Title:
Co-producing science for sustainability: can funding change knowledge use?

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Abstract:
There is widespread belief that meaningful interaction between scientists and practitioners, or co-production, increases use of scientific knowledge about sustainability and environmental change. Although funders are increasingly encouraging co-production, there have been few empirical studies assessing the outcomes of these efforts in shaping knowledge use. In this study, we systematically analyze research project reports (n=120) and interview project participants (n=40) funded by the U.S. National Estuarine Research Reserve System from 1998 to 2014 to support coastal management. Our analysis shows that escalating funding requirements for collaboration with users change research practice and strengthen connections between research outcomes and knowledge use. In consequence, a new model for science funding emerges, where sponsor, researcher, and user are more interactive with one another.

Author contributions:
JCA and MCL conceived and designed this study. JCA and RJN conducted documentary analysis and interviews. JCA conducted statistical analysis. All authors contributed to the manuscript.

Keywords:
Science-practice interaction; science policy; environmental management; coastal management; research utilization; societal impact of science; co-production; science funding

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1. Introduction

Identifying how science can best help society manage risk and solve sustainability problems remains a grand challenge for practitioners, scientists, and funders. Meeting this challenge may require systemic changes to the way research is practiced, funded, and disseminated. But making changes to the scientific enterprise while preserving its ability to generate new knowledge and societal value requires more evidence as to what drives scientific impact. This study analyzes new empirical data about how science funding requirements for interaction between researchers and users can increase the use of scientific knowledge for environmental decision-making. In particular, we test how changes in funding program structure shape scientific practices and how such changes may lead to increased use of scientific knowledge.

Scholars have long speculated that a gap between the science and policy communities in their norms, language, incentives, and goals works as a barrier for the use of scientific knowledge (Caplan, 1979). Accordingly, there has been growing interest in how the co-production of scientific knowledge can help to narrow this usability gap. However scientific knowledge co-production (hereafter, 'co-production') itself is not without controversy, ranging from different conceptualizations of what co-production means to divergent ideas for realizing goals and evaluating outcomes (Lemos et al., 2018; for a rich discussion on different definitions of co-production, see Bremer & Meisch, 2017). And while studies have shown that interaction between research and practice fosters improved use across various environmental research settings (Cash et al., 2003; Dilling & Lemos, 2011; Fujitani et al., 2017; Vogel, McNie, & Behar, 2016), others have warned about the need to fully attend to issues of equity and ethics in co-production (Klenk et al., 2015). Whether inspired by the evidence of increased use, or perhaps by deeper aspirations for a more inclusive and collaborative research culture, many funders, researchers, and practitioners across environmental research domains are keen to pursue co-production, which they often define as a meaningful interaction between these communities (Asrar et al., 2013; Beier et al., 2017; Vano et al., 2017).

Yet, despite promising reports about co-production and related approaches, the evidence for how it drives use remains relatively sparse and context dependent (Posner and Cvitanovic, 2019; Wall et al., 2017). Furthermore, to the extent that co-production works, more insight is needed about how to scale it up both across different scientific fields and contexts of application. As influential organizations well-poised to collect relevant data, funding agencies may play an important part in building this evidence base. However, existing science policy research presents mixed evidence about the influence of funders on the practice of science and offers little on the question of what drives it. While some studies reported benefits of funding approaches that encourage interaction with various practitioners (e.g., DeLorme, Kidwell, Hagen, & Stephens, 2016; Moser, 2016), others are concerned with unintended consequences and perverse incentives arising from interventions by funders (Lövbrand, 2011). Finally, studies also point to researchers sidestepping changes in rules to maintain the status quo, in spite of the best laid plans of funders and science policy-makers to effect change in research practices (Davis and Laas, 2014; Holbrook, 2012; Reale and Zinilli, 2017).

In this study, we analyze research projects funded by the National Estuarine Research Reserve System (NERRS, a program of the U.S. National Oceanic and Atmospheric Administration--

NOAA). Over the period between 1998-2014, the program periodically increased requirements for collaboration between researchers and coastal managers. This history affords a rich database for testing the hypotheses that funding can stimulate co-production and that co-production increases knowledge use. Using this data, we ask:

> Can funding requirements that encourage more interaction between scientists and users substantively influence research practice?
>
> Can changes in research practices, especially those related to co-production, result in more knowledge use?

We investigate four distinct generations of funding administered by NERRS, wherein each progressively requires more co-production by the grantees. By comparing each generation against the initial one – which closely approximates a traditional model of research funding and practice wherein funders allocate resources to scientists for largely independent investigations – we are able to study the shift toward more impact-oriented science funding. Using data from 120 final project reports and 40 interviews we find significant changes to research practice resulting from funding program design. We also find that more intensive interaction between researchers and users significantly increases the likelihood of use.

We organize this paper as follows. Section 2 describes knowledge co-production as a general strategy to increase the use of environmental knowledge, briefly reviews existing evidence about funders' influence on research practice, and introduces the National Estuarine Research Reserve System as the focus of our study. In Section 3, we present a detailed accounting of our mixed research methods approach, the results of which are presented in Section 4. Section 5 discusses these findings and their implications, and in 6 we state our conclusions. The appendices provide a detailed codebook (A-1), interview guide (A-2), additional coding results and analysis (A-3&4), and coding data (A-5).

2. Funding co-production of usable environmental change research

2.1. Knowledge co-production & research use

The assumption that science achieves more impact through intensive interaction with non-scientists challenges a long-held expectation that science serves society best when working in relative independence. Yet scholars of science have often described scientific knowledge as being unavoidably shaped and reshaped through interactions between scientists and the society in which they work, a process termed co-production (Jasanoff, 2004). When defined as a form of "iterative interaction," knowledge co-production can also refer to research-practice collaboration during one or more phases of the research process such as study design, implementation, analysis, or dissemination (Bremer and Meisch, 2017; Cash et al., 2006; Meadow et al., 2015; Michaels, 2009; Reed, 2008). In environmental research, this more instrumental sense of co-production has recently diffused more widely by advancing the idea that increased interactions between research and practice will increase knowledge use (Lemos and Morehouse, 2005). The extent and type of interaction may take on different forms and intensities (Klenk et al., 2015; Trencher et al., 2017) and a variety of other benefits may emerge, including more participatory or inclusive approaches to science. Furthermore, the use of the term co-production may encompass or overlap with other strategies such as co-design (Mauser et al., 2013), research-practice partnerships (Tseng, 2012), transdisciplinary research (Lang et al., 2012), and collaborative research (Matso et al., 2008).

There is growing evidence that this more deliberate form of co-production drives research use. For example, David Cash and colleagues (2003) found that environmental assessments generated through some form of interaction between research and practice were more likely to be used. Similarly, Dilling and Lemos (2011) suggest that there is a higher likelihood that seasonal climate forecast will be used if co-produced between providers and potential users. In a large scale experimental study, Fujitani and colleagues (2017) showed how local fishery managers retained new knowledge better and were more likely to pursue sustainable resource management practices when scientists interacted with the managers rather than merely presenting them with information. And for now over a decade, climate scientists, hydrologists, and water managers have explicitly embraced co-production as a strategy to develop climate and water projections to support long-range planning (Vogel et al., 2016), leading some of the involved practitioners to advocate for a more widespread practice of co-production (Beier et al., 2017)

However, gaps remain in understanding how to overcome institutional barriers that hinder co-production's appeal and use (Briley et al., 2015; Moser, 2016; Wall et al., 2017). Barriers to co-production include the intensive investment of time and other resources required by and from participants (Lemos et al., 2014), which can sometimes be exacerbated by low expectations and fatigue from non-researchers (Briley et al., 2015; Newton and Elliott, 2016). Moreover, while co-production is often predicated on the assumption that closer interaction between research and practice is necessarily better, it remains unclear how the outcomes of co-production can be achieved at scale, especially if relying on repeated in-person interaction and trusted relationships. For example, social experiments testing virtual and asynchronous options for interaction raises new questions about when and how to invest time and resources into face to face interaction (Kettle and Trainor, 2015; Lemos et al., 2019).

Both practical challenges and normative concerns arise in the linking between scientific knowledge co-production and use. From a practical standpoint, there are persistent methodological issues that constrain the ability to study the use of scientific knowledge as a phenomenon (Landry et al., 2003; Larsen, 1981). Most significant are the multiple ways of defining use as an outcome variable. Defining use can range from a binary construct of use and non-use (Ryan and Gross, 1943) to a multi-level variable that mirrors various opportunities of knowledge use in decision-making (Knott and Wildavsky, 1981). A typology introduced by Pelz (1978) distinguishes use between *instrumental* (i.e. direct use in problem solving), *conceptual* (i.e. informing awareness, enlightenment), and *symbolic* (i.e. supporting pre-determined positions or decisions). However, scholars have argued that any typology can be difficult to operationalize in systematic studies (Gitomer and Crouse, 2019). Furthermore, there are other practical challenges, such as the challenge of would-be users recalling what knowledge they draw upon for decisions and why (Spaapen et al., 2013) and making research design choices regarding the range of factors that could explain utilization (Landry et al., 2003).

Of more fundamental concern to some is the growing emphasis by funders, policy-makers, and researchers on the usability of science. Though breakthrough discoveries may occur through use-inspired science, as observed in Donald Stokes' classic text *Pasteur's Quadrant*, many innovations that eventually serve practical ends emerge when consideration of use is low (Stokes, 1997). In the introduction to the essay *Usefulness of Useless Knowledge*, Robbert Dijkraff (Flexner, 2017) articulates a concern we now frequently hear vocalized in different quarters of the scientific community:

> Driven by an ever-deepening lack of funding, against a background of economic uncertainty, global political turmoil, and ever-shortening time cycles, research criteria are becoming dangerously skewed toward short-term goals that may address immediate problems but miss out on huge advances that human imagination can bring in the long term. (p. 10)

Reasonable arguments such as these strengthen the rationale to increase the evidence base to guide interventions in research practice. Similar to our lack of broad, generalizable understanding about what factors drive knowledge use, expectations about the value of undirected research could be as much a function of longstanding research culture as of an understanding of what approaches are demonstrably better (Sarewitz, 1996). This study, therefore, aims to add to this ongoing discussion by providing evidence that does not invalidate the caution articulated by Dijkgraff and others, but does in our view offer evidence for how to accelerate the use of research on increasingly urgent societal problems related to global environmental change and sustainability.

2.2 Funder-driven changes to research practice

Funders of science may be in a key position to strengthen the evidence base for, and help implement, the kinds of practices that drive research use. Science policy research investigates changes in how research funding is structured and how that helps achieve societal goals. For example, studies evaluating the institutionalization of a Broader Impacts statement by the US National Science Foundation (NSF), found that few applicants considered engagement with users as a form of broader impacts and, on balance, researchers retained, as before, a high degree of autonomy (Holbrook, 2012). In a broader, comparative analysis, Davis and Laas (2014) contrasted the Broader Impacts funding approach of the NSF to the Responsible Research and Innovation (RRI) framework applied through European Union science funding. They uncovered how subtleties in messaging within each approach shape their ultimate impact. For example, whereas RRI was found to stimulate changes in research culture with respect to societal interaction, Broader Impacts was found to preserve autonomy of researchers by letting them define the public benefits of their research on their own terms. In another example, Reale and Zinilli (2017) studied new approaches to the proposal peer review process enacted by a national funding program in Italy and found that reviewers side-stepped more structured approaches to proposal evaluation or interpreted them in sufficiently different ways than intended. As a result, the overall process remained much the same as before the restructuring.

