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A roadmap to the Co-production of a decision support tool for coastal ecosystems

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ABSTRACT

Coastal ecosystems are complex and often support a broad spectrum of functions with competing objectives. In addition to their ecological value, they offer socio-economic benefits (i.e., ecosystem services) to coastal communities. One potential way to help address this complexity is to use decision support systems to help natural resources managers understand system dynamics and evaluate strategies to maintain the health and integrity of these ecosystems. This paper presents a roadmap and detailed application of co-production strategies where managers and researchers are fully engaged in a collaborative manner in the design of a decision support tool for coastal ecosystems. It also emphasizes the importance of capturing end-users' (i.e., natural resource managers) priorities to refine the conceptual design of the decision support tool, while maintaining a sound scientific and modeling framework. The case study presented here centers on the Northern Gulf of Mexico, but the concept can be exported globally to other systems. This effort highlights foundational co-production strategies, including transdisciplinary team assembly, a knowledge sharing workshop, Toolbox Dialogue Initiative workshops to facilitate working across disciplines, core team and focus group meetings, and design charrettes. Further, this paper articulates the benefits and difficulties of executing a co-production process through virtual collaborations.

1. Introduction

Coastal regions are complex social-ecological systems that require conservation and management by multiple stakeholder groups representing industries, government, tourists, and local communities. These groups are likely to have varying degrees of knowledge, and often conflicting desires, about how to best manage the system they are involved with or in which they live. Given the synergistic stressors occurring on ocean margins, the management of these ecosystems and their natural resources is an especially important yet challenging task (Masson-Delmotte et al., 2021; Nittrouer et al., 2017; National Academies of Sciences, 2022). Coastal ecosystems experience environmental stressors such as storm surge, severe rainfall events, sea level rise, and in certain regions, subsidence (Masson-Delmotte et al., 2021). These environmental processes make coastal ecosystems characteristically vulnerable, and gradually degrade their health as productive habitats. Coastal ecosystems also provide provisionary and cultural services of both commercial and non-commercial resources for coastal communities, while providing the supporting services of maintaining healthy natural system dynamics- including water filtration and carbon sequestration.

Coastal ecosystems and their natural resources provide services that support the environment, economy, and human society. The management objectives, and corresponding management strategies, across these three perspectives may not align, and often are antagonistic rather than synergistic to one another. It is quite rare, and practically impossible to identify strategies that fully serve the objectives of all three components. There is a myriad of examples where these complex networks interact. For instance, in the Mekong river basin (China, Myanmar, Thailand, Lao PDR, Cambodia and Vietnam),farming, fishing, sand mining, and upper basin water management practices (through extensive series of dams), directly influence the hydrology and morphology of the system and its ability to sustain valuable natural resources (Nittrouer et al., 2017). Similarly, Chesapeake Bay and Florida's Everglades (USA) represent

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Table 1
We provide definitions to terms frequently used in this paper to offer more clarity of this work for an interdisciplinary audience. We recognize that multiple definitions may exist in the literature, but in this paper, we are using the provided definition as our theoretical framework.

Term	Definition
Boundary Spanner	Entity (individual or organization) serving to prioritize the translation of information across disciplines (Meadow et al., 2015)
Community Context Expert	Those who live, work, and/or have experience in the coastal ecosystem of interest
Co-Production	A combined effort that requires interdisciplinary or transdisciplinary participants with perhaps varying degrees of investment to work together (often simultaneously) to understand and define the problem and develop a solution (Lemos and Morehouse, 2005; Meadow et al., 2015)
Decision Support Tool	Platforms designed to integrate, analyze, and display information to assist decision makers. They may provide information about the trade-offs of management decisions and supply scientific reinforcement to their management practice toolbox (Gibson et al., 2017).
Design Charrette	An intensive workshop that focuses on a specific problem addressed by the participation of members who employ a community-based and transdisciplinary problem solving strategy to achieve a design (Sutton and Kemp, 2006)
Natural Resource Manager	Individual responsible for making management decisions related to the natural resources in a particular domain. For this effort the decisions primarily include freshwater allocation and the planning, construction, and adaptive maintenance of restoration projects.
Non-academic actor	Member from any working sector outside of academia, namely Natural Resource Managers for this effort
Stakeholder	Individual with investment in the product. These are Natural Resource Managers for this project
Toolbox Dialogue Initiative	Workshop was organized to bridge gaps between disciplines and build avenues for team members to work together in a synergistic way. These workshops are coordinated to support cross-disciplinary research by facilitating conversations and team building communication for teams working in the realm of knowledge production (Crowley et al., 2010; Schnapp et al., 2012)
Trade-off	Acceptable negative outcome in return for achieving a desired positive outcome
Transdisciplinary	Research that combines interdisciplinary and multidisciplinary researchers and aims to co-produce knowledge with non-academic actors to unify knowledge to address complex socio-ecological challenges.(Lang et. al, 2012)
Uncertainty in modeling	Uncertainty caused by bias or imprecision associated with compromises made or lack of sufficient knowledge in structure specificity, parameter estimation, or model calibration

systems with major water quality challenges resulting from high density human development that ultimately altered the natural ecosystems and their living resources (National Academies of Sciences, 2020). Coastal ecosystems experience change through a range of natural and anthropogenic controls, and are likely impacted by the legacy of disturbances that perpetuate through the system in both time and space (McClenachan and Turner, 2023). Thus, management of these systems is increasingly complicated as we grapple with both the legacies of impacts and the future challenges of global change.

Considering the sensitivity of coastal ecosystems to natural and anthropogenic drivers, maintaining the health and vigor of coastal regions requires extensive, carefully coordinated management (CPRA, 2017). This task necessitates the collaboration of experts, including both academically trained content experts and community context experts, meaning those who live, work, or have experience in the coastal ecosystem of interest. This partnership can provide complementary perspectives about living and working in the system under consideration (Mauser et al., 2013; Lang et al., 2012). Here we present a transdisciplinary (see Table 1 for a list of comment definitions used in this study) and collaborative approach to co-produce science tools directly used by natural resource managers to support coastal ecosystems. Generally, co-production is a combined effort that requires interdisciplinary or transdisciplinary participants with perhaps varying degrees of investment to work together (often simultaneously) to understand and define the problem and develop a solution (Lemos and Morehouse, 2005; Meadow et al., 2015). The coastal ecosystem system presented in this case study is the Northern Gulf of Mexico (NGOM; Fig. 1). Like other coastal ecosystems, the NGOM supports a broad set of ecosystem services across multiple states and municipalities (CPRA, 2017). The NGOM experiences a direct, and often immediate, response to climate change drivers (sea level rise, subsidence, frequency and intensity of coastal storms), and anthropogenic alterations (deepening and widening of channels to support navigation, levee systems, oil and gas activities, and upper basin water management practices). Management of natural resources in the NGOM is a shared responsibility among various local, state, and federal agencies, adding yet another level of complexity.

The management practices of the NGOM basin range in scale (temporal and spatial) and strategy. Of particular interest are two primary management practices: the allocation of riverine freshwater through control structures and the construction and maintenance of restoration projects. Largely unique, but certainly related, these two management practices may require extensive analyses to fully understand, from a scientific perspective, the best approach for their on-the-ground implementation. The expertise required to support such studies resides within the research community (e.g., academia, federal laboratories, or specialized private firms) and is potentially disconnected from the natural resources management community and individuals who will be directly impacted by the management decisions.

