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Facilitating Integration in Interdisciplinary Research: Lessons from a South Florida Water, Sustainability, and Climate Project

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Abstract

Interdisciplinary research is increasingly called upon to find solutions to complex sustainability problems, yet co-creating usable knowledge can be challenging. This article offers broad lessons for conducting interdisciplinary science from the South Florida Water, Sustainability, and Climate Project (SFWSC), a 5-year project funded by the U.S. National Science Foundation (NSF). The goal was to develop a holistic decision-making framework to improve understanding of the complex natural–social system of South Florida water allocation and its threats from climate change, including sea level rise, using a water resources optimization model as an integration mechanism. The SFWSC project faced several challenges, including uncertainty with tasks, high task interdependence, and ensuring communication among geographically dispersed members. Our hypothesis was that adaptive techniques would help overcome these challenges and maintain scientific rigor as research evolved. By systematically evaluating the interdisciplinary management approach throughout the project, we learned that integration can be supported by a three-pronged approach: (1) Build a well-defined team and leadership structure for collaboration across geographic distance and disciplines, ensuring adequate coordination funding, encouraging cross-pollination, and allowing team structure to adapt; (2) intentionally design a process and structure for facilitating collaboration, creating mechanisms for routine analysis, and incorporating collaboration tools that foster communication; and (3) support integration within the scientific framework, by using a shared research output, and encouraging team members to adapt when facing unanticipated constraints. These lessons contribute to the international body of knowledge on interdisciplinary research and can assist teams attempting to develop sustainable solutions in complex natural–social systems.

Keywords Interdisciplinary science · Team science · Collaboration · Adaptive management · Knowledge co-production

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Introduction

Interdisciplinary research projects are increasingly called upon to understand, explain, and offer solutions to complex environmental issues. Such multi-faceted, dynamic problems demand an interdisciplinary lens because they often lack a definitively "correct" solution, hence sometimes referred to as "wicked problems" (Rittel and Webber 1973)—such as how to develop water management strategies that are resilient to climate change while sustaining ecological, social, and economic systems. Interdisciplinary research can provide tools for understanding interdependencies among complex systems, can offer strategies to balance competing social values and mitigate conflicts, and can provide a foundation of knowledge for decision makers to use in justifying new policies. Given these implications, funding agencies, university programs, think tanks, and private foundations have been encouraging researchers, through their funding programs, to work together across disciplines to address these challenging questions, and many efforts exist to assess the success of this research (e.g., Garner et al. 2013).

Like the issues that interdisciplinary research teams study, the organization and process of interdisciplinary research itself is complex, uncertain, and dynamic (Norris et al. 2016). The success of collective efforts to understand complex environmental challenges hinges, at least in part, on the ability of a research community to work together, to reflect upon and learn from interdisciplinary experiences, and to share insights with future interdisciplinary teams. Thus, an introspective assessment of processes and outcomes we achieve as we conduct interdisciplinary research can contribute to our collective learning.

This article presents a case study of the South Florida Water, Sustainability, and Climate (SFWSC) project, an NSF-supported research endeavor conducted by a team of 21 Principal Investigators (PIs) and their students representing 10 universities and four collaborators across the US. Through this case study, we examine team composition and leadership, the process and structure to facilitate collaboration, and integration within the scientific framework. Appropriate attention to these three organizational elements has been shown to be critical to the success of large-scale interdisciplinary research endeavors in the past, and can help address common challenges of large-scale and complex interdisciplinary research projects, including high diversity of membership, geographic dispersion, and high task interdependence (National Research Council 2015). Therefore, lessons from this case are applicable to other interdisciplinary research endeavors that share similar features and challenges, both within the US as well as internationally.

We first review existing literature on interdisciplinary research and team science, including perspectives on organizational and management tools that can mitigate challenges commonly encountered when conducting this type of research. We then introduce the SFWSC project and describe three organizational elements of the interdisciplinary project design: (1) team composition and leadership, (2) process and structure to facilitate collaboration, and (3) integration within the scientific framework. After describing the project, we assess strengths and weaknesses of the SFWSC endeavor with respect to effectiveness of collaboration (team, leadership, processes, and structure), as well as effectiveness of integration. Our examination of these strengths and weaknesses is based on several qualitative data sources collected during the project, including annual retrospective surveys and interviews with team members, project meeting notes, and experiential insights from task group and project team leaders. In our analyses, we also discuss the roles of both human-centered and object-centered mechanisms used in this project to support communication and collaboration across disciplines (Nicolini et al. 2012).