While public funding of science in the United States has traditionally afforded researchers autonomy (Bush, 1945; Sarewitz, 1996), some funders have begun to shape program goals, guidelines, or requirements toward co-production with the aim of increasing research use. For example, in response to seed funding for research-practice collaboration on full proposals solicited by Future Earth, unanticipated research collaborations occurred across disciplines and institutional boundaries, even among proposal teams not awarded full funding (Moser, 2016). Similarly, when funders solicited user input to an RFP and involved them as advisors during funded projects, shifts in thinking were reported by users about the kinds of research most appropriate or relevant for their problems (DeLorme et al., 2016). Yet, other reports suggest success is not guaranteed and new approaches warrant caution. For example, Ford, Knight, and Pearce (2013) analyzed research proposals in which co-production was not required but was implicit in the program's aspiration, and found that a lack of explicit guidance or requirements meant that few proposals demonstrated the intention to engage with users.

2.3 Competitive funding in the National Estuarine Research Reserve System

As a funder, the National Estuarine Research Reserve System (NERRS) has operated a nationally competitive funding program to generate usable research for coastal management since 1998 (Trueblood et al., 2019). NERRS was created by the Coastal Zone Management Act of 1972 as a network of research, stewardship, and educational centers based in ecologically sensitive coastal areas (92nd U.S. Congress, 1972). NOAA's National Ocean Service oversees the System of 30 reserves. Estuarine and nearby coastal regions face acute sustainability challenges due to complex ecosystem dynamics stemming from the combination of anthropogenic pollution, sea level rise and other impacts (Allison and Bassett, 2015). Understanding the causes, consequences, and potential options for these kinds of risks is an active area of research and a key concern for resource management and planning at local, state, and national levels (Tribbia and Moser, 2008; Ultee et al., 2018). Included in Figure 1 are example project titles funded by NERRS over time.

Previous research focusing on NERRS suggests the program to be a fertile setting to study scientific practice and use. For example, based on a survey of projects between 1997-2006 Riley and colleagues (2011) identified opportunities for more in-depth consideration of a sponsor's role in generating usable science but also pointed to the insufficiency of available resources to support the long-term cost of successful interaction. Similarly, in-depth qualitative case studies by Matso and Becker (2013, 2014) found changes in program direction enabled scientists to interact with users, though program resources were ultimately insufficient to fully support those interactions.

3. Methods

To understand drivers of scientific knowledge use, we created a database of 16 years of projects funded by NERRS. First, we reviewed requests for proposals to identify major breakpoints in program design, which we call generations (see Figure 1). Then, we conducted qualitative content analysis (Bernard, 2013; Miles et al., 2014) to code 120 randomly selected final project reports on attributes of usable knowledge (see Table 1), interviewed project team members and users (n=40) to triangulate and add context to the results of the documentary analysis, and, finally, used the software package R to analyze results using logistic and ordinal regression models ("R," 2016).

4.1 Organizing NERRS as a Natural Experiment

During the study period (1998-2014), approximately 180 research projects were funded. A review of Requests for Proposals during this time period revealed four distinctive generations of program design, characterized by major changes in the guidelines and requirements within the program's annual Request for Proposal (see Figure 1). Our understanding of the program's history and the rationale for change was greatly enhanced by the perspective provided to us by a veteran program manager with extensive institutional memory of the entire study period. To create a stratified random sample across this time period, 30 projects from each of these generations were randomly selected, for a total sample of 120 projects (for a more detailed description of the shifts in historical perspective see Trueblood et al., 2019). Figure 1 shows the four generations.

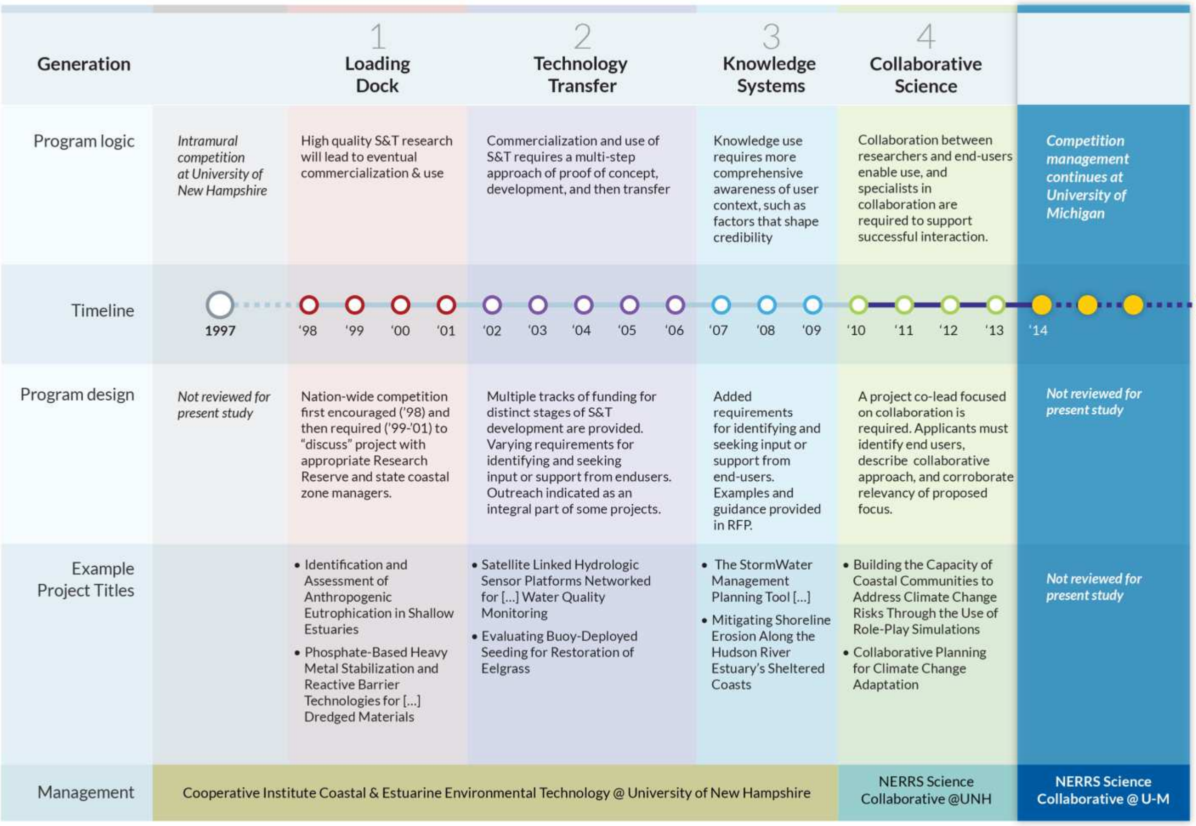


Fig. 1 outlines the timeline of the funding program examined for this study. The generations identified by the authors are explained by substantial changes in the program design and logic.

Generation 1: "Loading Dock". Between 1998-2001, NERRS solicited proposals from Federal and academic researchers, NGOs, and private industry to conduct research at NERRS sites in order to support the long-term conservation of the Nation's coastal and estuarine systems. During the pre-proposal stage, applicants were required to "discuss proposed project" with a NERRS site but no further formalized engagement was encouraged or required.

Generation 2: "Technology Transfer." Between 2002-2006, NERRS solicited ideas for research projects at different phases of development with an emphasis on technology. Small "proof of concept" projects were supported alongside larger "development" and, beginning in 2003, "technology transfer" projects, which emphasized application-focused activities. Additionally, during this period, the program began to require letters of support from potential users and changed review criteria to emphasize connections with users.

Generation 3: "Knowledge Systems." Between 2007-2009, program managers consolidated technology development and deployment into a single track of funding and identified other topic-specific funding tracks using surveys of coastal managers. This period was initiated in part when program managers became aware of social science literature on knowledge use, particularly the work of David Cash and his colleagues (Cash et al., 2003) that emphasized the concept of "knowledge systems," i.e. how interactions between producers and users of knowledge can create a context in which knowledge is more likely to be utilized. In a striking change of tone from earlier solicitations, the 2007 RFP begins: "Investigators funded by [this program] *must* collaborate with the coastal management and regulatory communities" (our emphasis). Beginning in 2008, a collaborative plan for research was required in the proposal.

Generation 4. "Collaborative Science." Between 2010-2014, management of funding was reorganized into a new initiative called the NERRS Science Collaborative. In this generation, applicants were required to provide a detailed collaboration plan and designate a collaboration specialist as a co-lead of their project (for case study descriptions of these types of projects see Matso & Becker, 2013, 2014). Additionally, program managers invested substantial resources in providing guidance and personalized support to project teams on collaboration methods and troubleshooting.

4.2 Documentary analysis

To systematically evaluate each selected project, two study authors conducted qualitative content analysis of final project reports utilizing NVivo (Miles et al., 2014). The coding scheme (see Table 1 for summary and A-1 for detail) was based on attributes related to research practice and use that stem from literature on knowledge co-production and research utilization. These included characteristics such as project activities and outcomes (Meadow et al., 2015), decision relevance (Moss, 2015), the readiness of users and the research itself for utilization (Bechhofer et al., 2001), science-user interaction intensity (Klenk et al., 2015), flow of information between researcher and practitioner communities (Meadow et al., 2015 citing Biggs 1989), and dissemination strategies (Reed, 2008). With exception of the coding cluster for Use, all coding involved two authors, who coded independently and met regularly to discuss and reconcile differences. Codes developed for this study are "high-inference themes" in the sense described by Bernard (2013, p. 545), that is, each of the attributes entailed coder judgements based on texts that usually did not directly provide direct evidence. To ensure consistency in coding over course of the research process and between documents, a second cycle of coding was completed by the two coders, which produced a final set of coding results for analysis. Due to resource limitations, an exception to the two-coder approach was made during the coding for the variable Use. Here, one author employed a secondary coding methodology, where passages previously tracked by two coders for User Readiness and Research Readiness were reexamined to assess Use. Because judgements pertaining to use originate from sections initially coded on User Readiness and Research Readiness, we excluded those attributes from statistical models that examine the outcome variable of Use.

Table 1. Abbreviated coding guide (see A-1 for expanded coding rubric)

1. Research Aims	Primary aim of project (produce new data or science, develop technology, test application of knowledge or tools, learn from users, build capacity)(Meadow et al., 2015).	**6. Use**	Evidence for use (non-use, indeterminate, use) and type of use (conceptual, instrumental) (Pelz, 1978)
2. Research Origins	How research questions and research designs were developed (by researchers, users, in combination) (Meadow et al., 2015).	**7. Direction of Communication**	How communication with users occurred (none at all, one-way, one-way with occasional consultation, or two-way) (Meadow et al., 2015). *See A-3 for results.*
3. Decision/ Management Relevance	Amount of detail (none, generic, specific) provided by researchers about decision-making or resource management context and criteria (Moss, 2015).	**8. User Involvement**	The way in which user involvement was situated in the project (none, passive, active) (Klenk et al., 2015; Meadow et al., 2015). *See A-3 for results.*
4. Dissemination	Venues and approaches to disseminating research findings (none, typical academic, loading dock (i.e. passive), active outreach to users, co-development of outreach with users) (Cash et al., 2006; Reed, 2008).	**9. User Readiness**	Characterization in the research report, regarding the ability of end users to apply research findings or products (Bechhofer et al., 2001). *See A-3 for results.*
5. Interaction Intensity	The extent of interaction between researchers and users (none, linking, match-making, collaborating, co-producing) (Klenk et al., 2015)	**10. Research Readiness**	Appraisal provided by the research team, regarding the readiness of results to be applied in decision or management contexts. *See A-3 for results.*

4.3 Interviews

Following the documentary analysis, we recruited grant recipients (i.e. Principal Investigators and other funded project personnel listed on the front page of project reports) to participate in a telephone interview. These individuals were typically scientists or workers at the boundary of research and practice. Thirty-four grantees were interviewed, and each of them were asked to refer us to users engaged during their project(s) for follow-up interviews, yielding an additional 6 interviews for a total of 40. Interviewees collectively represented 42 distinct projects, as some were funded on multiple occasions. Between seven and nine projects per generation were represented for Generations 1-3 and 17 projects were represented in Generation 4. Additionally, two project team members considered themselves users of previous NERRS sponsored research.