Several drawbacks result from these disconnections. For example, the scientific tools used to perform the analyses are complex and require substantial knowledge about ecosystem modeling, rendering them generally unusable by managers. Therefore, managers are perpetually dependent on the model developers and researchers who rarely have the means and/or time to make them more accessible for managers by training or model adaptation. Thus, managers are unable to directly ask specific (often time-restricted) management questions needed for their decision-making. Even still, many models are currently used to guide management decisions in the region, and the complexity and “black box” nature of the models is a cause for deep concern among the coastal residents. Furthermore, managers are often limited in time and resources and are restricted by barriers between science and management. Such barriers may include divergent views of the problem, priority of actions to be taken, political communication and translation. (Dale et al., 2019). Ultimately, due to the constraints of funding and time, incorporating community input is not usually feasible and managers are unable to prioritize studying the full range of scientific implications of their decisions. To account for the extensive complexities in the decision process, NRMs make management decisions that allow for adaptivity and iteratively with an emphasis on monitoring and learning how a problem evolves, changes, and responds to the external stimuli in response to the prescribed management actions (Rutherford, 1987, National Academies of Sciences, 2022).

In this study, we directly considered the disconnect between scientists and natural resource managers (NRM) in the development of a tool to support management practices This particular co-production effort used strategies, such as a virtual in-depth multi-day workshop (charrette), to prioritize the needs of NRMs. With resource managers as the primary stakeholders and end users (see Table 1 in Appendix), in collaboration with researchers, co-production strategies were used to design a science-based tool that captures the complexity natural resource management requires in the NGOM. The following research questions are addressed in this study: Can frequently applied co-production techniques be successfully used to scope a large, highly

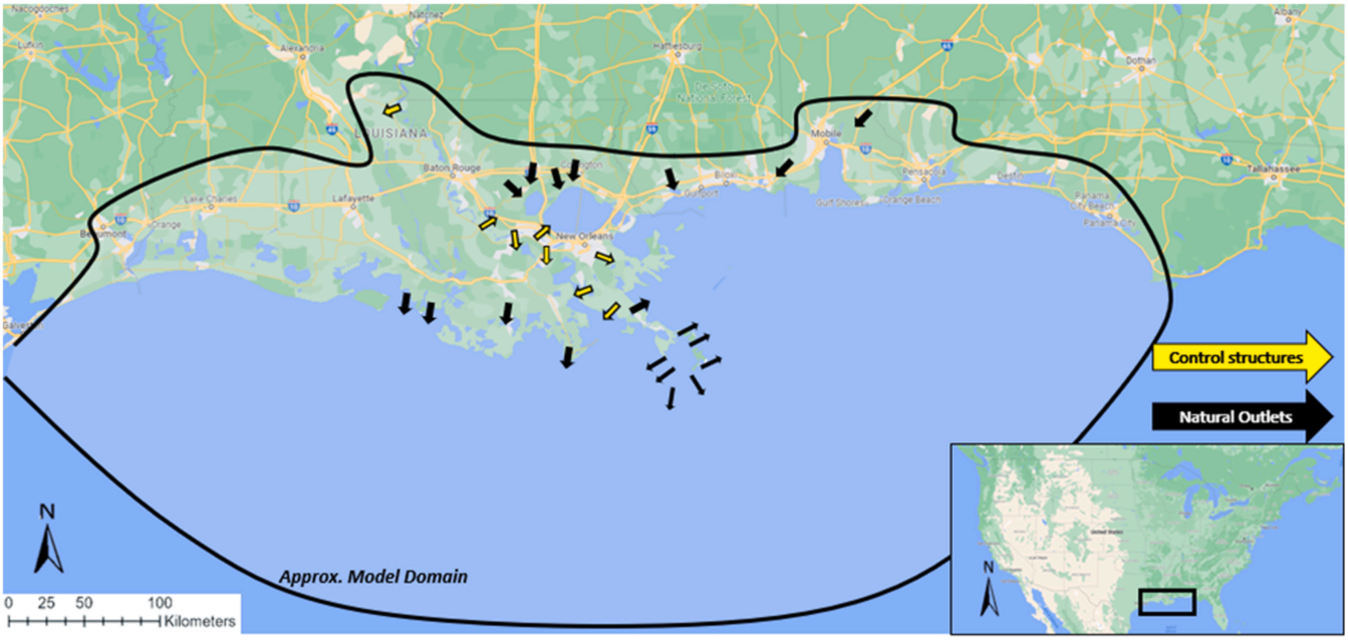

Fig. 1. Northern Gulf of Mexico with approximate decision support tool domain- yellow arrows depict existing and proposed controlled structures; black depicts rivers and natural outlets.

technical, transdisciplinary decision support system?" What are the advantages and challenges of executing a co-production effort through virtual communication and design methods? What role does decision making uncertainty have in the conceptual design of a decision support tool for coastal ecosystem management?

2. Background

2.1. Co-production theory

Effective solutions for large-scale environmental and water resources challenges require involvement from multidisciplinary managers and researchers with broad expertise (Cvitanovic et al., 2015, Cash et al., 2006). The method of integrating individual disciplines into a multidisciplinary effort can be executed in different ways. Cash, (2006), describe the more traditional linear style, referred to as a loading dock approach to problem solving, where each discipline participates to a complete extent and then transfers the entirety of their work on to the next participant. This approach may sound familiar in its assembly line style of transferring science from scientists to developers to end users. However, the translation of scientific information as it moves into the decision-making context, specifically for policy or regulation, becomes dependent on the interpretation of interest groups that may conflict, compete, and reconstruct the scientific reasoning to suit their concern. (Jasanoff, 1987). Therefore, the ability to retain scientific consistency in decision making presents a challenge if, at some point, the scientific community is disassociated.

Alternatively, for large-scale and complex environmental and water resources challenges, the co-production of strategies and solutions is a more effective approach (Arnott et al., 2020; Macher et al., 2021). Co-production is characterized by the democratic involvement of participants from multiple levels including scientists (physical, social, and ecological), managers, decision makers, and economists (Djenontin and Meadow, 2018). The co-production transdisciplinary research framework combines interdisciplinary and multidisciplinary researchers and aims to co-produce knowledge with non-academic actors to unify knowledge in an attempt to address complex socio-ecological challenges. Lang et al. (2012) argues, "Transdisciplinary, community-based, interactive, or participatory research approaches are often suggested as appropriate means to meet both the requirements posed by real-world problems as well as the goals of sustainability science as a transformational scientific field." Transdisciplinary research can be viewed as a supplement to disciplinary, interdisciplinary, and multidisciplinary research; it should be clear that transdisciplinary research is NOT the same as interdisciplinary or multidisciplinary work. Multidisciplinary research is the "cooperation of researchers from several different disciplines, but each working in their own context with little cross-fertilization among disciplines, primarily sharing information and results at the end of their research to support the overall combined findings" (Lawrence et al., 2022). Interdisciplinary research in contrast, involves a much closer interaction, including transferring methods and knowledge between the academic disciplines (sometimes in turn leading to the development of new academic disciplines, with their own characteristic knowledge, approaches, and boundaries to other disciplines (Lawrence et al., 2022). Transdisciplinary research is not meant to replace these other approaches to research, but to supplement and complement them. Defining transdisciplinary research, however, has been an ongoing debate in the literature for over 50 years, but it generally centers around two schools of thought: unity of knowledge and social engagement.