Understanding and Managing Challenges of Interdisciplinary Science

A growing body of literature reports on the organization and management of interdisciplinary research (Cummings and Kiesler 2005; Eigenbrode et al. 2007; Stokols et al. 2008; Lang et al. 2012; National Research Council 2015; Cheruvelil et al. 2014; Pennington 2016). Building on research from team science, and organizational and cognitive sciences, this research identifies several factors that challenge the ability of teams to collaborate and ultimately integrate knowledge effectively (Bennett and Gadlin 2012; Pennington 2016). Among these factors are team size and diversity of participants, who are likely to have different terminologies, norms, disciplinary incentives, analytical methods, and divergent research goals (Lang et al. 2012; Podesta et al. 2013; National Research Council 2015). Additionally, interdisciplinary teams often face communication challenges due to physical separation of team members or changes in team membership (Baker 2015; National Research Council 2015; National Academy of Sciences, National Academy of Engineering, and Institute of Medicine 2005; Stokols et al. 2008). On top of these issues are high levels of task interdependence among team members, which may require synchronization of data collection and research outputs (National Research Council 2015). Uncertainty associated with many research tasks (i.e., availability of data, or time required for modeling efforts) can further complicate coordination of the scientific process. Additionally, forming appropriate research teams can be difficult because the nature of the research problem may not be well understood at the outset of an interdisciplinary project (Norris et al. 2016). Given both the uncertainty of the research issue, and the high level of competition for large interdisciplinary research grants, large interdisciplinary teams may also tend to over-promise what they can accomplish, sometimes referred to as the “winner’s curse” (Thaler 1992).

In light of these challenges, previous work points to a number of strategies and tools for managing both the scientific process and for organizing team communication and coordination. While strategies may vary based on team size and research effort complexity (Stokols et al. 2008), common themes appear across the literature. One of these themes deals with building an informed, capable, and flexible research team. An initial step in building such a team is finding individual members who have openness to interdisciplinary work, along with diverse expertise and experience in fields central to the research topic (Podesta et al. 2013; Cheruvelil et al. 2014; National Research Council 2015; Norris et al. 2016). Prior collaboration experience can help build team cohesion and commitment (Halvorsen et al. 2016), and help overcome geographical distance and disciplinary and institutional barriers (Cummings and Kiesler 2008). Research projects can also benefit from including new team members who bring creativity and innovation (Cummings and Kiesler 2008).

Key to supporting an informed and capable team is ensuring that the research goals and objectives are developed collaboratively and that team members work together to identify operational strategies for implementing project goals (Lang et al. 2012; Podesta et al. 2013). Building a capable team also involves establishing a shared research framework that can facilitate both conceptual and methodological integration across diverse disciplines involved in the project (Lang et al. 2012; Ramaswami et al. 2012). Ensuring that the approach to research is transparent and iterative is another factor that will foster team adaptability. This means regularly reviewing scientific output as a team and discussing how output fits the overarching research framework, combined with appropriate flexibility to adapt project goals or the framework to unexpected project outcomes.

To support the success of the interdisciplinary scientific process, research teams need adaptive leadership and process tools that can build capacity, ensure coordination, and mitigate organizational and procedural problems as they arise (Lang et al. 2012; Lanier and Sukop 2016). Bark et al. (2016, p. 1457) recognize that “interdisciplinary research requires considerable planning, project management and time for integration inclusive of stakeholder engagement”, demands that they describe as “interdisciplinarity overhead”. Building interpersonal communication and team culture is essential to capacity, coordination, and problem solving (McGreavy et al. 2015). While effective use of diverse forms of communication technologies (e.g., videoconferencing, workflow schedules, shared databases) is fundamental to team management (National Research Council 2015), so are team exercises that foster social bonding, constructive dialog, and reflexive communication (Thompson 2009; Cheruvelil et al. 2014; Brown et al. 2015; National Research Council 2015; Halvorsen et al. 2016). Recognizing the likelihood for conflict and confusion in teams (Brown et al. 2015), and providing examples through team exercise to productively respond (i.e., negotiation, problem-solving dialog) can also improve team functioning (Marks et al. 2001; Lang et al. 2012; Cheruvelil et al. 2014).

Establishing policies and procedures for how teams should operate together (i.e., on data sharing and publishing) and in sub-groups can improve team productivity (Goring et al. 2014). Overall, processes through which project management tools are implemented require ongoing participation among team members, transparency, and flexibility (Lanier and Sukop 2016). Flexibility is particularly important as unexpected issues related to project coordination, timing, or research implementation arise. Building in opportunities to address new challenges and providing tools (objects of collaboration) that facilitate work across boundaries, and motivate and sustain collaboration are necessary (Nicolini et al. 2012). Successful knowledge integration also benefits from participatory processes (Pennington 2016).

Team management and leadership includes establishing expectations and criteria for what constitutes project success, and instituting tools to track and evaluate that success (Walter et al. 2007; Goring et al. 2014). Project evaluation tools (i.e., surveys, external reviews, stakeholder feedback) and open discussion of evaluation metrics provide structured opportunities to review project objectives and outcomes, and to reassess project strategies, team membership, and goals (Lang et al. 2012; Podesta et al. 2013). However, establishing clear criteria for success can be challenging, not only due to the diversity among research team members, but also due to the interests of funders or other external stakeholders, such as policymakers, who may have an interest in the research (Turner et al. 2016). Given the potential for over-commitment in project proposals (or under-estimation of project challenges) in interdisciplinary science, feasible and appropriate metrics of success can be important. Success metrics need to be accommodating of diverse interests, but also open to key components of interdisciplinary work, such as development of shared databases, mentoring, and public outreach, which may not be as obvious as peer-reviewed publications (Goring et al. 2014).

