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REVIEW

A How-to Guide for Coproduction of Actionable Science

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Abstract

Resource managers often need scientific information to match their decisions (typically short-term and local) to complex, long-term, large-scale challenges such as adaptation to climate change. In such situations, the most reliable route to actionable science is coproduction, whereby managers, policy makers, scientists, and other stakeholders first identify specific decisions to be informed by science, and then jointly define the scope and context of the problem, research questions, methods, and outputs, make scientific inferences, and develop strategies for the appropriate use of science. Here, we present seven recommended practices intended to help scientists, managers, funders and other stakeholders carry out a coproduction project, one recommended practice to ensure that partners learn from attempts at coproduction, and two practices to promote coproduction at a programmatic level. The recommended practices focus research on decisions that need to be made, give priority to processes and outcomes over stand-alone products, and allocate resources to organizations and individuals that engage in coproduction. Although this article focuses on the coproduction of actionable science for climate change adaptation and natural resource management, the approach is relevant to other complex natural-human systems.

Introduction

In the loading dock approach to linking science and action (Cash *et al.* 2006), science producers interact with resource managers, decision makers, or policy makers (henceforth *managers*) in a linear transaction. In one variant of this approach, the manager contracts a scientist for a specific product, which is delivered to the manager's desk (a small loading dock), and may later be used to inform management decisions. In another variant, a funder not affiliated with the manager (e.g., the U.S. National Science Foundation) might award a scientist a grant to develop a science product regardless of whether the manager has asked for it. The scientific product sits in the peer-reviewed literature (a big loading dock) until the manager finds it. In the latter variant, the scientist might take the additional step of outreach or science communication – i.e., making managers and those who influence managers (stakeholders, lawmakers) aware that the products exist. The loading dock approach works best in situations in which the manager knows what questions to ask, and the scientific answers readily apply at the spatial scale (a political or property boundary) and temporal scale (next year's budget, or a multiyear planning schedule) faced by the manager.

Some problems are not well served by the loading dock approach. For example, the problem of adaptation to climate change involves complex phenomena (such as range shifts, phenotypic plasticity, and evolutionary potential of many interacting species in response to multiple, highly uncertain, climate scenarios) that occur at spatial scales beyond the manager's sphere of influence and at temporal scales beyond the manager's budget or planning cycle. We became acutely aware of the limitations of the loading dock model during our work as members of the Advisory Committee on Climate Change and Natural Resource Science (ACCCNRS), which advises the Secretary of Interior on operation of the National Climate Change and Wildlife Science Center (NCCWSC) and eight regional Climate Science Centers (CSC). In their first years of operation (2009-2013), the NCCWSC and the CSCs generated and compiled hundreds of vulnerability assessments (USGS 2016), usually at the specific request of managers. Nonetheless, a reaction of many managers was "What do I do with these vulnerability assessments? Why did I ask for them?" Many vulnerability assessments remain on the loading dock, yet to support adaptation decisions. It became obvious to the CSCs, NCCWSC, and ACCCNRS that neither decision makers nor scientists working alone can specify what science products are needed, how they should be developed, and how they should be applied to climate adaptation.

As a result, the CSCs and NCCWSC have adopted a fundamentally different model, known as coproduction (ACCCNRS 2015). Although actionable science can, theoretically, be produced by scientists working alone, we believe that coproduction offers a more reliable route to actionable science for complex challenges such as managing the risks of climate change. Managers can explain the decision or planning issue at hand, the legal, political, social, and fiscal constraints, and explain how scientific information affects their decisions and downstream decisions. Scientists can ensure that the right product is developed and that managers understand how to appropriately use the information. Stakeholders (industry, landowners, potential downstream users of the information, and other persons who might be affected by the decisions) can provide insights on practical constraints and alternative courses of action that might affect the decisions and the science needed. Because various parties bring potentially unique contributions, they can better define the research goals, methods, and products if they work in concert than singly.

For the purposes of this article, we define *actionable science* as data, analyses, projections, or tools that can support decisions in natural resource management; it includes not only information, but also guidance on the appropriate use of that information. We define *coproduction* as collaboration among managers, scientists, and other stakeholders, who, after identifying specific decisions to be informed by science, jointly define the scope and context of the problem, research questions, methods, and outputs, make scientific inferences, and develop strategies for the appropriate use of science. We use the term *partners* to collectively refer to these coproducers.