Often, the process of co-production requires initial generalization in order to bridge communication barriers that inherently exist between disciplines (Guston, 1999). The advancement from general themes and overarching problem descriptions toward the detailed "nuts and bolts" of the solution is a well-documented, challenging aspect of co-production and is reflected in the iterative nature of efforts (Lemos and Morehouse, 2005), This integration and fusion of the technical expertise of each discipline can be eased by the facilitation of a boundary spanner or boundary organization (see Table 1), common to many co-production efforts.(Kirchhoff et al., 2013, Bednarek et al., 2018). The neutral zone or facilitation provided by a boundary organization creates an environment conducive to democratic participation and greater investment from participants (Gustafsson and Lidskog, 2018). Boundary organizations serve to prioritize the translation across disciplines (Meadow et al., 2015). For example, the timing and magnitude of flooding from an engineering discipline perspective (ex. max water depth/time to peak) can be translated into a timing of management actions and response discipline perspective (ex. road closures or deploy

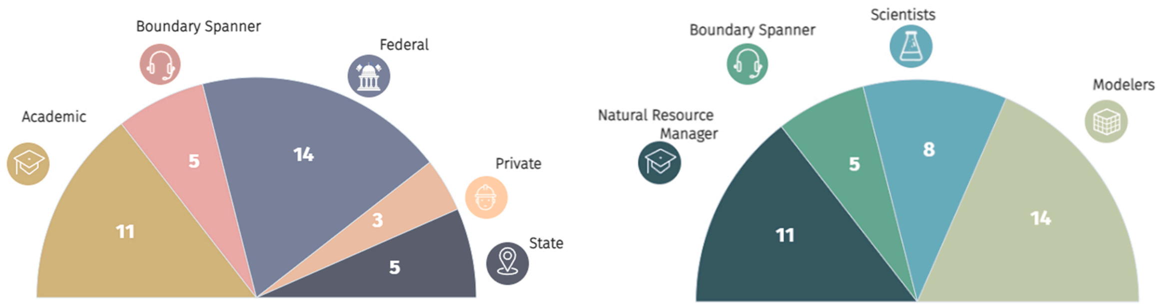

Fig. 2. Team Diversity based on Agency Type (left) and Discipline (right). Note: modelers included backgrounds in ecology, engineering, and geosciences.

emergency services for evacuation). This translator allows participants to focus on contributing their expertise with confidence that the third-party facilitator will ensure its conveyance to the larger group. Their presence provides a non-biased facilitation "node" that minimizes the possibility of one discipline dominating the effort over another.

Key to the success of a co-production effort is the initial and sustained investment of stakeholders in the problem being addressed (Tompkins et al., 2008). Stakeholders, specifically, help to drive the effort by expressing their needs, involvement, and interaction with the problem of interest. Framing the efforts in the context of stakeholder needs ensures that the outcome of the co-production is appropriate, and consequently, more likely to be applied following the effort.

A large factor in the success of a co-production effort is the level of trust that is held by participants throughout its execution (Karcher et al., 2022; Cvitanovic et al., 2021). A level of trust must exist in (a) the expertise of other team members in their respective discipline, (b) the relevance of team member's contributions and investment to the problem of interest, and (c) the co-production process itself. Co-production relies on the expertise of its participants in their respective fields. This expertise implies that members of a co-production effort must be proficient in their discipline and broad enough to navigate the project components that lie in the gray areas between disciplines. Participants may need to field questions related to their discipline to educate the larger team or make connections between project details. These participants may provide knowledge from managerial, researcher, practical, local, indigenous, and experimental backgrounds (Raymond et al., 2010). The process of co-production may be a novel experience for participants, resulting in initial hesitancy by participants, requiring the need for strong encouragement and explanation up front to stimulate engagement. Further, the co-production process itself often changes the thinking of participants (Kirchhoff et al., 2013) by increasing their awareness and knowledge of the complex problem at hand, enlightening them to different frames of reference for viewing the problem, and requiring them to exercise the skills required to work with a non-traditional group.

3. Methods

3.1. Co-production case-study for the NGOM

When comprehensively considering the management of a basin on the geographic scale of the NGOM, transdisciplinarity is requisite. The NGOM is complex, providing natural resources supporting the region's economy, safety, culture, and environment. Specifically, a significant challenge for the NRM community is understanding the complexities of *managing freshwater allocation* through control structures for the purposes of flood risk management, navigation, and ecosystem benefits and the *planning, construction, and adaptive maintenance of restoration projects* within the context of naturally occurring distributaries and long-term environmental change. For this reason, our transdisciplinary team aimed to design a comprehensive decision support tool (using integrated ecosystem models), driven by the needs and active participation of NRMs, to support NRMs in their decision making. Decision support tools are platforms designed to integrate, analyze, and display information to assist decision makers. They may provide information about the tradeoffs of management decisions and supply scientific reinforcement to their management practice toolbox (Gibson et al., 2017).

The co-production and transdisciplinary approaches themselves are not novel nor restricted to coastal ecosystem management. In fact, the U. S. Army Corps of Engineers (USACE) and other federal agencies have been organizing and planning projects this way for decades in a variety of applications and geographical locations (Barnes, 2010). These entities use transdisciplinary project development teams and often require stakeholder input prior to project execution to identify and resolve issues related to the project. We aimed to incorporate this line of thinking one step prior, by 1) using co-production in the preliminary design of a decision support tool and 2) formally involving stakeholders (the non-academic NRM community) as project members, rather than external/temporary participants. This co-production effort used virtual charrettes (Table 1) to prioritize the needs of NRMs in the NGOM and use those needs to drive the design process of the yet to be developed decision support tool. While this first effort did not include the community members or leaders as part of the process, we recognize the importance of expanding the co-production process to the coastal residents in the region. Here we outline the co-production process, which occurred over the course of 1 year, in temporal order before reflecting on the results and key topics that surfaced during the effort.

3.1.1. Team assembly

The complexities of coastal basin management require drawing together a team that represents the diversity of the problems. For the NGOM, some of these disciplines include NRMs, scientists, and engineers from entities in the public, private, and academic sectors. With an emphasis on the recruitment of NRMs, as their needs would drive the design process, a balanced team was formed. The balance reflects a blend in experience, geographical relevance, disciplines, level of expertise, agencies, and, subsequently, personalities. Team members were recruited through a series of individual or group virtual calls or emails, during which the project ideas were conveyed, and members expressed their level of commitment to join the effort. The members were solicited to capture: a) representation from both the federal and state sectors that participate in management of natural resources of this region; b) representation from broad set of academic backgrounds, e.g. ecology/biology, socio-economic, morphology, and hydrology; c) roles played by the team members, e.g., managers, decision makers, researchers, and planners. Diverse team composition is critical to ensure that a viable decision support system will be co-produced.