Project Background

Risks from potential climate change impacts, such as sea level rise, were major drivers for pursuing the SFWSC project. One of the planned components of SFWSC's framework for understanding and managing water resources in South Florida was a Hydro-Economic Optimization (HEO) model (Heinz et al. 2007; Harou et al. 2009; Mirchi et al. 2010). The regional-scale HEO model examined water demands from agricultural, urban, and environmental (i.e., fisheries, carbon sequestration) sectors in South Florida (Mirchi et al. 2015; Mirchi et al. 2018). The model served as an integration tool for the project by incorporating "penalty functions" across these water sectors (in this project, a penalty function is the economic penalty, or loss, resulting either from reduced allocation to a given sector or from excess water flows or levels). These functions were based on the work of different task groups, which we describe in more detail below. In addition to serving as a research integration tool, we planned to use the HEO model, along with other research products such as visualization of scenarios and behavioral science techniques, to build robust water management strategies that had broad support among stakeholders, including South Florida urban, agricultural, and environmental water users. We hypothesized that the use of iterative and adapative management techniques and methods found in organization science and used within the business world would ensure the success of this project.

Team Composition and Leadership

The SFWSC project had approximately 55 team members with varying levels of participation and roles. Project members represented a variety of disciplines, including hydrology, ecology, economics, engineering, and behavioral and decision sciences, and consisted of academic researchers, post-docs, External Advisory Board members, undergraduate students, and graduate students. The geographic distribution of the SFWSC members spanned 10 academic institutions across the nation from the start of the project.

Oversight of the project's several task groups, and overall SFWSC research progress, was provided by the leadership team, which consisted of the PI, Co-PI, Project Coordinator, and Project Management Coach. The leadership team was responsible for overseeing the research progress of each task group. The task group goals were to contribute to the HEO model and to derive implications for sustainability of regional water allocation in South Florida. The SFWSC project received further insight on the South Florida water management system from an External Advisory Board, to ensure the research remained relevant for the South Florida region. The External Advisory Board members were selected based on experience in the overall water management field, experience in South Florida water management, and relevance to the project. In addition to offering personal insight of the current South Florida water allocation decision making, they provided suggestions to assist the project when it faced obstacles in integrating knowledge across task groups.

The research project was set up as a collaborative project as defined by NSF. This meant that NSF distributed the corresponding budget to each collaborating institution at the outset, essentially creating a "shared project leadership" model. Shared leadership has been shown to support performance of teams that are more virtual (Hoch and Kozlowski 2014). Alternatively, having sub-contracts from a single lead institution to other collaborating institutions may have led to a more centralized leadership model.

The SFWSC team included several researchers who had worked together previously on a 1-year WSC project. Many new PIs were recruited for the SFWSC proposal, and the degree of prior collaborative experience was significantly lower among these team members.

SFWSC members were organized into task groups based on their project research focus. Task group team composition varied in both size and diversity of discipline, which was determined based on the academic expertise of the SFWSC members and their research focus. In total, there were eight task groups, seven of which focused on different project research areas and one designed to promote research integration across task groups. Task groups included: (1) Water Resources Economics; (2) Fisheries; (3) Carbon Cycling; (4) Ecosystem Services; (5) HEO Modeling; (6) Model Scenarios Visualization; (7) Behavioral Decision Analysis; and (8) Integration and Synthesis. While each task group examined different elements of natural and social systems in South Florida, there was considerable overlap between topic areas for several task groups' research objectives. For example, fisheries team activities included both measuring fishermen's willingness to pay, which is an economic issue, and fish tagging, which is a method used in fisheries research.

The leadership team managed both the scientific process for the project overall and supported team communication and coordination. An adaptive management philosophy was intentionally adopted that stressed adaptability, communication, self-reflection, and trust, based on experience with leadership and management models developed to address complex problems (DeCarlo 2004; Denning 2010). Further, management efforts were designed to assist team members in co-producing knowledge and to help team members identify interdependencies among different task groups, ensuring that cross-disciplinary goals would be achievable.

Process and Structure to Facilitate Collaboration

Leadership used various project tracking tools and management methods to support team alignment, and foster effective communication and transparency. These tools and methods were adapted throughout the project. Leadership provided resources for coordinating management efforts, continuously monitored where gaps in knowledge integration or model development were occurring and responded accordingly, and provided professional meeting facilitation (Lanier and Sukop 2016). Among resources provided for coordination were different communication tools, including one-way information sharing vehicles (email updates, newsletters, a 2-page informational document, a website, and database); and two-way communication, such as webinars and different meeting formats. As Cummings and Kiesler (2005, p. 704) stated, "a major challenge for dispersed scientific collaborations is coordinating work so that scientists can use one another's ideas and expertise without frequent face-to-face interaction". When possible, leadership encouraged face-to-face interactions, even if only virtual, which help in building trust (Cheruvelil et al. 2014), and are especially effective when dealing with potential conflict or uncertainty (Lang et al. 2012). Short, frequent meetings that ensured adaptability were used for ongoing team alignment and visioning.

On a less frequent basis, larger workshops were held. The large, facilitated face-to-face meetings included one project kickoff meeting, five 2-day annual meetings, four small-group cross-disciplinary data workshops, and two mid-year meetings. Many team members participated in these meetings in-person. These meetings were designed to encourage communication across and within task groups, to coordinate research efforts and understand cross-disciplinary dependencies. Integration planning was a focus of annual meetings, with team members interactively planning upcoming research.