We applied a semi-structured format for these interviews (see A-2 for interview guide). Some questions focused on validating attributes also examined through project report coding. Other questions focused on understanding more about project origins as well as its impact beyond the date of the final project report. The two interviewers regularly conferred and periodically conducted joint interviews to ensure consistency in approach. Interviews were recorded and transcripts produced through third-party transcription services. Additionally, interviewers logged interview contact reports immediately following each interview, where key themes relevant to research questions and other insights were documented. We coded interview transcripts using many of the same codes developed for the report coding.

4.4 Statistical Analysis

Selected coding from project report data (n=120) was analyzed in R. Coding groups related to research practice and use (Table 1) were read into R as ordinal or binary variables. Using ordinal or logistic regressions, we tested the magnitude and significance of change between generations for each of the variables related to research practice. Additional analyses were performed by re-leveling generations so that models could be run with each generation as the reference level as an outcome variable in the regression (see A-4). We also used logistic regressions to test the influence of multiple hypothesized drivers of the dependent variable Use (Table 2).

4. Results

4.1. Sponsor influence on research practice

Results from documentary analysis of final project reports shows significant change in how grant recipients oriented, designed, conducted, and disseminated their research. Attributes of research practice examined here included Aims, Research Origins (design and questions), Decision/Management Relevance, Dissemination, and Interaction Intensity with users (Figures 2 -3; see also A-1). Changes identified in these coding groups mostly correspond to the changing emphases of the program solicitation. For example, relative focus on New Science/Data versus New Technology or Method mirror the shifting emphases on technology development (Figure 2a-b). Similarly, the program's increasing attention to management needs and user collaboration is reflected by an increase in users helping to shape research questions and design (i.e., co-design; Figure 2c-d). Over time, grantees also offered more specific descriptions of the context within and criteria by which users make decisions (Figure 2e-f). Moreover, subtler changes were observed with respect to Dissemination (2g-h), indicating the persistence of Typical Academic outputs even as more user engagement occurred.

Our analysis focused in particular on the nature of user involvement in the research projects. Figure 3 presents coding results for Interaction Intensity, adapting a typology of stakeholder engagement offered by Klenk and colleagues (2015). These results depict consistent movement toward more direct (i.e. working with users themselves versus intermediaries), intense (i.e. more frequent and collaborative), and conversant (i.e. more two-way communication) interaction with users. In each of the first three generations, more than half of projects exhibited no interaction with users; yet by the final generation, nearly all projects reported some form of interaction, and more than half demonstrated higher levels of interaction. We analyzed ordinal and binary coded variables to generate odds ratios and other statistical values that portray the magnitude and significance of change between generations (Figure 3, and Tables 1-4 in A-4). This analysis shows the largest shifts in research practice occurring in Generation 4, when the most intensive collaboration requirements were instituted. In the case of Interaction Intensity, the odds ratio of moving from a lower level of interaction to one level higher (e.g., from Linking to Match-making) is two in Generation 2, five in Generation 3, and 500 in Generation 4. Odds ratios and p-values for Generation 4 relative to Generations 2 and 3 are also large and statistically significant, further suggesting the marked difference in Generation 4. Additional statistics for these variables with all other generations as the reference level are reported in A-4.

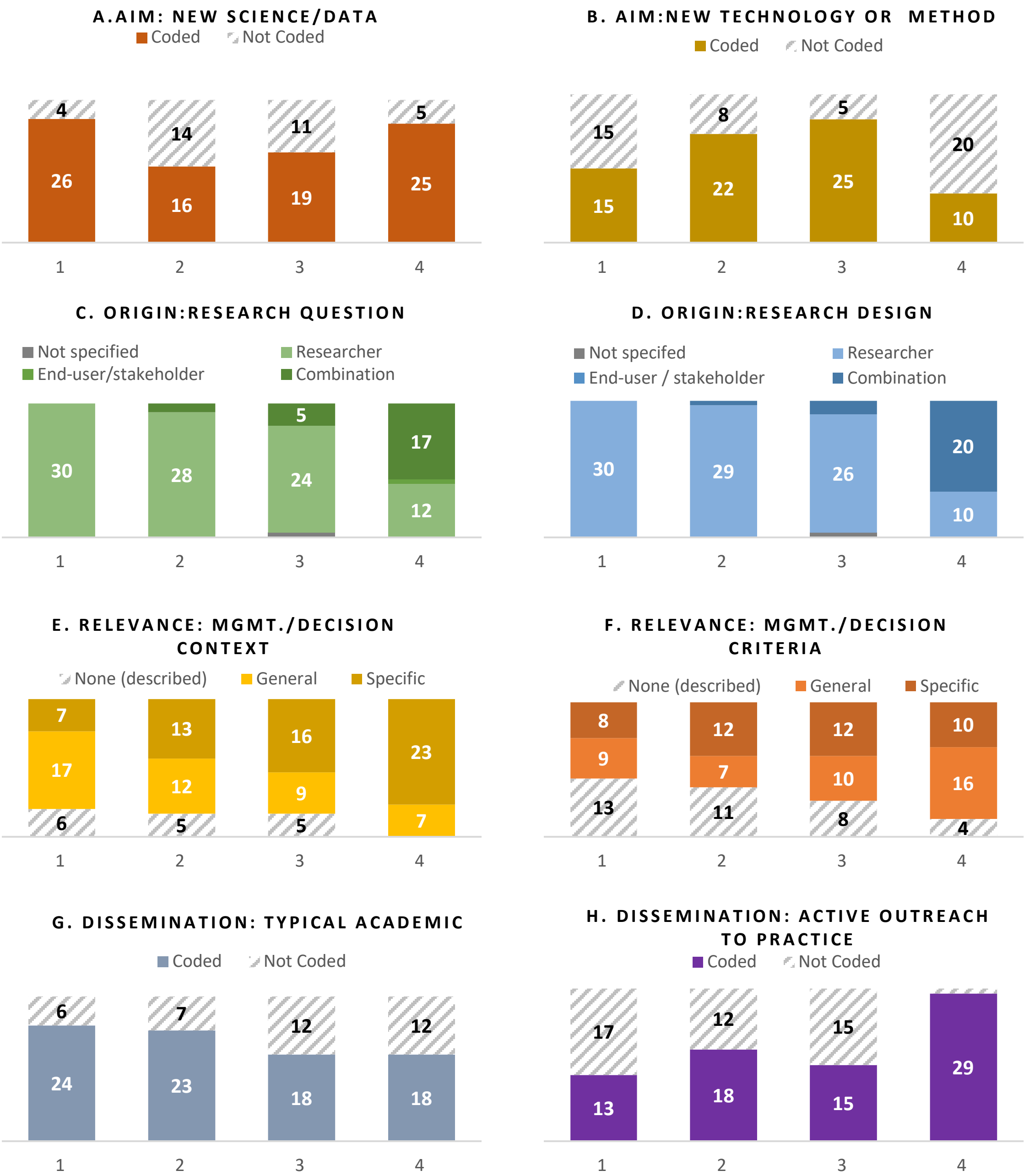


Fig. 2 (a-h) presents results of documentary analysis for each funding program generation labeled underneath bars. Thirty reports were randomly selected in each generation. Coding for Aim assessed the intended outcome of the research project: to generate New Science/Data (a), New Technology (b), and/or other (see A-1). Coding for Origin assessed who helped shape research questions (c) and Research Design (d). Coding for Relevance assessed the degree of specificity (none, general, specific) provided by the project team regarding the Management or Decision-making Context (e) or for Management or Decision-making Criteria (f). Coding for Dissemination indicated whether evidence of Typical Academic Dissemination (e.g., refereed publications, conference presentations) was present (g) and/or whether Active Outreach to Practitioners (h) occurred. The 'Not Coded' theme is used for binary themes that are either present or absent. See A-3 for additional results.

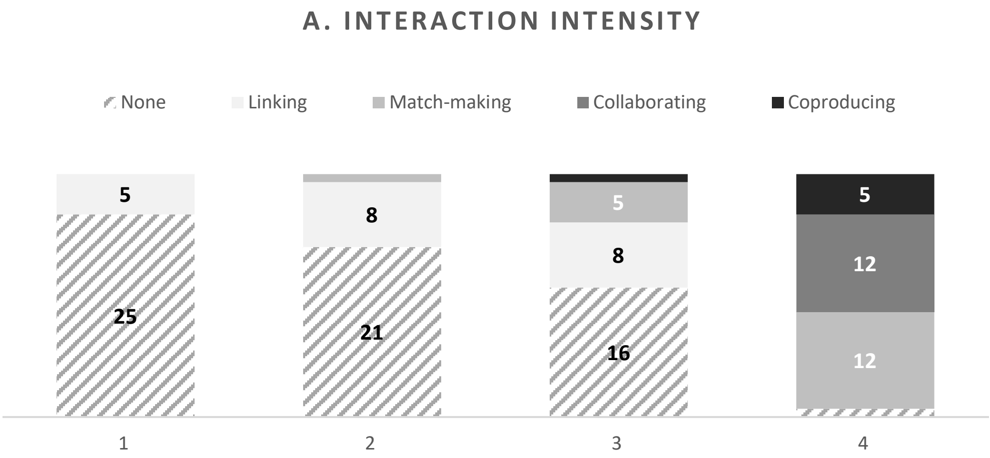


Fig. 3 provides results for coding on Interaction Intensity. Five levels of interaction were coded, ranging from "None" where no evidence for interaction with potential users was identified, to "Co-producing" where users either led or co-led the research project and engaged substantively throughout (coding scheme adapted from Klenk et al. 2015). Additional details on coding values and additional coding results and further analysis related to interaction provided in A-3 and A-4, respectively.

Interviews with grantees provided additional depth and context to project reports and in some cases were able to characterize change in individual perspectives on research that they associate with participation in the funding program itself. Box 1 shows how the way researchers think about their role in shaping research impact has evolved through time. Additionally, interviews with users referred to us by grantees, though too few in number to be representative of the program's multi-stage evolution, offer a helpful complementary viewpoint.