The diversity of team assembly influenced the progression of work through the stimulation of ideas, development of strategies and ultimately the translation of the product following project completion. Boundary spanning (Table 1) team members played a critical role in providing guidance and facilitation of the project efforts. The team composition is illustrated in Fig. 2. There is the exception where several team members are themselves multi-disciplinary (ex. John Doe is a

Module One: Values & Trade-offs

1. Ecosystem health in the northern Gulf of Mexico should be a constraint on any commercially viable use of the ecosystem.
2. Scientific knowledge is inevitably disconnected from the places to which it is applied.
3. Our forecast model must anticipate ecosystem shifts due to climate change.
4. Social concerns should outweigh ecosystem needs when making decisions about what is included in our forecast model.
5. Natural resource managers should have as much decision-making power as the modelers in developing the model.
6. There are aspects of our project that we would not modify even in light of stakeholder input.
7. Navigation and flood risk management are non-negotiable constraints on the optimization of natural resources in the northern Gulf of Mexico.
8. Existing models are not sufficient to meet the needs of natural resource managers.

Module Two: Communication & Collaboration

1. The success of our project depends on clear and regular communication between modelers and natural resource managers.
2. The biggest obstacle to successful management of natural resources in the northern Gulf of Mexico is divergence among the priorities of agencies and institutions that have a stake there.
3. We understand what co-development of a management and forecast system looks like for our project.
4. The most challenging part of our project will be reconciling the needs of the various resource managers while making a useful tool.
5. Scientific research is too abstract to be directly applicable to the problems natural resource managers face.
6. It is the researcher's responsibility to make their research accessible to natural resource managers.
7. Natural resource managers and researchers should jointly determine the criteria that guide particular management decisions.
8. New scientific tools should be designed to be easy to use by natural resource managers.

Fig. 3. Toolbox Dialogue Initiative (TDI) prompts provided to participants during the TDI.

natural resource manager (NRM) and numerical modeler), which provided unique perspectives to the group. Additionally, some disciplines, absent from the original team construct, were identified as valuable to solicit input from to continue this effort in future projects. Namely, economists and social scientists were vital to the continuation of this project, as the team worked to gather expertise that the tool development required for the next phases of tool development.

3.1.2. Core team and focus groups

The formation of a core team, consisting of 3–5 team members, was critical to the success of the co-production process for a large and complex ecosystem decision support system. For the application presented here, the core team was instrumental to maintain progress in the co-production effort while ensuring full engagement of all participants. The core team produced and synthesized material resulting from workshops and prepared material for the next steps. The group maintained the communication and coordination of the larger team and ensured that efforts and outputs aligned with the primary goals and objectives of the project.

While full-group meetings are essential to the co-production process, a series of focus group meetings were needed to address specific aspects of the conceptual design. Coordinating the timing of these various meetings supports team progress. Working in a space with members of the same discipline allowed for constructive and efficient communication, while keeping the larger project context in mind. These focused-group meetings also allow for a deep dive into individual disciplines with more freedom to use technical jargon. The two focus groups that met routinely included a NRMs group (the primary stakeholders) and a modelers group, since the decision support tool was designed as a suite of interconnected numerical ecosystem models. In sum, the focus-group meetings provided the opportunity for moments of clarity that could be concisely communicated back to the larger team and eliminate confusion.

3.1.3. Knowledge sharing

The foundational step was a knowledge sharing workshop, which provided an opportunity for team members to gain familiarity with each other and share their experience and expertise relating to the project content. This event, led by our boundary organization, The National Charrette Institute (NCI; https://www.canr.msu.edu/nci/) allowed the team to build relations and discuss the current state of knowledge on multiple NGOM issues. The knowledge sharing workshop also set the precedent for subsequent communications and design efforts by demonstrating the role of the boundary spanner in facilitating team interactions.

The workshop involved a balance of educational tactics, including presentations, small group discussion, question and answer segments, large group discussions, and interactive polling. The interactive style of the workshop was critical for establishing a confidence between team members and the co-production process itself. After introductions and a reiteration of the overall project goals, small group discussions led to the identification of "what is known", "where are the knowledge gaps", and "what activities are needed to address the challenges" for four main topics: operational policies, primary riverine systems, existing forecasting systems, and critical natural resource issues.

The workshop provided material that shaped the next steps and revealed aspects of the effort that would be unique moving forward. For example, one unique aspect is that the evolutionary style of designing the system was different from the traditional style of science development to which team members were accustomed. This process of co-production introduced ambiguity initially, but the importance of the work and the needs of NRMs remained at the forefront to encourage forward progress. Differences in the use and understanding of scientific terminology were identified and highlighted the general communication barriers that existed between the transdisciplinary team. Additionally, team members discussed varying degrees of investment in the project effort and some inherent conflicting natures of the interest of basin management. For example, geographic "scale" emerged as an important topic because some experts may be concerned with the representation of the space an individual or select species occupies, whereas other experts are focused on the larger scale space necessary for adequate hydrodynamic representation.

3.1.4. Toolbox Dialogue Initiative workshop

Following the Knowledge Sharing activity, the NCI then led a ©Toolbox Dialogue Initiative (TDI) workshop to bridge gaps between disciplines and build avenues for team members to work together in a synergistic way. These workshops are coordinated to support cross-disciplinary research by facilitating conversations and team building communication for teams working in the realm of knowledge production (Crowley et al., 2010; Schnapp et al., 2012). Prior to the TDI workshop, probing statements were developed (based on discussions in the knowledge sharing workshop) in prompts that would stimulate discussions. The prompts allowed topics to be explored from the perspectives of the whole team. The prompts in Fig. 3 were designed intentionally to surface varying perceptions and opinions surrounding NGOM basin management.

The discussions were facilitated by NCI and provided a democratic space for participants. The dialogue allowed the team to formulate strategies for working together moving forward and clarified discrepancies between terminology, assumptions, and project goals. Specifically, the group had discussions about the values and trade-offs related to coastal basin management in the NGOM and the collaboration and communication required to accomplish this task. NRMs emphasized that scientific tools are only one component of their decision-making process. They expressed that social, economic, and political factors influence decision-making and may conflict with the scientific suggestions for NR management. Another point highlighted in the TDI was the necessity of communication across disciplines in NR management beyond this particular project effort. Uncertainty was an important theme that