The primary formalized mechanism to promote task group interaction consisted of monthly meetings among team participants. Due to the geographic distribution of the SFWSC members, the meetings were conducted remotely using either teleconference or videoconference technologies. These meetings were designed to keep group members informed of their team's research progress and provide an opportunity for SFWSC members to collaborate across teams on project-wide objectives and overall knowledge of the South Florida water allocation system. Central management team members also participated in each task group's monthly meetings to track progress and assist in research integration. To track both research progress and discussion of system knowledge and implications, collaborative meeting notes were taken for each of the task group meetings. These notes were stored in an online database accessible to all project members.

Retrospective assessments (Kerth 2001; Derby and Larsen 2006) were used throughout the project to aid the central management team in iterating and adapting management processes and scientific integration support as the project proceeded. Three retrospectives, consisting of evaluative surveys and interviews, were conducted over the course of the project (in 2013, 2015, and 2017), each prior to annual meetings. Optimally, retrospectives would be conducted more frequently; however, funding for this activity was limited. Interview questions were organized primarily into two categories: (1) management leadership process and structure, and (2) research integration, collaboration, and team dynamics.

The primary goal of the retrospectives was to obtain team members' perspectives related to management changes for the upcoming year, to aid in designing upcoming annual meetings, and to support team collaboration. In addition, the 2017 retrospective was used to understand the extent of collaboration on the project. The first retrospective was conducted in late 2013 using phone interviews, while the second (conducted in 2105) was a combination of phone interviews and an online survey sent to the project listserv. Responses to questions from these retrospectives were qualitatively evaluated with one exception. We asked questions related to the management process (perceptions of how the project was being managed, aspects team members liked, and recommendations for changes). Questions were also selected to gauge integration to date, such as rating project effectiveness (on a scale of 0–10), identifying current collaborations, and reflecting on issues and concerns around collaboration/integration. In addition, we requested input on ways the management team could facilitate integration. Finally, we encouraged the team to consider how they themselves could facilitate integration. Results of these retrospectives were shared with the team.

The third retrospective was conducted in early 2017 as an online survey that was distributed to SFWSC members through the project listserv. While the two previous retrospectives were intended to assist in adapting future process to facilitate integration on the SFWSC project, this survey was conducted prior to the last official annual meeting, and therefore served as more of a reflection of the project as a whole. This survey was presented to the SFWSC members as an assessment of their prior interdisciplinary research and current research on the SFWSC project with the intent to improve future management based on the survey findings. The survey's central questions included: (1) What were the SFWSC members' prior experiences with working on interdisciplinary teams, (2) What were their views of team collaboration on their Task Group teams and across the

SFWSC project, and (3) How was the SFWSC project's management style and meeting structure impacting team collaboration?

Participants' prior experiences on interdisciplinary projects and their assessments of the SFWSC project's management style and meeting structure were measured using a series of multiple choice and write-in questions. Assessments of team collaboration within Task Groups and across the SFWSC project were measured using a Likert Scale.

During the 2017 Retrospective Survey, each of the SFWSC project participants was asked to indicate which team activities conducted during the SFWSC project meetings most helped with team collaboration by selecting from a list of team activities conducted over the first 4 years of the project. Indication of which team meeting activities were the most effective at encouraging collaboration was based on the number of participants who selected that activity on the survey. The activities that received the three highest scores were designated "highly rated" for facilitating project-wide collaboration.

Integration within the Scientific Framework

In its original design, the SFWSC research proposal positioned the HEO model at the center of the project, as an integrating tool for contributions from various disciplines involved. Disciplinary contributions from behavioral research, fisheries research, economic studies, regional hydrology, and agricultural studies were designed to inform development of the model, and, ultimately, to assess the model's influence in regional-scale water management discussions. From the project's inception, the integrating mechanism for disciplinary research products was conceived as the development of penalty functions for agriculture, fisheries, urban water management decisions, and environmental recreation (Mirchi et al. 2018). With these penalty functions, diverse research products would be integrated into the central overarching HEO model. The original proposal also was designed to incorporate stakeholder input into the development and evaluation of the model's potential as a tool for conflict resolution and to examine tradeoffs in decision making. In this way, the HEO model was envisioned as a boundary object, developed using an innovative and rigorous scientific approach, bridging diverse disciplines and integrating across project teams who would be developing new information linking hydrology with human behavioral response, fisheries, agriculture, and with economic indicators.

Prior studies identified both strengths and weaknesses of relying on models as central integrating tools for large-scale interdisciplinary projects (Stave 2003; Redman et al. 2004; Langsdale et al. 2009; White et al. 2010). For example, modeling has been described as a way to unify diverse group perspectives by providing a uniform language, set of goals, and framework while allowing a rigorous scientific approach. However, weaknesses, including pigeonholing of efforts, overly rigid expectation of outputs, and imperfect fit between different outputs, are also described (Lemos and Morehouse 2005). Others have described challenges associated with timing of model development and integration, particularly in regard to social science integration efforts (Raymond et al. 2010). Many of these studies warn of the potential pitfalls of waiting for a model to be complete before bringing the tool to stakeholders, which include delays in development and unmet expectations regarding the final product. Furthermore, studies describe common treatment of social science contributions to integrated modeling efforts as an add-on to physical science models and describe a need for innovative methods for more complete integration of human elements into models of complex systems (Braden et al. 2009).