Although the scientific literature on actionable science is limited, it is unanimous in concluding actionable science must be credible (scientifically sound), salient (relevant to a management decision), and legitimate (fair and respectful of stakeholders' divergent values), and that it is most reliably produced by iterative collaboration between scientists and managers (Cash *et al.* 2003, 2006; Lemos & Morehouse 2005; NRC 2009; Dilling & Lemos 2011; Kirchhoff *et al.* 2013; Meadow *et al.* 2015; Nel *et al.* 2016). Here, we try to translate these descriptions of coproduction into concrete recommended practices. For brevity and clarity, we express each recommended practice using imperative sentences directed at specific partners (e.g., "Scientists: do this"). We organize our recommended practices under three guiding principles, adapted from the six principles of effective decision support developed by NRC (2009). Our guiding principles are entirely consistent with the recommendations for science-practitioner interactions offered by Jacobs (2002), the five principles of knowledge exchange offered by Reed *et al.* (2014), and the 10 heuristics to guide scientist-practitioner collaborations offered by Ferguson *et al.* (2014). Meadow *et al.* (2016) note that these "principles are just that – guiding principles that need specific strategies to enact." Therefore, each principle is followed by recommended practices or strategies.

The first two guiding principles and eight recommended practices focus on individual coproduction efforts. Each of these eight practices is an activity associated with successful coproduction in case studies described by Cash *et al.* (2003, 2006), Lemos & Morehouse (2005), NRC (2009), Bowen *et al.* (2015), Lebel *et al.* (2015), Mukhopadhyay *et al.* (2014), Schuttenberg & Guth (2015), Wyborn (2015), and Nel *et al.* (2016), six case studies in our ACCCNRS report (Beier, Behar *et al.* 2015), and our experiences as participants or observers in efforts that incorporated elements of coproduction. Every activity or idea associated with successful coproduction in two or more case studies is reflected in one or more of our principles and practices; there was no instance in which a key conclusion of one study was contradicted by another study. The third guiding principle and final two recommended practices focus on the larger issue of supporting the enterprise of coproduction.

By advocating for wider use of coproduction and providing practical advice to managers, scientists, and funders, our goal is to increase society's ability to address the more challenging issues of our day, such as climate change. Readers should focus on the spirit of these recommendations and adapt the details to their particular situations.

Guiding principle #1: Coproduction begins with decisions that need to be made

Because research needs are rarely known (and almost never clearly specified) in advance, collaboration is a logical way to identify those needs. Cash *et al.* (2003)

compared two or more attempts to generate actionable science in each of five thematic areas (farm productivity, aquifer depletion, drought forecasts, ocean fisheries, and transboundary air pollution). In each case, Cash *et al.* (2003) concluded that effectiveness suffered when scientists assumed they knew what questions managers needed to answer, or when managers assumed that scientists knew how to provide usable answers to their important questions. In contrast, effectiveness increased when partners took management decisions as their starting point and jointly defined and produced science to support those decisions. For example, at the outset of an effort to coproduce a plan to conserve rivers and wetlands in South Africa, partners iteratively deliberated to identify 37 decision-making contexts and the types of scientific guidance needed in each context; as a result, the scientific guidance has been applied in 25 of these contexts during the first 3 years of the project (Nel *et al.* 2016). The first three recommended practices are intended to help ensure that science is focused on management decisions.

Recommended practice 1. Managers: Approach scientists with a management need, goal, or problem, rather than a request for a product.

For complex issues, managers must work with scientists and stakeholders to cospecify the project elements before the problem and decision can be fully articulated. This is especially true when managers need science to adapt to climate change, resolve conflicts among conservation goals, and integrate conservation goals with competing goals. For example, managers might initially assume they need scientific knowledge about impact of climate change on particular resources. However, after discussions with scientists, they may learn that uncertainty about impacts cannot be reduced in time for the intended decision. After additional discussion, the managers might realize they need more information about which alternative adaptation strategies are most robust to uncertainty, which actions can best manage risk, or the relative costs of alternative strategies. Managers acting alone might come to this realization, but collaboration between scientists and managers is more likely to ensure that the right questions are asked and addressed, producing useful outcomes with fewer delays and at a lower cost. Managers might not have requested vulnerability assessments (above) if the parties had discussed what decisions would be informed by science, how scientific understanding would be used, model uncertainties, the format of model outputs, and how uncertainty and format of the outputs would affect actionability.

Recommended practice 2. Scientists: Before suggesting specific products, make sure you understand the decision to be made, and the environment in which the decision will be made.