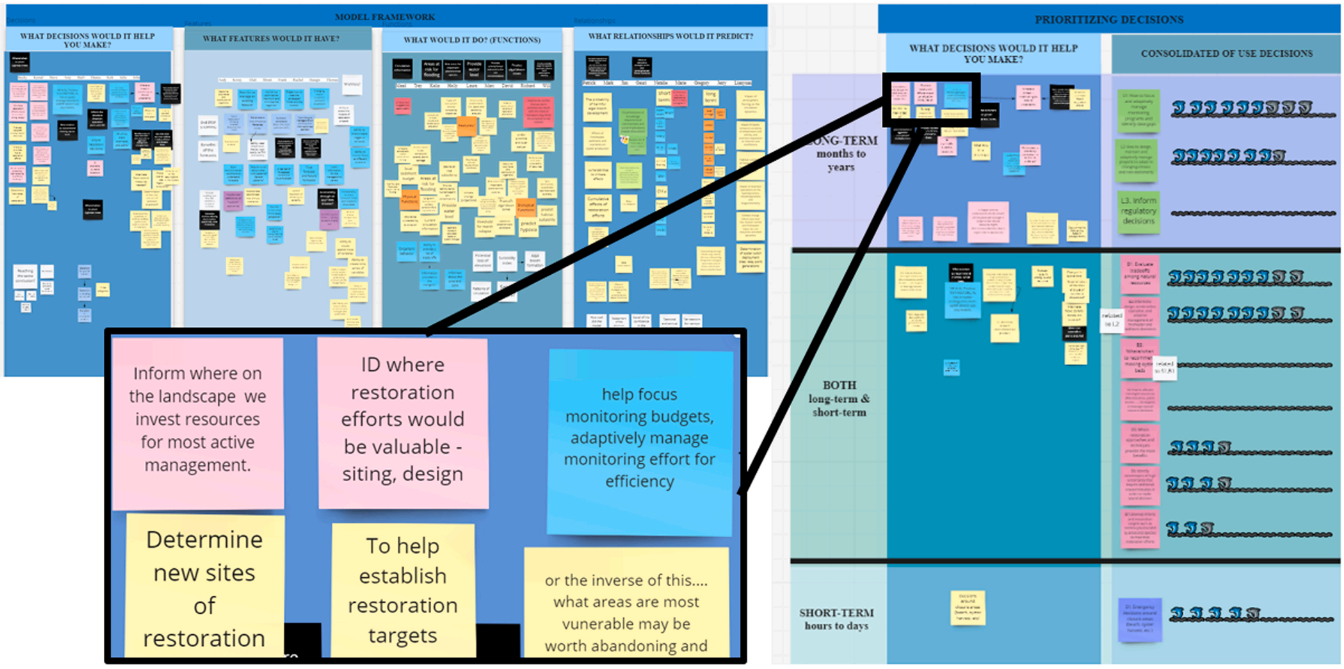

Fig. 4. *©Miro frames created during the design charrette populated by sticky notes from participants. See inset image for subset of responses to the prompt "what decisions would it (the tool) help you make?".*

emerged. The development of this decision support tool involves both the uncertainty related to model interpretation and inherent scientific uncertainties related to future projects.

3.1.5. Design charrette

One of the key elements of the co-production process presented here, is a multi-day charrette. The design charrette served as the primary mechanism for achieving a preliminary or conceptual system design. A design charrette is an intensive workshop that focuses on a specific problem addressed by the participation of members who employ a community-based and transdisciplinary problem solving strategy to achieve a design (Sutton and Kemp, 2006). This style of co-production is characterized by an iterative process of information sharing, idea generation, prototyping, and prioritization to culminate in a designed product (Howard and Somerville, 2014). Charrettes have historically occurred in the Gulf States, organized by the USACE and other agencies, to address problems in the NGOM (Louisiana Charrettes Move To Arabi, 2006, Engineers, 2003). This mechanism of design requires active participation, encouraging the team to "design with" stakeholders instead of "design for" them in producing the outcome. For the NGOM application, boundary spanners (i.e., the NCI team) worked with the core team members to organize and prepare for the charrette. Breakout groups were strategically arranged to reflect transdisciplinarity, and topics were carefully constructed to serve as the guideposts for discussions. Activities were planned to gather feedback/input, along with a selection of virtual platforms and tools that would be employed to execute this meeting to create the framework for the decision support tool. The preparatory work was important because it structured activities and assignments that provided enough directive to members to guide them into interdisciplinary dialogue around project relevant content yet was flexible enough to allow the meetings/working sessions to evolve in response to the team's momentum.

The charrette was executed by the entire team working together in a concise time frame (~3 days, 5–6 h/day, ~25 participants) to produce a preliminary design of the system framework. While charrettes are commonly held in person, due to COVID-19, this charrette was conducted through an extended video conference. It involved group-organized dialogue with the entire team and small breakout group discussions, ranging from 4 to 8 participants/group. It included an iterative process of brainstorming and review that was required for several design components to evolve concurrently. The process equated to efficiency and quality control of material produced. The primary platforms used to record and document the virtual workshop were ©Zoom and ©Miro. ©Miro frames and tiles were designed and refined throughout the charrette. Some tiles included material such as: decision support tool features, short term forecast questions the tool could help NRMs answer, applications of the tool, plans for advancing the design following the charrette, and more. Fig. 4 illustrates two of the several ©Miro frames utilized during the charrette.

Following the charrette, the core team synthesized the outputs and delivered it back to the team. As the charrette was the main vehicle for the conceptual co-produced system, the outcomes of the charrette are worth mentioning, listed next in sequential order. For the management system, NRM needs were defined. These needs were the driving focus of the design and were continually referred to by the team to maintain appropriate focus. From there, the team focused their efforts on the "nuts and bolts" of the system's conceptual design. The drivers, processes, parameters, and visuals of the system were organized and documented. The work reflected the aspects of existing scientific tools in combination with novel components, reflecting the needs unique to this project.

3.1.6. Virtual collaboration and support material

Considering the amount of dialogue required by this co-production effort, it is worth mentioning that nearly the entire case study presented here was conducted in a virtual format. The ability to maintain stakeholder engagement and project advancement through virtual means has been recently evaluated in wake of the Covid-19 pandemic (Köpsel et al., 2021). Although some suggest that virtual collaboration may produce some hinderances to equal participation (Beaunoyer et al., 2020), we propose unique advantages to virtually executing the co-production effort. The notably recent shift of work from in-person to virtual platforms was advantageous for this effort, partly due to the level of proficiency that team members have with virtual meetings and participation. Additionally, the logistics (and cost) of physical team assembly was eliminated, allowing for a larger and more frequent degree

Fig. 5. Communication tools employed for the project.

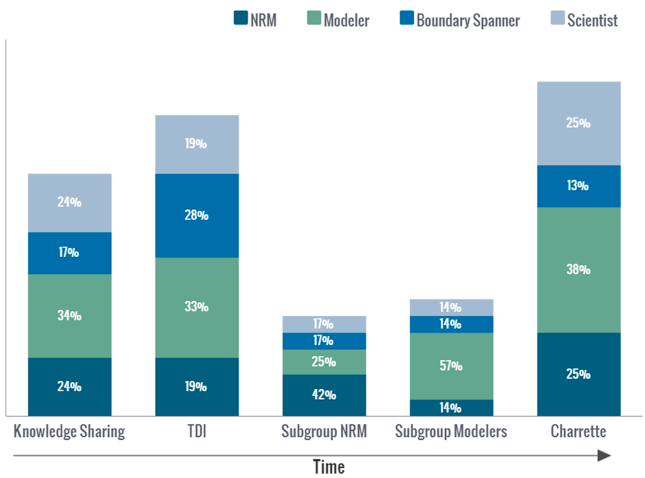

Fig. 6. Participant involvement in the co-production process, separated by discipline.