Recognizing such potential obstacles and shortcomings, the SFWSC project was designed to test novel approaches to integrating social science research products into the modeling framework and broader research goals. Behavioral responses and economic impacts of different hydrological conditions, like flood, water shortage, and sea level rise, were estimated and, when possible, included into penalty functions. Additional efforts sought to apply ethnographic methods to improve understanding of the decision environment and current treatment of tradeoffs in regional water resource management. These efforts were based on collection of qualitative data through interviews and observations of relevant water practitioners and stakeholders in the region.

Evaluating Strengths and Weaknesses

In this section, we describe successful components of the project as well as areas for improvement. We used several data sources to assess strengths and weaknesses of the organizational elements of team composition and leadership, process and structure to facilitate collaboration, and integration within the scientific framework. Survey results from internal retrospective evaluations are used to inform assessment of effectiveness of team collaboration, and effectiveness of process and strategies implemented toward supporting collaboration. Integration within the scientific approach is analyzed according to progress toward goals set forth in original project design, as well as analysis of meeting notes and discussions during the project life. Key themes emerging from the data as drivers of success were adaptability and flexibility.

Team Composition and Leadership

Team members, when asked to describe the leadership, indicated that they liked the overall management structure, collegial leadership style, and hands-off approach. They also liked the adaptive, democratic nature of the management, and ability to make changes. While adaptability and flexibility in the management style were appreciated by many, in the first year there was uncertainty about what would be required by management and task group leads. In addition, one team member felt that leadership was centralized and that more trust was needed. Another team member indicated that productivity of task groups appeared to be dependent on frequent contact with the leadership team, which was time-consuming.

One example of how the project leadership adapted to overcome challenges in team collaboration occurred halfway through the project. At that time, the project faced challenges from both the irregularity of task group meetings and technical obstacles with the HEO model. In response, central management held an additional meeting mid-year that focused on discussing these technical challenges and collaborating on how to address them moving forward. Although it was not included in the original project schedule, many team members attended either in-person or remotely. To illustrate the importance of team-wide collaboration, a mapping activity was introduced during the meeting to help task groups visualize their research dependencies in achieving project goals. The outcomes of this meeting included providing a revitalization or "boostershot" to team member motivation and collaboration and a determination of which challenges would be feasible to overcome within the project's timeframe.

As with any project management approach, ongoing discipline was required. In the 2015 retrospective, regular communication between leadership and different task groups was considered a positive attribute of the project; however, for a time, many meetings were canceled by leadership, contributing to a perception of "start and stop" or intermittent management. In response to the 2015 retrospective, management re-committed to the monthly task group communication schedule. A request was also made for more follow-up on the decisions and roadmap made at the annual meeting, and setting specific milestones. To address this, management began reviewing the upcoming year's roadmap quarterly with each group.

In addition, more team members were invited to monthly task group meetings to help improve communication within and across disciplines. Some team members began to work with multiple task groups, creating more opportunity for collaboration. Additionally, two task groups merged their annual planning as their research on this project became increasingly integrated. In the 2017 retrospective, over 75% of team members who responded felt the quality of their research improved due to their collaboration with other SFWSC members. In addition, approximately 76% of team members felt that their participation in interdisciplinary research on the SFWSC project increased their understanding of what their discipline can provide other disciplines.

Process and Structure to Facilitate Collaboration

Integration challenges due to size of project team can be minimized by providing a variety of tools for high-quality communication. Multiple communication avenues were provided to the team to support collaboration across disciplines. The most frequent opportunity for collaboration was monthly task group meetings, which allowed members of each group to discuss research updates and their contribution to overall project goals. These meetings were identified as a strength of the SFWSC's research approach to co-produce knowledge about the South Florida water allocation system, and highlighted the importance of providing mechanisms to assist in sustaining interactions and coordination among interdisciplinary team members examining complex natural–social systems.

One benefit of the meeting approach was the use of technology for remote meetings, which provided flexibility to sustain interactions among dispersed team members. In retrospective surveys and interviews conducted among SFWSC members, several members identified the remote meetings and offsite approach as effective and a regular opportunity for communication among task group members. A second benefit of the meeting approach was the variety of methods available to researchers to participate in remote meetings. Moreover, some members unable to attend meetings would email their updates to other members to be added to their task group's meeting notes. The frequency of email correspondence was identified by several SFWSC members as an effective aspect of the SFWSC management approach, and several SFWSC members identified the project's use of collaborative document sharing tools and other online resources as a strength for promoting collaboration.

Despite these benefits, the SFWSC's task group meeting approach also faced several challenges that created obstacles for maintaining interaction and impacted knowledge co-production among team members. One challenge was associated with using technology to conduct the task group meetings remotely. At times, the videoconference technology failed to work properly, which required changing meetings to another venue (such as teleconference) or rescheduling. A second challenge was the original focus on conducting separate task meetings, which may have limited collaboration and knowledge co-production. A third major challenge was the significant coordination required to conduct monthly meetings with each task group. As expected, monthly attendance at meetings could be demanding at times for both task group and leadership team members, and particularly intensive for leadership team members.