Although the CSC were created specifically to provide science "geared to the needs of fish and wildlife managers as they develop adaptation strategies in response to climate change" (Salazar 2009), about 90% of initial CSC projects focused on downscaled climate predictions and vulnerability assessments and less than 10% on developing, evaluating, or operationalizing adaptation strategies (Beier, Hunter *et al.* 2015). We suspect this mismatch was partly driven by scientists assuming that managers needed more accurate projections of climate change impacts at finer spatial resolution. But a particular adaptation decision may hinge less on assessment of impacts than on assessment of how well various options will reduce vulnerability and minimize risk. Sometimes no-regret strategies can be devised that do not require projections. Even when projections are useful, they are almost never the end point (NRC 2009). To generate actionable science, the scientist must understand the type of decisions a manager can make, the fiscal, policy, social and political constraints on the manager, and incentives and disincentives faced by the manager.

Recommended practice 3. Partners: Invest in at least one in-person meeting of all potential partners and stakeholders to specify the types of decisions to be made and the types of scientific information needed to support those decisions.

Before this in-person meeting (identified here as the Goal-Defining Meeting), the convenors should identify the types of decisions needing scientific support, the types of scientific information that might be relevant, the timeframe needed for completion, and key stakeholders. Then, the convenors schedule a meeting to which they invite the key decision makers, scientists in the appropriate disciplines, implementers, and (when appropriate) funders and other stakeholders. The invitation should state the tentative goal and agenda of the meeting. Stakeholders with different values and objectives should be invited, as long as they are willing to contribute to the goal of the project (e.g., to support decisions that promote conservation). Stakeholders might include land owners, community groups, associated agencies, business interests, or others who affect or are affected by potential decisions and actions. Organizers should use some combination of semistructured interviews, expert opinion, and snowball sampling (whereby early invitees nominate additional participants) to create a diverse and representative stakeholder collaborative (Reed *et al.* 2009).

Sometimes conservation advocates, agencies, or scientists oppose inviting participants who may not share the goal of the project – e.g., inviting real estate developers or mining industry representatives to participate in a project to codevelop a conservation plan. However, in our experience this has never been a problem if the purpose of the meeting is clearly stated. For example, Beier (2008) described efforts to coproduce eight wildlife corridors in densely populated southern California, United States. Most invitees from industry declined to participate, but appreciated that the process was transparent, honest, and inclusive. When industry representatives did participate, they brought useful local knowledge and insight into options for implementation. Beier (2008) concluded that partners have nothing to lose and much to gain by inviting anyone who wants to advance sound decisions and their implementation.

At this meeting, participants should produce a clear goal statement so that success can be assessed later. In some cases, it may be necessary to modify tentative goals that emerge as infeasible, or expand the menu of policy options beyond those initially envisioned (Lovbrand 2011). Participants should refer to the goal statement throughout the process. If the goals must be revised during the process, partners should seek consensus. Goals should be specific, measurable, achievable within time and budget constraints, and realistic.

This meeting may require 1-2 full days. The agenda should include questions such as those listed in Table 1. It may help to have a skilled facilitator lead the meeting. A summary of the meeting, and each subsequent meeting, should be promptly sent to all partners.

Table 1 Questions that could be used as agenda items at a Goal-Defining Meeting for a coproduction project

- What is the issue at hand? What questions are being addressed? What topics are included or excluded from consideration?
- What decisions are being made? Are they flexible or limited in scope?
- Who will use the scientific information (including downstream uses) and how will they use it?
- In what form, process, or product will the data be most useful to the users?
- Given that decisions must be made before the science can be “settled,” what is a realistic expectation of what is possible and useful within the available time and budget?
- What is necessary to make data accessible to all projected users? Who will own the data or other products? Where will the products reside?
- What would success look like for all parties?
- What alternatives are available to achieve success? What is gained or lost by pursuing one alternative over another?
- What variables does the decision maker care about? What resolution of data? What spatial extent? What level of precision is realistic, achievable, and adequate for the decision? If such precision is not feasible, should the project be abandoned or modified?
- What is the planning time horizon? Is this horizon appropriate for the purposes agreed on by the stakeholders?
- How will uncertainty be addressed? To what extent can multiple projections (e.g., emission scenarios, general circulation models) bracket uncertainty?
- Is a technical advisory group or steering committee needed for this project? If so, who should serve?

Guiding principle #2: Partners should give priority to processes and outcomes over stand-alone products

NRC (2009) admonished producers of actionable science to “give priority to process over products.” This rhetorical overstatement was intended to nudge scientists away from their traditional focus on products that are left on a loading dock. Giving priority to process does not mean that shabby products will be tolerated – there is a dire need for quality scientific products relevant to management and adaptation. Rather, it points out that facts (scientific products) do not speak for themselves but require guidance for their proper interpretation and use. A focus on process, outcomes, and adequate interaction must be explicitly built into project design from the beginning. An emphasis on process not only affirms that good process leads to good product, it points out that decision-support *services* are fundamentally different from decision-support *products.*

Recommended practice 4. All partners: For a large, complex project, engage a subset of key people to serve on a technical advisory group that will adjust goals, review key methodological decisions, and coproduce inferences. Recruit a smaller steering committee to manage the project calendar, products, and workflows.