Grantees, most of whom would identify as researchers, were candid about their "*cravenly opportunistic*"—as one marine ecologist put it—approach to seeking funding from NERRS. In some cases, this level of entrepreneurship merely led to a self-selection process, where recipients chose to apply to a program when it was a good fit. For example, a geochemist from Generation 1 said *"[the program] had a problem that needed to be solved[…] and we had the right approach*," while another marine ecologist from Generation 4 said, "*[the program] was just a really good fit: it gave us sort of the natural…landscape in which to implement ..the framework of the project."* One particular recipient who managed both research and outreach components of three different projects funded in Generations 3 and 4 revealed how working to meet funder requirements did not forestall opportunity for a more authentic embrace of collaborative science eventually. At the start, they confessed to "*trying to get the right answer*" when writing their proposal, and at the outset having a "*not very sophisticated idea of how to bring in an end user*." Yet, over time, this changed. In their words, "*We really got […] inoculated with it in phase one and it was just such a successful model that we've continued*." As this grantee elaborated, lessons learned during earlier stages of the project helped guide their efforts toward more meaningful outcomes as they also doubled down on their commitment to a more collaborative style of research and refined their vision along the way for who their users were and how best to engage with them.

Box 1. Representative interview quotes by generation

Generation 1: "I feel like it's my responsibility to convey this information but it's their responsibility to either use it in a constructive way or ignore it."
Generation 2: "Applied research is no longer a derogatory term. Applied research requires that you go beyond a silo in which you were trained."
Generation 3: "It moves you from just a research mode to […] thinking much more critically about factors of adoption and of use..."
Generation 4: "if you didn't have a collaborative outreach partner, you weren't going to get funded. That was clear from the get-go. I think it had a big influence on what we did and how we thought…"

Those who were funded only once by NERRS provide a point-in-time perspective about how the funding program shaped their research design. As indicative of early-on expectations, a Generation 2 biologist said: *"I didn't have any intimate knowledge…of what the needs of the sites were. I was responding specifically to what was in the solicitation package."* Even without the benefit of comparison to other generations, statements by one-time recipients in Generation 4 emphasize this through comments referencing the influence of the funder, such as, "*I don't think we would have done anything that ambitious nor that highly connected to the communities, nor that highly networked nationally"* and "*I liked the idea of being challenged to modify the project in response to the stakeholders*".

Those funded by NERRS over multiple generations offer complementary and longitudinal perspectives. For example, a researcher funded on four occasions during Generations 1, 2, and 3 reflected on his early work saying, "*I think that in general the work that I had done in the past would have been more successful if I had spent the time and effort on those important relationships and kept those people as an integral part of these projects."* A geospatial and data scientist funded on two different generations and involved with NERRS over the entire period said, *"[In the early days […] you could fake [collaboration…] and you could get support. But as time went on, [the funder] became more and more attuned to importance of those aspects and I think became more and more cognizant of how the RFP structure itself could improve those outcomes."* In earlier generations, a team leader funded multiple times said that at first they "w*ere not in knowledge co-production mode when we were doing this work with the various entities. Even though we probably said something to that effect, I think it probably was not really true.*"

Although grantees seemed to understand and respond to the logic of interacting with potential users to increase the likelihood that their research was used, we also routinely found interviewees embracing the mode of knowledge co-production for more than one reason. Frequently, when responding to our question about what the most memorable aspect of the project was, interviewees would describe the experience of collaboration itself. Though the utilitarian merits of collaboration to increase project effectiveness and use of outputs were not neglected, a deeper, oftentimes personal, embrace of collaboration was evident. This interview excerpt exemplifies this blending of motivations:

> Interviewee: I really enjoyed working on this project. You know, perhaps more so than other projects that are strictly science focused. I really enjoy working with stakeholders and having that kind of involvement. So it was fun for me to do for sure.

> Interviewer: And anything in particular about why that's more enjoyable or meaningful?
>
> Interviewee: It just felt like it was more useful in the end. Our goal is always to publish papers and be part of the peer reviewed scientific literature. But those don't always translate to people on the ground making decisions. They're not going out to the scientific literature to ... It's a bit more complicated than they might want to try to read. So, it was just rewarding in that aspect.

From interviews with users we gained new insights into some of the projects. From these, we identified two important themes. First, collaborative work has progressively become a part of their jobs, whether collaborating with other researchers or community stakeholders. One user referred to this as part a "*cultural shift in the way people work*." While some described this as just a more personally satisfying approach, there was a general recognition of its efficacy. For example, a user participant in a Generation 3 project simply stated with regard to the collaborative approach, "*I don't know how it would've gotten done otherwise.*" Second, users spoke about how different forms and intensities of collaboration are appropriate to meet different objectives. From one user engaged during a Generation 1 study: *"I'm not right there with [the researcher] standing in the water with him when he is doing the work."* In this person's view, such proximity is unnecessary except at particular stages. Another user engaged during Generation 4, emphasized the importance of enabling different individuals to engage at different levels of intensity and that different forms of collaboration may be necessary depending on the outcome. As he said, "*For a large manual like this, I think you've gotta have a big group."*

4.2 Influence of interaction with users on knowledge use

Our coding process identified where evidence of Use was presented, when it was not presented (i.e. Non-use), and when there was no basis for a judgement either way (i.e. Indeterminate). In this process, we refrained from judging quality of use but rather made a summary judgement of what grant recipients communicated. An example of reported use (redacted to preserve anonymity) reads like this: "*Our project has resulted in updates to [state agency guidance document]. [The state agency] updated the bioretention specification in the manual during the project.*" An example of definitive Non-Use could read like this: "*Because the biosensor technology is not yet at the stage where it is useful for management applications, it has not been widely transmitted.*" An "Indeterminate" judgement was made when either use was anticipated at some future point in time, when no statements were made regarding any type of use, or when text in the report reffering to use was too vague to support a judgement. In this screening, dissemination activities alone did not satisfy the threshold for Use. When evidence of Use was identified, secondary codes distinguished the use type based upon on Pelz (1978): direct use for decision-making and management actions was coded as "Instrumental" and indirect use to inform priorities and increase general awareness of issues was coded as "Conceptual." We attempted to code for "Symbolic" use for when research was applied to justify pre-existing positions, but no evidence for that form of Use was presented, reinforcing the challenge of operationalizing this typology.

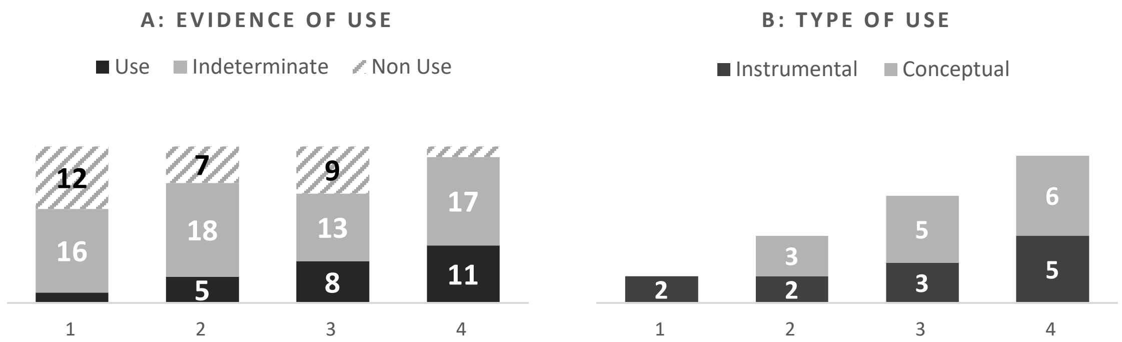


Fig. 4 presents coding results related to use. Panel A provides the first level of coding on use. In that coding, Indeterminate refers to when evidence of use was deemed insufficient or not present. Non-use was coded when specific evidence of non-use was provided in the project report. Panel B provides coding data on the type of use identified for those projects where evidence of use was coded.

Project report coding identified modest increases in evidence of research use, though this signal is likely dampened due to the nature of standard research reporting. Nevertheless, coding results for use (Figure 4) show three meaningful trends. First, in each successive funding generation there is an increase in Use as well as an overall decrease in Non-Use. Second, across all generations, the majority of projects provide no conclusive evidence for Use or Non-Use; that is, in most cases regardless of funding generation, demonstrable evidence for Use or Non-Use was not found in the final project report. This high proportion of Indeterminate codes may be explained both by the timing of when project reports are completed (90 days following project completion) and by the lack of systematic and specific reporting on research use in the context of standard research reports. Third, except for the Generation 1, there is a relative balance between Conceptual and Instrumental Use. The analysis of Use alongside attributes of research practice suggests that a stronger user-orientation of research is associated with greater Use (Figure 5).

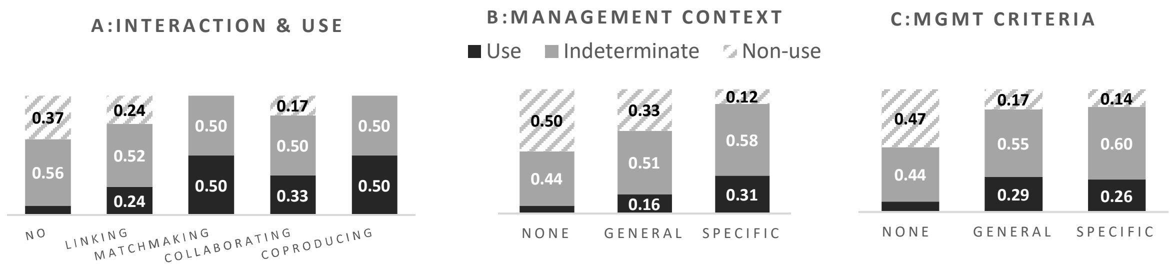


Fig. 5 presents cross tabulations between use and the previously presented research attributes of Interaction Intensity (a), Management Context (b), and Management Criteria (c).

To examine drivers of scientific knowledge use, we consolidated coding data for Use as a binary outcome variable ("Indeterminate" and "Non-use" combined). Then, we ran a set of logistic regression models that tested the influence of year, generation, and other independent variables on Use (Table 2). In Model 2, odds ratios suggest that evidence for use of sponsored research increased by almost a factor of three for Generation 2, by a factor of five for Generation 3, and a factor of eight for Generation 4. In the next sequence of models presented, Interaction Intensity emerges as a consistently significant determinant of Use.

Table 2. Logistic regression results for binary outcome variable "Use"

	Model 1		Model 2			Model 3		Model 4		Model 5	
	Coeff.	*z*	*Coeff.*	*OR (95%CI)*	*z*	*Coeff.*	*z*	*Coeff.*	*z*	*Coeff.*	*z*
Year	0.16	2.96***									
Funding generations											
Generation 2			1.03	2.80 (0.55, 20.78)	1.17	0.87	0.98				
Generation 3			1.63	5.09 (1.14, 35.05)	1.94*	1.10	1.25				
Generation 4			2.09	8.12 (1.91, 56.34)	2.54**	-0.00	-0.00				
Research practice variables											
Aim: New Science/Data										-0.60	-1.00
Aim: New Technology										-0.15	-0.28
Origin: Research Question										-0.08	-0.21
Origin: Research Design										-0.46	-1.22
Relevance: Context								0.19	0.38	0.24	0.46
Relevance: Criteria								0.30	0.79	0.31	0.77
Dissemination: Academic										-0.74	-1.38
Dissemination: Practice										0.91	1.75*
Interaction: Intensity						0.83	2.63***	0.58	2.88***	0.74	2.36**
Model diagnostics											
df	119 (118)		119 (116)			119 (115)		119 (116)		119 (112)	
AIC	119.6		123.95			118.1		117.94		120.5	
Res.Dev.	115.6		115.65			108.1		109.84		104.5	

p < 0.1 - *, <.05 - **, <.01 ***

Since the interviews took place several years or more after the conclusion of the project and included more targeted questions regarding use than prompted by project reports, they add richness to the data from project report coding. Thus, we also coded interviews for Use similarly to project reports. The interviewees addressed use in 49 projects. Out of those, 17 interviewees provided comments regarding use that resulted in a lower level appraisal than gathered from project reports, (i.e., from Use to Indeterminate, or Indeterminate to Non-use), 15 interviewees provided comments that resulted in a higher-level appraisal (i.e., from Non-use to Indeterminate, or Indeterminate to Use). No change occurred for the remaining 17 projects. The results from the interview coding provide a similar depiction to the report coding, though with less change in any of the use categories from Generations 1-3 and a lower proportion of projects coded as indeterminate. This is perhaps because direct questions during the interview on use as well as the additional time elapsed since final report writing enabled respondents the ability to offer more detail than before.

