessment based on stable isotopes and community metrics. Marine Biology, 164:54. DOI: 10.1007/s00227-017-3084-2.**

Rindone, R. and D. B. Eggleston. 2011. Predator–prey dynamics between recently established stone crabs (*Menippe* spp.) and oyster prey (*Crassostrea virginica*). Journal of

Experimental Marine Biology and Ecology, 407 (2): 216-225. DOI: 10.1016/j.jembe.2011.06.018.

Rybovich, M., M.K. La Peyre, S.G. Hall, J.F. La Peyre. 2016. Increased Temperatures Combined with Lowered Salinities Differentially Impact Oyster Size Class Growth and Mortality. Journal of Shellfish Research, 35(1) : 101-113. https://doi.org/10.2983/035.035.0112.

Schulte, D.M., R.P. Burke, R.N. Lipcius. 2009. Unprecedented Restoration of a Native Oyster Metapopulation. Science, 325 (5944): 1124-1128. DOI: 10.1126/science.1176516

Sehlinger, T., M.R. Lowe, M.K. La Peyre and T.M. Soniat. 2019. Differential Effects of Temperature and Salinity on Growth and Mortality of Oysters (Crassostrea virginica) in Barataria Bay and Breton Sound, Louisiana. Journal of Shellfish Research, 38(2): 317-326. DOI: 10.2983/035.038.0212.

Shepard, CJ Brenner, KL Goodin, and KW Ames. 2018. Ecological Resilience Indicators for Oyster Ecosystems. In: Goodin, KL et al., Ecological Resilience Indicators for Five Northern Gulf of Mexico Ecosystems. NatureServe, Arlington, VA. 40 pages.

Soniat, T.M., N. A. Cooper, E.N. Powell. 2019. Prospects for the Sustainable Management of Public Oyster Resources. Journal of Shellfish Research, 38(2):337-349. DOI: 10.2983/035.038.0214.

Soniat, T.M., C.P. Conzelmann, J.D. Byrd, D.P. Roszell, J.L. Bridevaux, K.L. Suir and S.B. Colley. 2013. Predicting the Effects of Proposed Mississippi River Diversions on Oyster Habitat Quality; Application of an Oyster Habitat Suitability Index Model. Journal of Shellfish Research, 32(3):629-638. DOI: 10.2983/035.032.0302

TinHan, T.C., J.A. Mohan, M. Dumesnil and B.M. DeAngelis. 2018. Linking Habitat Use and Trophic Ecology of Spotted Seatrout (Cynoscion nebulosus) on a Restored Oyster Reef in a Subtropical Estuary. Estuaries and Coasts, 41: 1793. DOI 10.1007/s12237-018-0391-x.

Tolley, S.G., A.K. Volety and M. Savarese. 2005. Influence of Salinity on the habitat use of oyster reefs in three southwest Florida estuaries. Journal of Shellfish Research, 24(1): 127-137. DOI: 10.2983/0730-8000(2005)24[127:Iosoth]2.0.Co;2

Vignier, J., A.Rolton, P.Soudan, F.L.E.Chu, R.Robert and A.K.Volety. 2019. Interactions between *Crassostrea virginica* larvae and *Deepwater Horizon* oil: Toxic effects *via* dietary exposure. Environmental Pollution, 246 : 544-551. DOI: 10.1016/j.envpol.2018.12.057.

Volety, A.K., L. Haynes, P. Goodman, P. Gorman. 2014. Ecological condition and value of oyster reefs of the Southwest Florida shelf ecosystem. Ecological Indicators, 44: 108-119.

Wang, H., Q. Chen, M.K. La Peyre, K. Hu and J. F. La Peyre. 2017. Predicting the impacts of Mississippi River diversions and sea-level rise on spatial patterns of eastern oyster growth rate and production. Ecological Modelling, 352: 40-53. DOI: 10.1016/j.ecolmodel.2017.02.028.

Appendix B-This appendix is published as Appendix B CSS-140-2022.xls. Available at: https://doi.org/10.3996/10.3996/css38643714