In response to challenges identified in the task group meeting structure, leadership made adjustments to different aspects of both the meeting processes and overall structure throughout the project. For example, leadership restructured meetings to include members from across task groups or to focus specifically on ongoing interdisciplinary research. Meeting schedules were also shifted to better accommodate schedules. However, despite these efforts, partial evidence for the lingering effect of this challenge was derived from examining SFWSC members' self-reported active communication within and across task groups in the 2017 retrospective survey. While over 63% of SFWSC respondents reported that they actively communicated with another member of their task group every 2–4 weeks, approximately 64% of SFWSC respondents reported that they actively communicated with SFWSC members outside of their own group less than once every 2 months.

The structure of the project's annual meeting was also adapted to support collaboration among team members. Traditional task group status updates were delivered during annual meetings. In addition, a consensus brainstorming activity (Stanfield 2002) was incorporated into annual meetings to help team members build a visual roadmap of the upcoming year research plans, as well as an overall project roadmap. A facilitated stakeholder role-playing activity was introduced during the 2015 annual meeting to engage team members in developing water management scenarios.

More opportunities to collaborate on academic papers were requested. To facilitate this, the activity "Dynamic Teaming and Knowledge Networking" based on World Café (Brown and Isaacs 2005) was included in the 2015 annual meeting to begin a lightly structured dialog on potential collaborative papers. At the 2017 annual meeting, an "open market" activity, inspired by Open Space Technology (Owen 2008) was combined with "story-boarding", a process of mapping out an idea in a high-level way, to help facilitate collaboration on interdisciplinary papers. Through this approach, team members identified paper topics and teams, and then arranged the papers' topics and described the desired story of a special issue of a journal.

Overall, interactive dialog-based activities incorporated during annual meetings were highly rated. For example, when asked in the 2017 retrospective which meeting activities helped in collaboration, over 60% of project members indicated building the project roadmaps. Over 47% identified "Mapping task group dependencies", the activity used during the mid-project booster shot meeting, and "holding a conversation about interdisciplinary papers using Dynamic Teaming and Knowledge Networking", the activity used during the 2015 annual meeting, as aiding in collaboration. However, stakeholder role-playing, which involved small groups with team members facilitating, was rated as helpful by just 19% of project members.

Although both benefits and challenges were identified in assessment of the SFWSC project's processes to facilitate collaboration, evaluative data collected from SFWSC members do not suggest that the challenges hindered the SFWSC members' interest in each other's progress or their perceived benefits of collaboration in co-producing knowledge. SFWSC members' ratings of annual meeting activities on the 2017 retrospective survey revealed status updates from each task group as the highest rated activity to assist in project-wide collaboration. Other highly rated activities, such as road-mapping exercises coupled with the team's interest in collaborating on interdisciplinary papers for a special issue, provided further evidence of members' interest in each other's research progress and their link to the team's knowledge of the complex South Florida water system.

Integration within the Scientific Framework

The strengths and weaknesses of the scientific framework for the project with respect to effectiveness of integration were evaluated through analysis of meeting observations, including detailed notes which were collected during all project meetings, and interviews.

From its inception, the HEO model was imagined as an integrated model that incorporated four types of penalty functions, each to be developed by a different task group: carbon, agriculture, urban water use, and fisheries. In task group meetings, we discussed progress in developing penalty functions and focused on anticipating and managing obstacles as they arose. Leadership maintained knowledge of overall progress of different teams, envisioning how individual products might or might not work together, even though, as described in retrospectives, all team members did not interact directly.

By mid-project, leadership determined the proposed regional-scale, integrated HEO model would likely be unachievable within the timeframe of the project. This realization was clarified by discussions between disciplinary teams that occurred during the mid-project meeting and Year 3 Annual Meeting. The rationale for the original design of our HEO model and penalty functions was largely based on an earlier model of the South Florida water management system (Watkins et al. 2004) and a related model developed for California, called CALVIN (Draper et al. 2003; Jenkins et al. 2004). The CALVIN economic-engineering optimization model's focus is to manage water infrastructure and demand in California's connected water systems to minimize net scarcity and operating costs. With some exceptions, both of these studies focused on water scarcity, whereas in Southeast Florida water overabundance presents more of an issue in many years. During the mid-project review workshop, researchers identified the complexity of and probable limits to applying a high-level optimization modeling approach in this context, with the impacts of floods and droughts having disparate time and spatial scales. Once the limitation was realized, the team recognized that it was likely unrealistic to shift the project focus away from the central modeling approach. Another complication arose because of different approaches and data sources that were used in the development of penalty functions for the model. Some of the penalty functions could not be developed as anticipated and presented potential limits to integration, signaling a need for project leaders to make a major decision on how to move forward. From early project meetings with a few task group leaders, it became clear that some penalty functions likely would not be entirely representative of the South Florida setting. For example, identifying an a priori penalty function for urban water use would not account for long-term, structural changes in water demand (e.g., water uses, technologies, consumer behavior), and it would not accurately represent episodic responses to water scarcity, such as water use restrictions. As another example, the initial approach for development of the agricultural penalty function came into question once the lack of economic data was better understood, along with the fact that South Florida water managers primarily manage groundwater levels rather than surface diversions for irrigation.