Grant recipients and users spoke to the importance of interactions with each other as influential factors that shaped the usability of end results, reinforcing the statistical analysis of project report data, though with greater nuance. In trying to attribute user participation to the success of the project, one grantee gave two explanations: "*Part of it was being involved in a process in the project that had a forward-looking, proactive, positive appeal, organizational culture… [The other part was], they said they needed these things and they got them.*" Others highlighted how the "*iterative nature provides much greater confidence [for users], in that they were involved somewhat in terms of the design of the tool itself.*" Additionally, user participation was also linked with credibility as represented in this quote:

I think that if we had just done this in a closed room with a bunch of engineers or if we

> sat around with [organization name] and did something like this, I think nobody would've paid attention, but having all these different people involved and able to provide their experience and perspective really lent that credibility that was absolutely necessary.

Despite the centrality of interaction to many grantee's recollection of their project and how they attributed success in generating usable outcomes, they pointed to other factors working in conjunction with interaction. These included the motivation and readiness of users, the demonstrable feasibility of a particular technology or method, and social and political factors that shaped the broader context for use.

5. Discussion

The two most compelling findings from the data analyzed here are that funding agencies have significant influence on research practice and that there is a relationship between the intensity of the interaction between researchers and practitioners and use. First, in contrast with studies that pointed out the limitations or risks of funders' interventions (De Rijcke et al., 2016; Holbrook, 2012; Lövbrand, 2011; Reale and Zinilli, 2017), our evidence suggests a critically important role for funders in driving meaningful changes to research practice. Second, going beyond qualitative case studies, this research provides a larger and more systematically analyzed dataset that suggests that more interaction between researchers and practitioners increases use, further supporting earlier scholarship in this area (Dilling and Lemos, 2011; Fujitani et al., 2017).

When considering approaches to science funding program management, this evidence helps compare alternative, more impact-oriented funding models with conventional, more linear approaches. As described earlier, NERRS funding was initially organized similarly to most US basic research programs. As described by one of its longstanding program officers, NERRS began with the assumption that "*the information, knowledge, and technology resulting from the funded research will make their way into actual management and use through the traditional means of conveying scientific information*." This approach, still commonplace in research funding today, is often depicted as a linear, one-way pipeline of resources and knowledge from funding to research to end-use (See Figure 6a). But the progression of NERRS over time—represented by both the evolving spirit and letter of the program design—gathered users, researchers, and the sponsor into an arrangement where two-way interaction would occur more actively between the three groups and lead to changes within each. Currently, for example, the program operates through a series of multi-way interactions with collaborative research continuing between users and researchers. Program managers also provide ongoing feedback, support, and check-ins between program managers and researchers. Finally program manager administer pre- and post- questionnaires with users to more directly assess use and other outcomes (Trueblood et al., 2019; see Figure 6b).

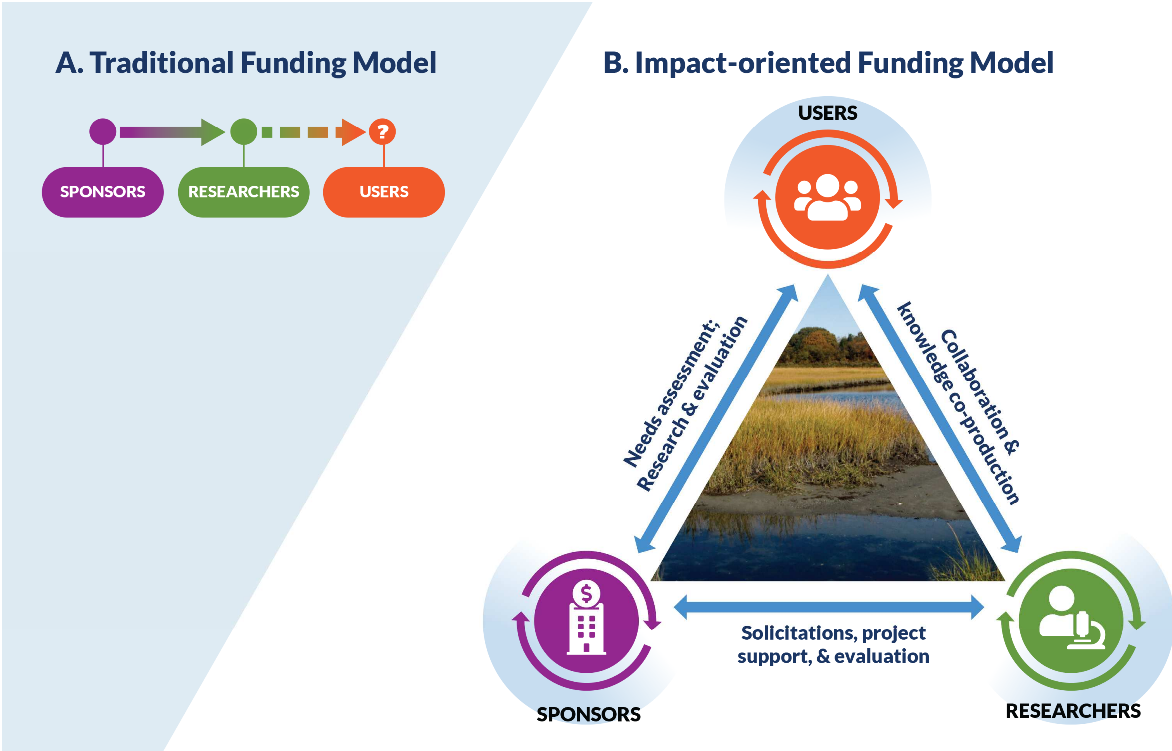


Fig. 6 depicts two different models to structure funding for research. In a), the traditional funding model, research sponsors provide directives and financial resources to selected researchers, who are afforded general autonomy to pursue proposed research. Connections between the researchers and users are tenuous, and it frequently remains unclear whether use occurs. In b), the impact-oriented funding model—which the NERRS example is evolving towards—sponsors, researchers, and users all maintain active lines of two-way communication and interaction that can inform research program agendas, research projects aims and methods, and well as new insights for problem solving in the contexts for application.

Additionally, similarly to other scholars in this field, we caution against wholesale transition to funding models that are guided by utilitarian principles alone (Flexner, 2017). Ultimately, our data shows that not all research need to be conducted in high-intensity interaction modes in order to be utilized and that not all co-produced science leads to use (Lemos et al., 2018). In this sense, this study also contributes to current thread of discussion in the literature about how much interaction between research and practice is optimal (Lemos et al., 2019; Trainor et al., 2016). Still more research is needed to understand how different forms and intensities of interaction influences use in different settings, and this research would benefit from incorporating questions about how different mediums for interaction (e.g. virtual, asynchronous) help or hinder the co-production process and achievement of intended outcomes. Our examination of NERRS—and hopefully future studies of funding programs like it—could be fertile ground for the examination of these issues in different settings. Furthermore, a methodological finding of this study is how labor-intensive it can be to interpret drivers and outcomes from standard research reports – hence, we encourage funders to modify project reporting structures if the goal is to foster use.

6. Conclusion

The desire to make science usable for solving societal problems is challenging the traditional conceptualization of science and society as separated realms. Guided by different motivations, global change and sustainability scientists are in many cases departing from conventional approaches by embracing co-production and looking to practical problems and expertise from non-scientists to guide and apply their science. Given what we already know about the potential benefits of co-production, this change may lead to significant increase in the societal impact of science. At the same time, this study also raises important, and still unresolved, issues surrounding the grand challenge we introduce at the outset: how can science best help society manage risk and make progress toward sustainability in the midst of global environmental change? At its core, this question begs critical examination as to whether scientific structures can (or should) change to be more collaborative, inclusive, and de-siloed; and if such a move to more interactive and engaged research practice will yield meaningful gains in the use of scientific knowledge. Understanding in greater detail what particular benefits arise and the pathway to achieving them at scale amid accelerating environmental challenges often remain unclear.

This study makes progress on this understanding by providing new empirical evidence for how funders can catalyze more collaborative research and help increase its use in support of environmental sustainability goals. Specifically, we examined a coastal and environmental research program that, over 16 years, transformed from a traditional funding model to embrace, and eventually incentivize, more engaged research. We found these changes influence research practice beyond perfunctory compliance and that a movement toward co-production supports increased utilization. These findings provide stronger validation—but also nuance and some caveats—to the conclusions of prior literature on co-production. Indeed, we still need to be cautious when designing research funding programs to ensure that research-practice relationships proceed equitably, effectively, and efficiently. Ongoing research into how forms and intensity of interaction can be optimized and how different approaches are deemed satisfying, or equitable, by participants could help contribute to improve what works best. Research that ties together cohorts of funders pursuing similar approaches simultaneously would further strengthen the evidence base across contexts and foster learning more relevant to guiding program intervention. In this, we see great opportunity for funders to work with science policy and evaluation researchers to re-imagine project reporting approaches to reduce grantee burden while also accelerating learning and safeguarding against "lip service" or exploitative arrangements with stakeholders. In fact, such collaboration could be another potentially fruitful form of knowledge co-production, helping to make knowledge about co-production, itself, more usable.

These results are not intended to suggest conventional forms of research funding and practice are necessarily unsuitable for making progress in some areas of science intended to help to manage risk from global change or to enhance sustainability. But we do see immense potential in emerging and alternative designs as enabling science to better help society meet the challenges of solving environmental problems. Indeed, through this research we see evidence of cultural shifts underway that embrace co-production for both its practical and intrinsic benefits. We hope that this research will help to guide researchers, users, and funders alike.

References

92nd U.S. Congress, 1972. Coastal Zone Management Act. Government Printing Office.