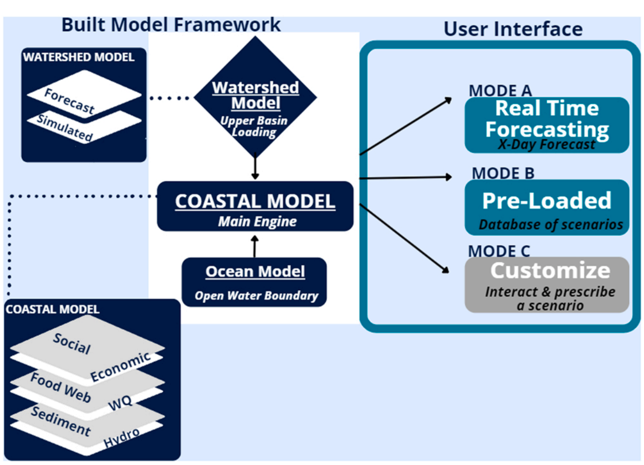

Fig. 7. Preliminary decision support tool design developed during the co-production process.

of participation from team members who otherwise would have required extensive travel arrangements. As mentioned previously, the team used the online design tool ©Miro, through boundary spanner facilitation, as a working environment or design studio for the project. Often, activities within the meetings involved participants contributing to the design process anonymously (for example through adding an idea on a sticky note). The anonymity was advantageous to less outspoken team members, who might typically shy away from expressing their views had the meetings been conducted in person. The virtual and anonymous space created an unbiased and inclusive platform for members to participate and evaluate responses objectively, which is desirable in any scientific endeavor. In addition to virtual meetings, the team employed several communication tools (Fig. 5) to maintain transparency, inclusivity, participation, and quality of work.

The team shared online databases, archived documents, video recordings of all main meetings and workshops, and an active website. The dissemination of this material, particularly recordings that allowed the team to be privy to any meeting dialogue, provided a level of transparency that may not be achievable in all co-production efforts.

Team participation cycled from large to small working groups throughout the project life. The involvement of various disciplines fluctuated throughout the design process (Fig. 6). A strong level of initial engagement of the entire team is evident, with intermittent smaller working sessions. The emphasis on initial engagement is important because of the characteristic time needed to establish cohesiveness among diverse stakeholders. (Karcher et al., 2022). Once engaged, the collaboration fostered continued ownership and accountability for both the problem and developed solution. (Mauser et al., 2013). Maintaining stakeholder investment was a critical component of this effort and was sustained through individual and group “check ins.”

4. Results

Together, the authors represent members from the disciplines of science, engineering, management, modeling, and boundary spanning. The results discussed here express a collective reflection by the authors, who all participated in the co-production process for the duration of the effort.

4.1. Conceptual design

It should be noted that formulating a system design does not necessarily equate to a successful co-production effort. Moving forward, an effectively developed system needs to be available and fully operational to a NRM to examine scenarios and issue a decision regarding freshwater allocations or siting/funding/prioritizing restoration projects. Starting with a clear and accessible conceptual design was the first step toward developing a tool that is accessible to NRMs, specifically those without modeling expertise. The design depicted in Fig. 7 was developed to encompass the contributions from the co-production effort.

The conceptual model framework (Fig. 7) consists of a coastal model equipped with computational layers required to address the management decision in question. The coastal model is driven by freshwater, sediment, and nutrient loading from the upper basins and by the Gulf of Mexico conditions provided through an Ocean Circulation model. The team outlined a web-based portal that would operate in three modes: A) Operational Real Time Forecasting, b) Rapid Decision Support, and C) Customized Analysis. Mode A would provide real time forecasting of the basin in the time frame of days to weeks. Mode B consists of a preloaded database of model output that has been populated by a series of predefined permutations. These permutations (in the order of 100’s or 1000’s) would be formulated by NRMs based on envisioned upcoming needs and wish lists. Mode B would allow a NRM to browse scenarios that have already been computed to gain an understanding of tradeoffs and system response to basin management. Mode B may provide insight to the system’s dynamics and response so that the NRMs can gain quantitative insights and help them formulate effective strategies beneficial to their NR of interest. Finally, Mode C would provide NRMs the opportunity to customize the modeling system for their particular decision of interest and produce output to reflect the scenario they have developed.

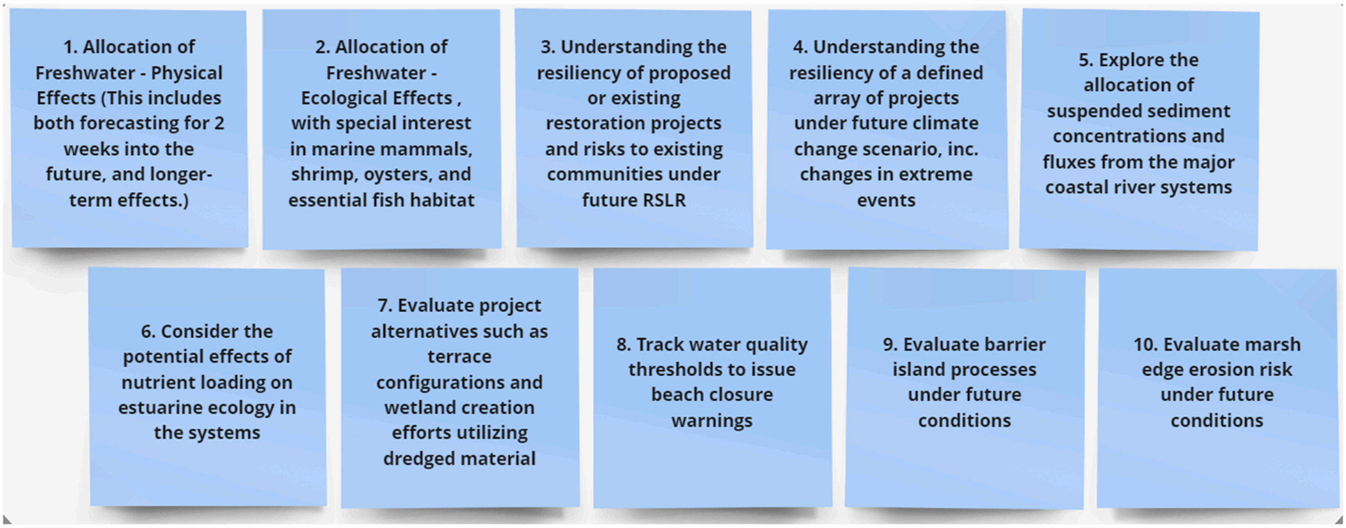

Fig. 8. *©Miro frame of example applications of the decision support tool.*

Application #1 – Freshwater Allocation: Physical Conditions (example 1)

Objective: Explore options between the allocations of freshwater at the various man-made and natural diversions on the lowermost Mississippi River to simultaneously address flood risk management, navigation considerations, and natural resource management.

Description: There are numerous man-made and natural locations which divert freshwater out of the Mississippi River. Currently, there is no comprehensive tool which explores the relative merits and costs of utilizing one system over another (synergies and unforeseen outcomes to tone it down a bit – use effects instead of impacts). This tool will allow for various flows at all locations and report the resultant salinity at numerous nodes across the northern Gulf.

Participants: USACE, USGS, NOAA, States of AL, MS, LA

Regulatory Context: Water Control Manual for existing diversions including: ORCC, Morganza, Bonnet Carre' Spillway, Davis Pond, Caernarvon

Workflow:

Drivers	Parameters	Processes	Visuals
• Riverine FW inflows • Tides • Winds • Rainfall	• Discharge • Water level • Salinity • Temperature • Velocities	• Hydrodynamics • Estuaries, shelf, gulf circulation • Economic Impacts • Social Impacts	• Timeseries- at key locations in Maurepas, Pontchartrain, Bay St. Louis, Mobile Bay, Barataria, and Breton Sound Basins • Spatial static maps • Animations

Time Scale: Short term- days to months

Spatial Scale: ORCC to the AL/FL line to Atchafalaya

Data Sources: USGS, USACE, CRMS, NOAA,

Data Characteristics (format and metadata): projections, coordinate systems, units

Model Sources: Tulane Delft + Economic + Social +?