Despite recognized limitations in project design, the decision was made to continue with the original research plan—an integrating HEO model including penalty functions—while supporting development of additional research products that were not originally included in the proposal. This decision resulted from the recognition that all task groups had developed strategies to pursue different but related research approaches, which were seen as more feasible within project constraints. It had become apparent that, though different than anticipated, novel interdisciplinary research and integrated products were resulting from interactions across task groups, exemplifying that successes in large-scale interdisciplinary projects may look different from originally planned.

In terms of the modeling framework, the focus was shifted onto a subset of penalty functions that could be more readily developed and integrated into the HEO model, including fisheries, carbon, and an urban flood penalty function. With these realizations, the original vision of a final product, being a HEO model with economic penalty functions representing a wide range of water use sectors and ecosystem services, began to shift to focus on a few sectors and services, with some tradeoffs expressed in non-economic terms, such as reliability with respect to pre-defined target water deliveries. Task groups whose work would not fit neatly into penalty functions, or whose proposed tasks depended on model output (task groups 1, 3, 4, and 7), still pursued high-quality original research, albeit with products that may be less integrated than originally planned. In addition, the focus of stakeholder engagement efforts and alignment of these efforts with the greater project shifted toward more individual interactions and observations of decision-making fora. While the data collected from these ethnographic methods of stakeholder interviews and observations continue to inform model development, the overall engagement strategy has evolved away from a direct link between stakeholder and modeling processes.

Detailing the obstacles encountered during the course of SFWSC research is not to imply a lack of integration, but that integration looked different than the original vision. Management of shifting expectations from integration efforts and discussion of what integrated products actually look like are topics deserving of further attention. For example, the notion of "integration" brings grand ideas of everything coming neatly together; in practice, integration looks different. To maintain scientific integrity and rigor, it is necessary to embrace the innovative contributions of the work, even if the innovations stray from the original vision and plan. In the SFWSC case, novel methods to connect fisheries biology, economics, and hydrology were developed as a result of interdisciplinary efforts (Boucek and Rehage 2015; Boucek and Rehage 2016; Brown et al. 2018). In this work, an integrated methodology linking Everglades hydrology to economic values was developed in order to assess the effects of freshwater flow in the Florida Everglades on recreational fisheries. This aspect of the project also resulted in the first ever estimate of anglers' willingness to pay for the Everglades recreational experience. Further, innovative approaches to quantify hydrological decisions and economic impacts from flooding were developed (Czajkowski et al. 2018). This economic analysis of the relationships between flood losses and groundwater levels by several cross-disciplinary team members will enable water managers to better understand tradeoffs between high water levels (to prevent saltwater intrusion) and flood risk. Another innovation was the development of the social costs associated with mangrove estuary inorganic carbon fluxes, which again required integration across several disciplines. These examples indicate successes in overcoming obstacles in research design and the reality of interdisciplinary research process and product.

This discussion would not be complete without highlighting the integration success that was achieved by using the water resource system optimization model as a boundary object, or integration mechanism. Team members across the disciplines of engineering, hydrology, economics, fisheries biology, and social sciences worked closely together to incorporate the economic value of water in the model (Mirchi et al. 2018). To this end, researchers from different disciplines pooled their expertise to develop the required mathematical functions (i.e., penalty functions) to facilitate HEO of the South Florida water resources system. Examples include the value of water to urban, agricultural, and environmental sectors. Furthermore, economic losses due to flood damages associated with water management were quantified and incorporated in the model. This was an innovative interdisciplinary research approach, which facilitated knowledge integration and application using hydro-economic modeling as a platform for generating new information about the sectoral values of water in South Florida. A collection of papers in a special issue further illustrates success in integration and co-production of knowledge both across the academic project team and in collaboration with practitioners (Sukop et al. 2017), in addition to many other papers and book chapters credited to the project. The team continues to work on an additional special issue, under a 1-year no-cost extension, in hopes of furthering the integration and synthesis of the knowledge produced to date.

There are lessons to be learned from those obstacles that prevented an even higher level of integration across the broader project, especially with respect to integrating social sciences. For example, the model has limited ability to represent the effects of sea level rise on some management objectives. In response to this limitation, behavioral studies focusing on risk response to visual simulations were shifted to focus on novel approaches to measure potential response to sea level rise (Treuer et al. 2018). Additionally, delays in model development affected original research plans for bringing model output to stakeholders and incorporating their feedback. The lesson learned here is that incorporating flexibility into all planned research would be beneficial.

The lessons presented point to the realization that flexibility in research design is critical to integration and that having a model as the "boundary object", or overarching mechanism of integration, does not always provide the necessary flexibility. Overall, the original vision of the model as a boundary object served as both a help and hindrance. Once the team realized it might not work out exactly as envisioned, it was difficult to shift project design, personnel and resource allocation, shifts that might have facilitated re-scoping outcomes from and timing of task group research activities. These limitations in flexibility result from institutional constraints of both funding agencies and universities. The timing of model and penalty function development also created an obstacle for some planned stakeholder engagement work, for most of the reasons described in prior studies, suggesting that projects reliant on large-scale interdisciplinary model development create a contingency plan for stakeholder engagement.