Allison, E.H., Bassett, H.R., 2015. Climate change in the oceans: Human impacts and responses. Science (80-.). 350, 778–782. https://doi.org/10.1126/science.aac8721
Amara, N., Ouimet, M., Landry, R., 2004. New evidence on instrumental, conceptual, and symbolic utilization of university research in government agencies. Sci. Commun. https://doi.org/10.1177/1075547004267491
Asrar, G.R., Hurrell, J.W., Busalacchi, A.J., 2013. A need for "actionable" climate science and information: Summary of WCRP open science conference. Bull. Am. Meteorol. Soc. 94. https://doi.org/10.1175/BAMS-D-12-00011.1
Bechhofer, F., Rayman-bacchus, L., Williams, R., 2001. The dynamics of social science research exploitation. Scottish Aff. 36.
Beier, P., Hansen, L.J., Helbrecht, L., Behar, D., 2017. A How-to Guide for Coproduction of Actionable Science. Conserv. Lett. 10, 288–296. https://doi.org/10.1111/conl.12300
Bernard, H.R., 2013. Research Design, in: Social Research Methods: Qualitative and Quantitative Approaches. Sage, Thousand Oaks, CA, p. 789.
Bremer, S., Meisch, S., 2017. Co-production in climate change research: reviewing different perspectives. Wiley Interdiscip. Rev. Clim. Chang. 8, 1–22. https://doi.org/10.1002/wcc.482
Briley, L., Brown, D., Kalafatis, S.E., 2015. Overcoming barriers during the co-production of climate information for decision-making. Clim. Risk Manag. 9, 41–49. https://doi.org/10.1016/j.crm.2015.04.004
Bush, V., 1945. Science: the endless frontier, A report to the President on a Program for Postwar Scientific Research. Washington D.C. https://doi.org/10.2307/3625196
Caplan, N., 1979. The Two-Communities Theory and Knowledge Utilization. Am. Behav. Sci. 22, 459–470.
Cash, D.W., Borck, J.C., Patt, A.G., 2006. Countering the Loading-Dock Approach to Linking Science and Decision Making. Sci. Technol. Hum. Values 31, 465–494. https://doi.org/10.1177/0162243906287547
Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. U. S. A. 100, 8086–91. https://doi.org/10.1073/pnas.1231332100
Davis, M., Laas, K., 2014. "Broader Impacts" or "Responsible Research and Innovation": A Comparison of Two Criteria for Funding Research in Science and Engineering. Sci. Eng. Ethics 20, 963–983. https://doi.org/10.1007/s11948-013-9480-1
De Rijcke, S., Wouters, P.F., Rushforth, A.D., Franssen, T.P., Hammarfelt, B., 2016. Evaluation practices and effects of indicator use-a literature review. Res. Eval. 25, 161–169. https://doi.org/10.1093/reseval/rvv038
DeLorme, D.E., Kidwell, D., Hagen, S.C., Stephens, S.H., 2016. Developing and managing transdisciplinary and transformative research on the coastal dynamics of sea level rise: Experiences and lessons learned. Earth's Futur. 4, 194–209. https://doi.org/10.1002/2015EF000346
Dilling, L., Lemos, M.C., 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. Glob. Environ. Chang. 21, 680–689. https://doi.org/10.1016/j.gloenvcha.2010.11.006
Flexner, A., 2017. The Usefulness of Useless Knowledge. Princeton University Press, Princeton, NJ and Oxford, UK.
Ford, J.D., Knight, M., Pearce, T., 2013. Assessing the 'usability' of climate change research for decision-making : A case study of the Canadian International Polar Year. Glob. Environ.

Chang. 23, 1317–1326. https://doi.org/10.1016/j.gloenvcha.2013.06.001
Fujitani, M., McFall, A., Randler, C., Arlinghaus, R., 2017. Participatory adaptive management leads to environmental learning outcomes extending beyond the sphere of science. Sci. Adv. 3, 1–12. https://doi.org/10.1126/sciadv.1602516
Gitomer, D.H., Crouse, K., 2019. Studying the Use of Research Evidence: A Review of Methods.
Holbrook, J.B., 2012. Re-assessing the science – society relation: The case of the US National Science Foundation's broader impacts merit review criterion (1997 – 2011). Technol. Soc. 27, 437–451.
Jasanoff, Sheila, 2004. The idiom of co-production, in: Jasanoff, Shiela (Ed.), States of Knowledge: The Co-Production of Science and the Social Order. Routledge, pp. 1–12.
Kettle, N.P., Trainor, S.F., 2015. The role of remote engagement in supporting boundary chain networks across Alaska. Clim. Risk Manag. 9, 6–19. https://doi.org/10.1016/j.crm.2015.06.006
Klenk, B.N.L., Meehan, K., Pinel, S.L., Mendez, F., Lima, T., Kammen, D.M., 2015. Stakeholders in climate science: Beyond lip service? Science (80-.). 350, 743–744. https://doi.org/10.1126/science.aab1495
Knott, J., Wildavsky, A.B., 1981. If dissemination is the solution, what is the problem, in: Rich, R.F. (Ed.), The Knowledge Cycle. SAGE, Beverly Hills, pp. 99–136.
Landry, R., Lamari, M., Amara, N., 2003. The extent and determinants of the utilization of university research in government agencies. Public Adm. Rev. 63, 192–205. https://doi.org/10.1111/1540-6210.00279
Lang, D.J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., Thomas, C.J., 2012. Transdisciplinary research in sustainability science: Practice, principles, and challenges. Sustain. Sci. https://doi.org/10.1007/s11625-011-0149-x
Larsen, J.K., 1981. Knowledge Utilization: Current Issues, in: Rich, R.F. (Ed.), The Knowledge Cycle. SAGE Publications, Beverly Hills, pp. 149–167.
Lemos, M.C., Arnott, J.C., Ardoin, N.M., Baja, K., Bednarek, A.T., Dewulf, A., Fieseler, C., Goodrich, K.A., Jagannathan, K., Klenk, N., Mach, K.J., Meadow, A.M., Meyer, R., Moss, R., Nichols, L., Sjostrom, K.D., Stults, M., Turnhout, E., Vaughan, C., Wong-Parodi, G., Wyborn, C., 2018. To co-produce or not to co-produce. Nat. Sustain. 1, 722–724. https://doi.org/10.1038/s41893-018-0191-0
Lemos, M.C., Kirchhoff, C.J., Kalafatis, S.E., Scavia, D., Rood, R.B., 2014. Moving climate information off the shelf: Boundary chains and the role of RISAs as adaptive organizations. Weather. Clim. Soc. 6, 273–285. https://doi.org/10.1175/WCAS-D-13-00044.1
Lemos, M.C., Morehouse, B.J., 2005. The co-production of science and policy in integrated climate assessments. Glob. Environ. Chang. 15, 57–68. https://doi.org/10.1016/j.gloenvcha.2004.09.004
Lemos, M.C., Wolske, K.S., Rasmussen, L.V., Arnott, J.C., Kalcic, M.M., Kirchhoff, C.J., 2019. The closer, the better? Untangling scientist-practitioner engagement, interaction, and knowledge use. Weather. Clim. Soc. https://doi.org/10.1175/WCAS-D-18-0075.1
Lövbrand, E., 2011. Co-producing European climate science and policy: a cautionary note on the making of useful knowledge. Sci. Public Policy 38, 225–236. https://doi.org/10.3152/030234211x12924093660516
Matso, K.E., Becker, M.L., 2014. What Can Funders Do to Better Link Science with Decisions? Case Studies of Coastal Communities and Climate Change. Environ. Manage. 54, 1356–

1371. https://doi.org/10.1007/s00267-014-0347-2
Matso, K.E., Becker, M.L., 2013. Funding Science that Links to Decisions: Case Studies Involving Coastal Land Use Planning Projects. Estuaries and Coasts 38, 1–15. https://doi.org/10.1007/s12237-013-9649-5
Matso, K.E., Dix, M.O., Chicoski, B., Hernandez, D.L., Schubel, J.R., 2008. Establishing a minimum standard for collaborative research in federal environmental agencies. Integr. Environ. Assess. Manag. 4, 362–8. https://doi.org/10.1897/IEAM_2007-070.1
Mauser, W., Klepper, G., Rice, M., Schmalzbauer, B.S., Hackmann, H., Leemans, R., Moore, H., 2013. Transdisciplinary global change research: The co-creation of knowledge for sustainability. Curr. Opin. Environ. Sustain. 5, 420–431. https://doi.org/10.1016/j.cosust.2013.07.001
Meadow, A.M., Ferguson, D.B., Guido, Z., Horangic, A., Owen, G., Wall, T., 2015. Moving toward the Deliberate Coproduction of Climate Science Knowledge. Weather. Clim. Soc. 7, 179–191. https://doi.org/10.1175/WCAS-D-14-00050.1
Michaels, S., 2009. Matching knowledge brokering strategies to environmental policy problems and settings. Environ. Sci. Policy 12, 994–1011. https://doi.org/10.1016/j.envsci.2009.05.002
Miles, M.B., Huberman, A.M., Saldana, J., 2014. Qualitative Data Analysis, 3rd ed. Sage, Thousand Oaks, CA.
Moser, S.C., 2016. Can science on transformation transform science? Lessons from co-design. Curr. Opin. Environ. Sustain. 20, 106–115. https://doi.org/10.1016/j.cosust.2016.10.007
Moss, R.H., 2015. Assessing decision support systems and levels of confidence to narrow the climate information "usability gap." Clim. Change. https://doi.org/10.1007/s10584-015-1549-1
Newton, A., Elliott, M., 2016. A Typology of Stakeholders and Guidelines for Engagement in Transdisciplinary, Participatory Processes. Front. Mar. Sci. 3, 1–13. https://doi.org/10.3389/fmars.2016.00230
Pelz, D.C., 1978. Some expanded perspectives on the use of social science in public policy, in: Yinger, J.M., Cutler, S.J. (Eds.), Major Social Issues. The Free Press, New York and London, pp. 346–357.
Posner, S.M., Cvitanovic, C., 2019. Evaluating the impacts of boundary-spanning activities at the interface of environmental science and policy: A review of progress and future research needs. Environ. Sci. Policy 92, 141–151. https://doi.org/10.1016/j.envsci.2018.11.006
R, 2016.
Reale, E., Zinilli, A., 2017. Evaluation for the allocation of university research project funding: Can rules improve the peer review? Res. Eval. 26, 190–198. https://doi.org/10.1093/reseval/rvx019
Reed, M.S., 2008. Stakeholder participation for environmental management: A literature review. Biol. Conserv. 141, 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014
Riley, C., Matso, K.E., Leonard, D., Stadler, J., Trueblood, D., Langan, R., 2011. How research funding organizations can increase application of science to decision-making. Coast. Manag. 39, 336–350. https://doi.org/10.1080/08920753.2011.566117
Ryan, B., Gross, N., 1943. Acceptance and Diffusion of Hybrid Corn Seed in Two Iowa Communities. Rural Sociol. 8, 15–24. https://doi.org/citeulike-article-id:1288385
Sarewitz, D., 1996. Frontiers of illusion: science, technology and the politics of progress. Temple University Press, Philadelphia, PA.