Mode of Operation: Explain how it will be used in various modes of operation

(Prototype developed)

Fig. 9. Expanded example application illustrating the context for utilizing the decision support tool.

4.1.1. Applications

To explain and justify the continuation of this project from design to development, real-world applications were defined during the charrette to communicate the utility of this type of system. These example applications (Fig. 8) were developed to concretely illustrate instances of system employment.

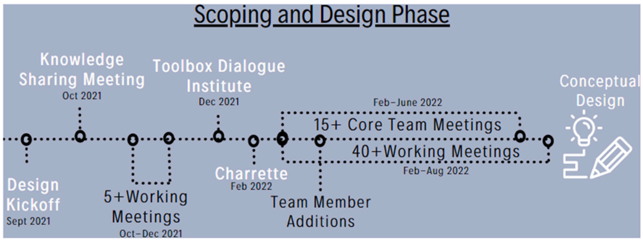

Fig. 10. Summary of the timeline for the co-production of conceptual design of a decision support system.

Each application carries a description such as the context, scale, agencies involved, and desired model outputs. The specificity dually serves to verify the utility of the design that was formulated in the charrette and provides information that could supplement or enhance the proposed system design. It was a particularly useful exercise, requiring a thorough review of the charette material to capture the collective team sentiments. An example of an expanded application for the tool is provided (Fig. 9).

4.2. Uncertainties of the decision-making process

One of the biggest concerns of NRMs regarding the use of decision support systems and computer models in general, are the uncertainties associated with numerical-modeling-based decisions (Lempert, 2019). Thus, the team carefully considered effective approaches to address uncertainties in the decision-making process. Due to the presence of varying types and degrees of uncertainty, it is necessary to outline the specific uncertainties that relate to and emerged within this case study.

Commonly, two kinds of uncertainties are defined, epistemic uncertainty and aleatory uncertainty (Yoe et al., 2010). Epistemic uncertainty is due to a lack of knowledge on the part of the observer, and, in theory, is reducible, though it may be expensive or difficult to do so. A collateral advantage of setting up a numerical model or decision-support system is often that the structure of the system will expose obvious data gaps and the lack of critical knowledge about relationships between environmental factors, which can then be prioritized by the research community. An excellent example of epistemic uncertainty in the case study that describes a lack of precise understanding between the relationship of coastal salinity and the health of specific animal species. This topic was explicitly mentioned during the co-production process by NRMs from state and federal agencies. Aleatory uncertainty is due to a random process and is attributed to the natural variability of a quantity over time or space. It is considered irreducible and cannot be known simply by collecting more data, though the understanding of the variability of the parameter might change with more information. In this case study, the annual variation in the flow of the Mississippi River is an example of aleatory uncertainty.

Yoe et al. (2010) also states that it is common to see uncertainty categorized by its source. Uncertainty caused by bias or imprecision associated with compromises made or lack of sufficient knowledge in structure specificity, parameter estimation, or model calibration is called model uncertainty. Quantifying uncertainty arises when there is uncertainty associated with the value to use for an input parameter in a model to estimate outcomes. This source of uncertainty generally results from aleatory uncertainty. The uncertainty that results when the elements of a scenario or application to be tested are unknown or incomplete is called scenario uncertainty. Not fully understanding the response of an ecosystem to a specific aspect of climate change is an example of this type of uncertainty.

Many of the above types of uncertainties will be addressed within the development of the numerical model that will be used as the basis of the decision support system using a series of techniques common to model development, including the identification and focus on key uncertainties and sensitivity analysis. Using best available observations for extensive sensitivity analyses, along with careful model calibration and validation, will reduce (but obviously not fully eliminate) these uncertainties.

More important is the role that this decision support tool can contribute to guiding decision making when there is "deep uncertainty." Lempert (2019), Lempert et al. (2003) consider the resulting situation to

Table 1
NGOM co-production effort stakeholders.

End User Stakeholders Organization
US Army Corps of Engineers
NOAA- Fisheries, Southeast Regional Office
National Park Service
Alabama Department of Conservation and Natural Resources
Louisiana Department of Wildlife and Fisheries
NOAA- Office of Water Prediction
Louisiana Coastal Protection and Restoration Authority
Mississippi Department of Environmental Quality
US Fish and Wildlife Services
Mississippi State University
Morgan State University
University of New Orleans
Louisiana Department of Environmental Quality
University of South Alabama
United States Geological Survey
Environmental Defense Fund
Pontchartrain Conservancy
Coalition to Restore Coastal Louisiana
The National Wildlife Federation

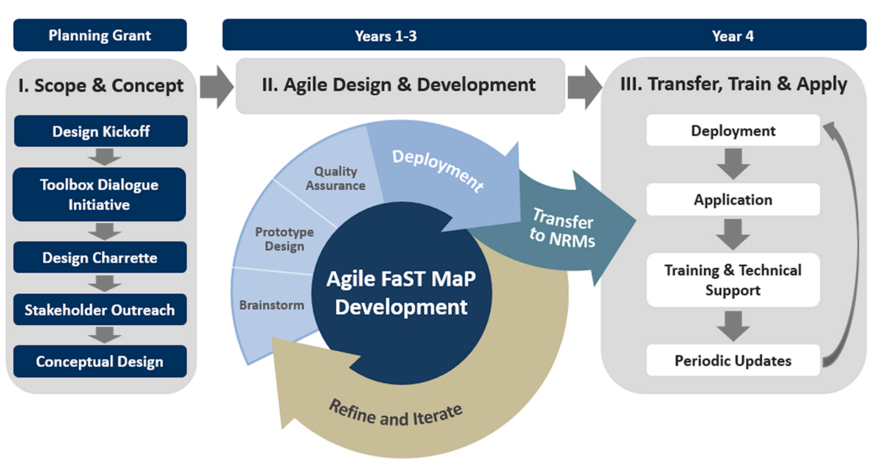

Fig. 11. Co-production plan for design and development of NRM decision support tool.

be “deeply uncertain”—a situation in which the experts do not know or the parties to a decision cannot agree upon “(1) the appropriate models to describe the interactions among a system’s variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes”. Haasnoot et al. (2013) adds that “deep uncertainty also arises from actions taken over time in response to unpredictable evolving situations.” These descriptions define the situation in the NGOM where magnitude and intensity of long-term changes in many features such as climate change impacts on relative sea level rise, river flows and plant growth as well as effects from subsidence, ocean acidification, tropical storm frequency and intensity are unknown (National Academies of Sciences, 2022). Additionally, there are many non-scientific uncertainties, including future social and political positions, funding constraints and the timeframe in which decisions will be made.

To apply methods for decision making under deep uncertainty it is necessary to use analytical methods for decision support. Lempert, (2019) suggest using a definition from the US National Research Council (National Research Council, 2009), which states that decision support represents a “set of processes intended to create the conditions for the production and appropriate use of ”decision relevant information.” Three key tenets for decision support are emphasized: 1) the way in which information is integrated into decision making processes is important; 2) the knowledge used must be co-produced by information users and producers; and 3) the decision process must be designed to facilitate learning. In this way, the development of this decision support tool, which is co-produced and designed to facilitate learning by NRMs, will address deep uncertainty by providing a reproducible analytical method to test scenarios and illustrate tradeoffs. Additionally, the collaborative process of designing the decision support tool incorporates the multiple types of knowledge relevant to solving problems with inherent uncertainty (Armitage et al., 2009).