In Table 1, we summarize key strengths and weaknesses of the SFWSC project across the three key organizational areas studied.

Lessons and Conclusion

This article sought to contribute to the literature and knowledge on interdisciplinary science by critically assessing the SFWSC project, which aimed to evaluate alternative management scenarios for urban, agricultural, and environmental users in the region. While the goals of the project were unique, the challenges of organizing the team, conducting the science, and leading the effort were similar to other large-scale, complex interdisciplinary projects. Building from insights from the literature on ways in which researchers can manage the challenges associated with interdisciplinary science, we drew lessons from the case study about team composition and leadership, process and structure to facilitate collaboration, and the scientific framework and model. These lessons are summarized in Table 2. The lessons summarized in Table 2 are pragmatic—aimed at guiding researchers working on interdisciplinary projects—and highlight how theoretical lessons on project management and adaptation offered in the literature can be deployed in practice at different phases of a project.

While the literature widely acknowledges the challenges of organizing team science and has recommended several approaches for mitigating these challenges, our study offers a straightforward three-pronged approach that brings several key insights from the literature together. As highlighted in Table 2, this includes building a well-defined team and leadership structure for collaboration across geographic distance and across disciplines. In developing the team and leadership structure, it is necessary to consider adequate funding for the coordination needed for interdisciplinary efforts at project inception, encouraging cross-pollination of team members throughout the course of the project, and allowing the team structure to adapt. Second, an intentionally designed process and structure for facilitating collaboration is needed. This includes creating mechanisms for routine analysis of project outputs, opportunities for reviewing project metrics together as a team, and collaboration tools that foster cross-team communication in diverse formats. The third lesson focuses on integration within the scientific framework, which requires encouraging team members to think outside the box when facing unanticipated constraints (i.e., lack of data availability, resource constraints, challenges with integrating data at different scales) and embracing new approaches for overcoming

Table 1 Key strengths and weaknesses of the SFWSC project across three organizational areas

Area	Strengths	Weaknesses
Team composition and leadership	Able to sustain communication and collaboration across geographic and participant diversity, supported by communication technology, regular meetings, adaptation to meeting structures, and prior experience working together	Challenges to keeping up with meeting schedules due to competing commitments among team members
Process and structure to facilitate collaboration	Flexible and iterative with intentional touch points for team reflection, along with deployment of tools for improving communication, identifying challenges and opportunities, coordinating work, and aligning team	Objective project evaluation metrics could have been identified more explicitly at the outset and reviewed frequently
Integration within the scientific framework	Provided a central point of integration and common metrics, methods, and language for key points of integration	Unanticipated limitations with the model and inputs made it difficult to integrate as planned across all research areas. Boundary object is sometimes constraining

Table 2 Lessons for interdisciplinary research teams and projects

Area	Lesson	Project phase/examples
Team composition and leadership	Ensure coordination functions are sufficiently funded	Project inception (e.g., budget overhead for necessary coordination tasks and include resources for facilitation/coordination staff)
	Structural approach needs to allow time for people across task teams to cross-pollinate	Annual meetings (e.g., break-out sessions that mix members of different task teams to focus on key project questions or challenges)
	Collaboration needs to be adaptive to constraints	Ongoing (e.g., identifying when new team members are needed for unanticipated project tasks)
Process and structure to facilitate collaboration	Institute structured supports for routine self-analysis	Annually at a minimum (e.g., team surveys)
		After face-to-face meetings (e.g., meeting process retrospectives)
	Review success metrics and vision early and often	Project inception (e.g., kickoff meeting)
		Ongoing
		Annually (e.g., project evaluations)
	Establish collaboration tools that assist in improving communication and building shared understanding	Ongoing (regular meetings for diverse purposes—kickoff, booster shot, annual, monthly status update meetings)
Integration within the scientific framework	Embrace innovations from research that can emerge in the face of unanticipated challenges and allow the scientific approach to evolve as team knowledge advances	Ongoing
	Provide a central point of integration	Ongoing (e.g., integrative model where feasible, or integrated datasets)
		Project completion (e.g., collection of publications in a special issue or edited book

these barriers. Integration within the scientific framework also can be facilitated through a shared research output—like a model or dataset—that helps answer an interdisciplinary question while allowing learning across the team. Developing a shared message of joint findings across the team through a special issue of a journal—even where integrated models are infeasible—can also help bring together an overarching understanding of the scientific framework. Ultimately, flexibility was a key characteristic across all three areas. But we recognize that flexibility had to be both embraced in the design of the project and both challenges and unexpected difficulties had to be accommodated and anticipated.

This paper illustrates that integration innovations can be achieved by an interdisciplinary research team formed to address a "wicked" problem, especially when the project is creatively and flexibly managed, although success may not occur in as "linear" a way as originally envisioned (Halvorsen et al. 2016; Norris et al. 2016).

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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