Spaapen, J., Shinn, T., Msh-paris, C., Marcovich, A., 2013. SIAMPI final report.
Stokes, D.E., 1997. Pasteur's quadrant: basic science and technological innovation. Brookings Institution Press, Washington, D.C.
Trainor, S.F., Kettle, N.P., Gamble, J.B., 2016. Not another webinar ! Regional webinars as a platform for climate knowledge-to-action networking in Alaska 117–138.
Trencher, G., Nagao, M., Chen, C., Ichiki, K., Sadayoshi, T., Kinai, M., Kamitani, M., Nakamura, S., Yamauchi, A., Yarime, M., 2017. Implementing sustainability co-creation between universities and society: A typology-based understanding. Sustain. 9. https://doi.org/10.3390/su9040594
Tribbia, J., Moser, S.C., 2008. More than information: what coastal managers need to plan for climate change. Environ. Sci. Policy 11, 315–328. https://doi.org/10.1016/j.envsci.2008.01.003
Trueblood, D., Almazán-Casali, S., Arnott, J., Brass, M., Lemos, M.C., Matso, K.E., Read, J., Vaccaro, L., Wondolleck, J., 2019. Advancing Knowledge for Use in Coastal and Estuarine Management: Competitive Research in the National Estuarine Research Reserve System. Coast. Manag. 0, 1–10. https://doi.org/10.1080/08920753.2019.1598221
Tseng, V., 2012. Commentary on The Uses of Research in Policy and Practice. Soc. Policy Rep. 26, 1–16. https://doi.org/10.1007/s10833-011-9177-7.Roderick
Ultee, L., Arnott, J.C., Bassis, J., Lemos, M.C., 2018. From Ice Sheets to Main Streets: Intermediaries Connect Climate Scientists to Coastal Adaptation. Earth's Futur. 6, 299–304. https://doi.org/10.1002/2018EF000827
Vano, B.J.A., Behar, D., Mote, P.W., Ferguson, D.B., Pandya, R., 2017. Partnerships Drive Science to Action Across the AGU. Eos (Washington. DC). 98, 1–7.
Vogel, J., McNie, E., Behar, D., 2016. Co-producing actionable science for water utilities. Clim. Serv. 2–3, 30–40. https://doi.org/10.1016/j.cliser.2016.06.003
Wall, T.U., Meadow, A.M., Horganic, A., 2017. Developing evaluation indicators to improve the process of coproducing usable climate science. Weather. Clim. Soc. 9, 95–107. https://doi.org/10.1175/WCAS-D-16-0008.1

LIST OF APPENDICES

A-1. CODEBOOK

A-1 Table 1. Complete codebook for documentary analysis of final reports

Coding Group	Coding Options	Coding Criteria	Ref.	CSV Variable Name

1. Research Aims	a. new science/data	a. Project seeks, as a primary aim, to produce new scientific understanding or data	(Meadow et al., 2015)	1.1
	b. new technology or method	b. Project seeks, as a primary aim, to develop prototype for new technology/method/practice for use by management		1.3
	c. dissemination	c. Project seeks, as a primary aim, to disseminate knowledge to communities of practice (as a primary goal)		1.2
	d. testing in applied settings	d. Project seeks, as a primary aim, to test applicability of new knowledge/technology/ method in user/management contexts (not field research).		1.4
	e. learning from users	e. Project seeks, as a primary aim, to learn from information/technology users to guide applied research		1.5
2. Origins	**Research question**		(Meadow et al., 2015)	
	a. Not specified	a. Origin of research question not identified		5.0a
	b. From researchers only	b. Researchers develop research question		5.1
	c. From users only	c. End users develop research question		5.3
	d. From combination	d. Combination of researchers and end users develop research question		5.5
	Research design			
	a. Not specified	a. Origin of research not identified		5.0b
	b. From researchers only	b. Researchers develop research design/tech. development		5.2
	c. From users only	c. End users develop research design		5.4
	d. From combination	d. Combination of researchers and end users develop research design		5.6
3. Relevance	**Decision/management *context***		(Moss, 2015)	
	a. None identified	a. No specific decision/management context identified		2.0a
	b. General	b. Identification of general decision/management *context* for information/technology use		2.1
	c. Specific	c. Identification of specific decision/management *context* for information/technology use		2.3
	Decision/management *criteria*			
	a. None identified	a. No specific decision/management criteria identified		2.0b
	b. General	b. Identification of general		2.2

	c. Specific	decision/management *criteria* for information/technology use c. Identification of specific *criteria* of information to existing decision/management		2.4
4. Dissemination	a. None b. Academic c. Loading-dock to practice d. Active to practice e. Dissemination co-designed	a. No description of information/ knowledge/technology dissemination b. Information/knowledge/technology disseminated through typical research outlets (e.g. academic conference proceedings, peer-reviewed publications, etc.) c. Information/knowledge/technology passively disseminated to communities of practice, such as made available on researcher website (i.e. Loading Dock approach) d. Information/knowledge/technology actively disseminated to communities of practice e. Dissemination strategy co-designed and implemented with end users	(Klenk et al., 2015; Meadow et al., 2015)	10.0 10.1 10.2 10.3 10.4
5. Intensity of interaction	a. None (described) b. Linking c. Match-making d. Collaborating e. Coproducing	a. No interaction identified b. Targeted dissemination of knowledge to inform decision-making/management (Linking) c. Diverse types of knowledge producers are connected with users to frame research questions and interpret results (Match-Making) d. Knowledge users are active throughout the process, including articulation of research questions, design of projects, collection and analysis of data, and production of outputs (Collaborating) e. Users are empowered and have capacity to critically assess and (co-)lead project.	(Amara et al., 2004; Klenk et al., 2015; Michaels, 2009)	7.0 7.1 7.2 7.3 7.4

6. Use ***(coded only by 1 coder)***	a. Evidence of use i. Instrumental ii. Conceptual b. Indeterminate c. Evidence for non-use	a. Demonstrable evidence of use of research outcomes i. direct use for decision-making and management actions (i.e. "Instrumental") ii. indirect use to inform priorities, agendas, and awareness (i.e. "Conceptual") b. Use was either not describe or it was anticipated without adequate evidence of eventual outcome c. Specific evidence of inability for use provided	(Landry et al., 2003)	Use
7. Directionality	a. None (described) b. Unidirectional c. Unidirectional w/ some consultation d. Bi-directional	a. No flow of information to end users described b. Unidirectional (i.e. From knowledge/technology producers to knowledge/technology users) c. Unidirectional but with occasional consultation (i.e. Knowledge producers consult knowledge users) d. Bi-directional (i.e. Knowledge producers work with knowledge users to produce, understand, and apply knowledge in practice/decision-making)		4.0 4.1 4.2 4.3
8. User involvement	a. None (described) b. Primarily passive participant c. Participate in specific stages d. Continuously involved	a. Non-existent b. Primarily as passive recipient of new knowledge or technology c. Participating in specific stages only d. Continuous involvement		8.0 8.1 8.2 8.3
9. User readiness	a. None (described) b. Initial stages c. Adding value	a. No discernable reference to user readiness/ or explicit mention of lack of readiness. b. Project indicated that users were only at initial stages of readiness to utilize knowledge/technology produced (i.e. planned use or early stages of initial use) c. Research produced is adding (or very likely to) add value to existing practitioner knowledge (i.e. user readiness such that new knowledge complements/builds upon existing knowledge/practice)	(Bechhofer et al., 2001)	3.0 3.1 3.3

10. Research readiness	a. None described	a. No discernable reference to the readiness of available knowledge/technology to meet user needs	3X.0
	b. Not yet ready	b. Knowledge/technology not yet available or ready to meet user needs, even after project completion (i.e. gaps still exist)	3X.1
	c. Partial/potential	c. Knowledge/technology potentially available to end users, may be tested at least partially in real world context, but still not indicated as fully usable form, as of project completion	3X.2
	d. Available for or in use	d. Knowledge/technology available (e.g. concluded, patented, published, or commercialized) and/or supplied in usable form as of project completion (regardless of user readiness or desire) [e.g. disseminated to communities of practice, etc.]	3X.3

A-2. SEMI-STRUCTURED INTERVIEW GUIDE

Potential questions to ask of funded projects, stakeholder participants, designated end users connected to projects funded by the National Estuarine Research Reserve System (1998-2014).

Interview will proceed in a semi-structured manner.

Potential interviewees:
- Project Team Leader or other (incl. reserves)
- End user (as designated, incl. reserves, with slight modifications to questions as appropriate)
- Other stakeholder (if no end user ID'd, with slight modifications to questions as appropriate)

Interview START:
- Warm welcome
- Thank you for agreeing to be interviewed today.

Informed consent
- There are some things I have to cover at the outset in order to properly obtain your participation in this study.
  - FIRST: I'm going to ask questions about your experience conducting research and the application of that research into practice.
  - SECOND: I'd like to be able to record this interview to produce a transcript to be used only by our research team for reference and analysis. While I plan to utilize the insights you share with me to complete this study, anything you share with me will not be attributed to you personally and any potentially identifying information in what you share will be removed before sharing more broadly.
  - Is it okay with you to proceed with this interview and to record it? Or do you have any questions for me before we proceed?
- If YES, say we'll put on hold for a second and be back momentarily
- If NO, ask if there are any specific questions or concerns about doing the interview. And then if concern about recording persists, offer to continue the interview with only notetaking by
---
- Thanks, ____, for agreeing to participate. We're now on a recorded line. We're hoping to talk to you

about the project(s), ____. Just to let you know, we've had the opportunity to read the final report your team submitted on behalf of the project. We are now interested to hear from you what you recall about the project since its completion as well as some specific insights you might have about how research becomes utilized in practice.

Opening question:

- As a start, I want to hear any highlights you remember about the project. I realize that these activities took place [quite] some time ago, so don't worry if you can't remember everything. Please just tell me what you can remember that stands out as memorable or significant. [ACTIVITIES/OUTCOMES/IMPACT]
  - *If recollection is limited, remind interviewee of few keywords from abstract, end date of project, other collaborators, and other tidbits from abstract as needed.*
  - PROBE: How did the design of the project and its objectives come together? Who was involved? [ORIGINS]
  - PROBE: What do you recall were some of the main achievements of the project? [OUTCOMES]
  - PROBE: Is there anything noteworthy that has occurred in relation to the project since its completion? [OUTCOMES]

Note: Most of the interview may proceed organically from this opening question. See following questions for follow up in key areas of research interest.

Follow on questions

- What were the coastal/estuarine management issues this project was seeking to address? [RELEVANCE/CONTEXT]
  - PROBE: Were there specific needs resource managers or decision-makers that you were trying to provide for?
    - Or, were there other types of users?
  - PROBE: From your position, how did you come to what decision-makers or others needed? [INTERPLAY]
  - PROBE: Throughout the project, did your understanding about their needs change over time? If so, how? [INTERPLAY]
  - PROBE: What were some of the aspects of the project that enabled you to better understand their needs? [INTERACTION/INTERPLAY]
- [If nothing has been volunteered up to this point about interaction] During the project, to what extend did you interact with decision-makers, resource managers, or other potential users? [INTERACTION]
  - PROBE: What was the nature of that interaction? What forms? What was communication like? [INTERACTION/COMMUNICATION/REPRESENTATION]
  - Was the input open ended or focused?
  - PROBE: How often do you recall interacting? [INTERACTION]
  - PROBE: How did the interaction influence the project and its outcomes?
  - PROBE: clarify users versus advisors/stakeholders
- Either during or after the project, do you know whether outputs from the project were utilized by practitioners, resource managers, or decision-makers?
  - PROBE [If no use]: To what do you attribute this? Was this not part of the original intent of the project, or were there barriers to the ability for this to become usable?
    - In your opinion was the research ready to be utilized?
    - Were end users prepared to be able to utilize your research?
  - PROBE [if use]:
    - Could you describe the way in which this new knowledge (or technology) was utilized)
    - How have you come to understand this?