Furthermore, the team reviewed three approaches for decision support under deep uncertainty that will be integrated into the design of the decision support system. The first, Robust Decision Making (RDM) is a set of concepts and processes that use computation not only to make better predictions but to make better decisions under conditions of deep uncertainty by systematically exploring the consequences of assumptions with myriad model runs (Lempert, 2019). Secondly, Walker et al. (Walker, 2000) describe Dynamic Adaptive Planning (DAP) as an approach which focuses on implementation of an initial plan and subsequent adaptation of the plan over time as new knowledge is attained. This method specifies the development of monitoring programs and outlines specific responses when explicit targets or trigger values are reached. Thirdly, Haasnoot et al. (2013) describe Dynamic Adaptive Policy Pathways (DAPP) as an approach which explicitly considers the timing of actions and is based on Adaptation Tipping Points. Although none of these approaches eliminate uncertainty, the implementation of these approaches can provide a more global perspective of the potential impacts of NRMs decisions. Furthermore, designing the decision support tool with both real-time forecasting and a long-term planning mode will provide a degree of scenario adaptation functionality (customizable by the end-user) that both DAP and DAPP suggest is key to addressing deep uncertainty inherent in management decision making.

5. Challenges and reflections

This team was able to make unique contributions as a large group collaboration despite significant geographical and time zone disparities, along with prominent disciplinary differences. Using NRM’s needs as the driving focus, the team accomplished its intended goal of a preliminary system design. Non-tangible outcomes were achieved, as well, which is fairly common in co-production efforts (Djenontin and Meadow, 2018). Generally, an overall enhanced understanding of the management of the NGOM and strategies for improvement. Team members were educated on the current state of basin management and gained a transdisciplinary understanding of the system.

Some of the challenges of our co-production efforts highlight opportunities for improvement in future efforts. One difficulty, as previously mentioned, is the variety in terminology across fields. With neighboring disciplines, several of the same words are used with a slightly different context. For example, the terms “urgency” and “stability” imply different meanings for the range of disciplines involved: ecologist, geomorphologist, engineers, etc. The term “uncertainty” begs elaboration and input from multiple disciplines because of its several interpretations and as discussed previously. This disciplinary jargon can be grounds for confusion, uncertainty, or lack of confidence in proceeding. Another challenge is that the initial vagueness of co-production efforts leads to a hesitancy of trust in the process. A lack of trust cascades to a more passive energy of members in their contribution to the conceptual design effort. Approximately halfway through the design charrette, core team members saw a decline in participation, likely attributed to frustration and fatigue that emerged during the system design and workshop proceedings. The presence of a third-party facilitator helped to counter this issue by providing structure for the communication and evolution of the system design. Another challenge in many co-production activities, is when dominant personalities cause an unbalanced level of participation by team members. By providing options, such as polling, voting, or group editable documents, we were able to minimize this difficulty and encourage healthy equal participation.

A notable challenge remains that the majority of this effort was conducted in a virtual format, equating to a lack of in-person, informal interactions. Although we pointed out the usefulness of virtual meetings, we contend that unstructured conversations between team members can often provide stimulation for new ideas or enhancements to the project. One counter to this challenge was the team’s ability to take advantage of an event external to the project: the 2022 Gulf of Mexico Conference. This professional conference took place during the co-production period. The team communicated the degree to which they would be in attendance and were able to arrange small meetings around the conference schedule. The conference interactions proved to be a great stimulus for design advancement, networking, and even a morale boost.

One key success metric is the interdisciplinary team retention beyond the planning effort described in this case study. Given that around 30 team members participated in the planning effort over the 1-year period, 30 members committed to a developmental phase of the decision support tool. Of the members who participated in the planning phase, 9 members were either replaced or added to the team. These team member changes occurred for various reasons, such as the need to incorporate economists and social scientists in the next phase of development, or other participants changing careers and leaving their discipline. In addition to team preservation, the 1-yearlong co-production planning effort documented ~70 meetings and ~8 presentations/conference outreaches involving the participation of anywhere from 3 to 30 team members per meeting. The buy in from the NRM community to employ such a sophisticated scientific tool is a crucial achievement of this process. The sustained engagement of NRM stakeholders provided expertise, trust, and commitment to the effort that could not be substituted by other means.

6. Conclusions

The management of a system as geographically large and complex as the NGOM requires the participation of several entities with various technical disciplines, jurisdictions, and regulatory authority. The representation and participation of this unique pool of managers and researchers who interact with and influence the ecosystem management, is key to the successful co-production of decision support tools. The transdisciplinary co-production described in this paper is not a rigid nor a linear process, but rather a flexible and collaborative approach to address complex ecosystem challenges where "traditional" and discipline-specific approaches have fallen short.

The team's co-production effort led to the design of a decision support framework to support NRMs that was driven by the specific needs of managers and reflected the desired attributes of those decision makers. In addition to designing tool components, NRMs explored specific applications of how they would be able to use the tool for their individual management decisions, paving the way for direct utility once the tool is developed. A summary of the steps and stages that ultimately resulted in the conceptual design are provided (Fig. 10).

Though the preliminary conceptual framework will require refinement to move the product into development, the framework has the potential to provide support to NRMs in a manner currently unavailable to them. More importantly, the process that led to its development educated and invested a team of NRMs and set the infrastructure for their continued collaboration to see this product through development. The plan for continued collaboration and co-production is shown in Fig. 11.

The plan for continued collaboration contains features reflecting the direct enhancement of using a co-production pursuit. Namely, the iterative design and deployment of the tool requires that the NRM community remains active in the transdisciplinary effort. In this way, a co-productive feedback loop can refine the tool design as it translates from concept to form. This type of user feedback would be completely void from a design effort that was restricted to a technical, academic, or single-disciplinary design group.

Through this effort, the priorities of NRMs focused on decision support systems that (a) provides information in a timely manner (short response time), (b) synthesizes and expresses the output in a manner directly relevant to management decisions, and (c) and integrates physical and biological sciences with socioeconomic outcomes. This collaborative effort also highlighted the need to focus on the ability of predictive tools to support making better natural resources management decisions, rather than dedicating effort to simply improve the numerical models to make better predictions. Further, the case study presented here clearly highlights the strong interest from the natural resource management community in actionable and translational science. We encourage others in the research community to dedicate efforts and attention to producing scientific tools that can be readily used to support management decisions.

CRediT authorship contribution statement

Laura Manuel: Conceptualization, Writing – original draft, Writing – review & editing. **Ehab Meselhe:** Conceptualization, Supervision, Methodology, Writing – review & editing. Barbara A. Kleiss, Validation, Supervision, Writing – review & editing. **Kristy A. Lewis:** Conceptualization, Writing – review & editing. **Holly Madill:** Conceptualization, Methodology, Writing – review & editing. **Mead Allison:** Validation, Writing – review & editing. **Steve Giordano:** Validation.

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Appendix

See Table 1.

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