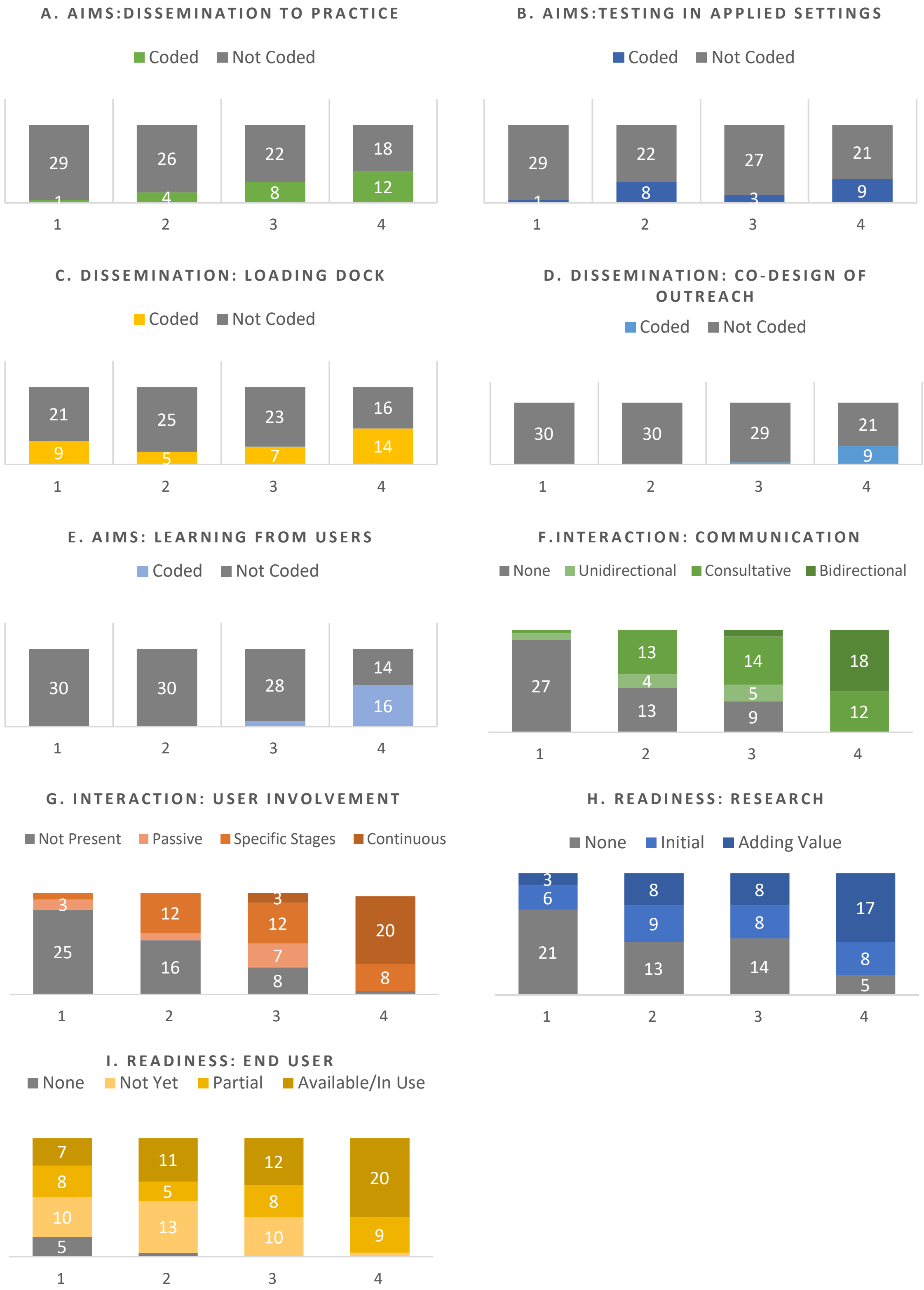
        - To what do you attribute the success in uptake?
        - PROBE (as appropriate): Could this kind of uptake occurred without the participation of [end user, stakeholder, etc.]
            - PROBE: What specifically about their participation helped aid in the application?
- What outcomes in the coastal/estuarine environmental resulted from this?
- Do you think that funding source for this project (e.g., NERRS – CICEET or NSC) had any influence over the approach you pursued?

[Opportunity for additional questions]

- Getting toward the conclusion of this interview… Is there anything you know now (about applied or collaborative research) that you wish you knew when you were involved with this project?
    - PROBE: Did you ever find that the interaction or collaboration was unnecessary, too much, or a hindrance?
- Is there anything else you would like to share about your recollections of the project?
- Is there anyone you could recommend that might fit into the category of an user that we could talk to get their perspective? This could be someone that was actively involved in the project, or if that's not possible, someone that came to utilize results from the project afterwards…

A-3. ADDITIONAL CODING RESULTS

A-3 Figure 1. Additional coding results



A-4 ADDITIONAL ANALYSIS

A-4 Table 1. Modelling results for research practice coding relative to Generation 1. “Loading Dock.”

Coded variable	Model type	Generation 2		Generation 3		Generation 4	
		t/z-value	*Odds Ratio*	*t/z-value*	*Odds Ratio*	*t/z-value*	*Odds Ratio*
Aim: New Science/Data	L	-2.68***	0.18	-1.33***	0.27	-0.26**	0.77
Aim: New Technology	L	1.83*	2.75	2.63***	5.00	-1.30	0.50
Origin: Research Question	O	1.11	3.42	1.67*	7.18	3.65***	62.64
Origin: Research Design	O	0.61	2.22	1.09	4.04	3.89***	101.98
Relevance: Context	O	2.32	1.90	1.95*	2.65	3.97***	9.09
Relevance: Criteria	O	0.98	1.62	1.46	2.04	2.71*	2.24
Dissemination: Academic	L	-0.31	0.82	-1.67*	0.38	-1.67	0.38
Dissemination: Practice	L	1.29	1.96	0.52	1.31	3.36***	37.92
Interaction: Intensity	O	1.20	2.11	2.68*	5.11	6.60***	503.48

$p < 0.1$ - *, <.05 - **, <.01 ***. *L – logistic regression (binomial), O – ordinal logistic regression. All results relative to Generation 1. See A-4 for modelling results with other generations as reference level.*

A-4 Table 2. Modelling results for research practice coding relative to Generation 2. “Technology Transfer”

Coded variable	Model type	Generation 1			Generation 3			Generation 4		
		t/z	*OR*	*95%CI*	*t/z*	*OR*	*95%CI*	*t/z*	*OR*	*95%CI*
Aim: New Science/Data	L	2.68***	5.69	(1.71, 22.91)	0.78	1.51	(0.54, 4.31)	2.41**	4.38	(1.39, 15.77)
Aim: New Technology	L	-1.84*	0.36	(0.12, 1.05)	0.93	1.82	(0.53, 6.80)	-3.01***	0.18	(0.06, 0.53)
Origin: Research Question	O	-1.01	0.29	(0.01, 2.61)	0.86	2.10	(0.41, 13.2)	3.76***	18.31	(4.66, 104.40)
Origin: Research Design	O	-0.61	0.45	(0.02, 5.58)	0.55	1.82	(0.22, 19.64)	4.1***	45.79	(9.28, 423.82)
Relevance: Context	O	-1.32	0.53	(0.20,0.52)	0.66*	1.39	(0.52,3.78)	-2.82***	0.21	(0.07, 0.60)
Relevance: Criteria	O	-0.98	0.62	(0.23, 1.62)	0.46	1.26	(0.48, 3.30)	0.68	1.38	(0.54, 3.52)
Dissemination: Academic	L	0.31	1.22	(0.35, 4.31)	-1.38	0.46	(0.14, 1.37)	-1.38	0.46	(0.14, 1.37)
Dissemination: Practice	L	-1.29	0.51	(0.18, 1.41)	-0.78	0.67	(0.23, 1.85)	2.73***	19.33	(3.40, 367.45)
Interaction: Intensity	O									

$p < 0.1$ - *, <.05 - **, <.01 ***. *L – logistic regression (binomial), O – ordinal logistic regression. All results relative to Generation 1.*

A-4 Table 3. Modelling results for research practice coding relative to Generation 3. "Knowledge Systems"

Coded variable	Model type	Generation 1			Generation 2			Generation 4		
		t/z	*OR*	*95%CI*	*t/z*	*OR*	*95%CI*	*t/z*	*OR*	*95%CI*
Aim: New Science/Data	L	2.01**	3.76	(1.10, 15.28)	-0.78	0.66	(0.23, 1.85)	1.72	2.89	(0.89, 10.51)
Aim: New Technology	L	-2.63***	0.20	(0.06, 0.63)	-0.93	0.55	(0.16, 1.90)	-3.69	0.10	(0.03, 0.32)
Origin: Research Question	O	-1.66**	0.14	(0.01, 1.05)	-0.86	0.48	(0.76, 2.47)	3.37***	8.73	(2.66, 34.32)
Origin: Research Design	O	-1.09	0.35	(0.01, 2.5)	-0.55	0.55	(0.05, 4.60)	4.06***	25.23	(6.2, 151.60)
Relevance: Context	O	-1.95*	0.38	(0.14,0.99)	-0.66	0.72	(0.26,1.92)	2.20**	3.43	(1.17, 10.81)
Relevance: Criteria	O	-1.46	0.49	(0.19, 1.27)	-0.46	0.79	(0.30, 2.08)	0.20	1.10	(0.44, 2.74)
Dissemination: Academic	L	1.67*	2.67	(0.86, 8.95)	1.38	2.19	(0.73, 6.98)	0.00	1.00	(0.35, 2.83)
Dissemination: Practice	L	-0.52	0.76	(0.27, 2.11)	0.78	1.50	(0.54, 4.23)	3.12***	29.00	(5.13, 550.01)
Interaction: Intensity	O									

A-4 Table 4. Modelling results for research practice coding relative to Generation 4. "Knowledge Systems"

Coded variable	Model type	Generation 1			Generation 2			Generation 3		
		t/z	*OR*	*95%CI*	*t/z*	*OR*	*95%CI*	*t/z*	*OR*	*95%CI*
Aim: New Science/Data	L	0.36	1.30	(0.31, 5.78)	0.36**	1.30	(0.31, 5.78)	-1.72*	0.35	(0.10, 1.12)
Aim: New Technology	L	1.30	2.00	(0.71, 5.81)	3.01***	5.50	(1.88, 17.54)	3.69***	10.00	(3.13, 37.28)
Origin: Research Question	O	-3.65***	0.02	(0.00, 0.10)	-3.76***	0.05	(0.01, 0.21)	-3.37***	0.11	(0.3, 0.38)
Origin: Research Design	O	-3.89***	0.01	(0.00, 0.07)	-4.07***	0.02	(0.00, 0.12)	-4.06***	0.04	(0.01, 0.16)
Relevance: Context	O	-3.97***	0.11	(0.04, 0.31)	-2.82***	0.21	(0.07, 0.60)	-2.19**	0.29	(0.09, 0.86)
Relevance: Criteria	O	-1.71*	0.45	(0.18, 1.12)	-0.68	0.72	(0.28, 1.84)	-0.20	0.91	(0.36, 2.27)
Dissemination: Academic	L	1.67*	2.67	(0.86, 8.95)	1.38	2.19	(0.73, 6.98)	0.00	1.00	(0.35, 2.83)
Dissemination: Practice	L	-3.36***	0.03	(0.00, 1.5)	-2.73***	0.05	(0.00, 0.30)	-3.12***	0.03	(0.00, 0.19)
Interaction: Intensity	O									

A-5. COMPLETE CODING DATA (.CSV FILE)

See attachment named: "NERRS_codes.csv"