The Goal-Defining Meeting will not be able to map out every detail of the project. Surprises will occur and adjustments will need to be made. It could be cumbersome for all participants from the first meeting to manage these surprises and many participants would not want to do so. Many participants at the first meeting may be agency heads who are one step removed from using science to make decisions; they may prefer to have end-users on their staff serve on the technical advisory group. If the first meeting is run well, participants will trust the small technical advisory group and steering committee to keep the project on track. Spencer *et al.* (2010) and Nel *et al.* (2016) illustrate how a technical advisory group and steering committee can avoid stakeholder burnout and maximize the ability of stakeholders to provide meaningful input at each stage of coproduction.

Recommended practice 5. All partners: Over the course of the project, iteratively discuss key assumptions, models, approaches, data sources, and criteria.

At the Goal-Defining Meeting (see Practice 3 and Table 1), partners should have resolved many issues, but may still have divergent opinions on scientific models and products, and difficulties encountered along the way may require adjustment. Addressing these issues will often require three additional in-person meetings (or sets of meetings): the Work Plan Meeting, the Science Implementation Meeting, and the Rollout Meeting.

At the Work Plan Meeting(s), scientists explain alternative scientific approaches to achieve the goal, discuss the key assumptions, data needs, and costs of each approach, and describe strengths and limitations (including uncertainties) of available data. Under the direction of the steering committee, the scientists should provide a written overview and agenda, so that invitees can decide whether to participate. Participants (typically the technical advisory group) discuss these issues to reach consensus on the scientific approaches to be used. If pilot or demonstration work is needed to evaluate competing approaches, more than one Work Plan Meeting may be required. During this discussion, it may be necessary to revisit some issues, such as spatial extent, focal species, key processes, or resolution of data or outputs, that had been tentatively agreed at earlier meetings.

At the Science Implementation Meeting (see Recommended Practice #7), draft scientific products are presented and discussed in relation to the decision-making contexts defined earlier. The meeting should occur early enough to allow time for significant adjustments if needed. At this meeting, participants should discuss how various draft or hypothetical outputs would inform particular management or policy options. Participants should request that the scientists provide specific guidance on proper use of science in particular contexts.

At the Rollout Meeting, scientists describe the information and appropriate use of the information in decision making, and key decision makers explain how they intend to use the information. All the participants from the initial meeting should be invited to participate. At least 1 hour should be allotted for questions and discussion. Training programs may also be appropriate.

After engaging in a lengthy Goal-Defining Meeting (Table 1), it is easy for scientists to overlook the need for these additional meetings. For example, the Southeastern CSC engaged in a 2-day meeting with potential users of downscaled climate information to conserve plants and animals in Puerto Rico. The managers were pleased that scientists solicited and honored requests for specific climate variables (e.g., duration of longest rain-free period), but were dismayed that there were no additional opportunities to develop context-specific guidance on use of the products before the downscaled climate variables were delivered.

Recommended practice 6. Decision makers: Explain to scientists how risk is evaluated and managed in your organization. Help scientists appreciate how you make informed decisions (not perfect decisions) despite uncertainty about current or future conditions and the outcomes of interventions. Explain the context in which decisions are made, the limitations on your authority, and to whom you are accountable. If multiple agencies are responsible for decisions, make sure that scientists provide the array of scientific information that each agency needs to act independently.

This practice is an important part of all four types of in-person meetings. In our experience, scientists will not fully grasp this information the first time they hear it. Repetition, through multiple speakers, smaller breakout groups, working lunches, and/or end-of-day summary sessions, can help scientists understand. For example, an effort to define key connectivity areas among significant natural areas in California involved 220 participants representing 62 federal, state, tribal, regional, & local agencies (Spencer *et al.* 2010). At the start of the discussion, all scientists and most managers wanted the scientists to develop importance scores for each connectivity area. Over the course of several meetings, the scientists learned that different management agencies needed different scientific information to make decisions, that each institution had unique values (not always the values other parties assumed), and these differences affected how each agency would use a given type of scientific information. As a result, eventually it was decided that a single importance score would be counterproductive. Instead, the scientists were asked to provide a dozen key descriptors of each linkage area, allowing each entity to interpret importance in light of its own mission and values.

Recommended practice 7. Scientists: Honestly convey the meaning of uncertainty in your results, but (respecting the fact that decisions must be made) clearly convey the main implications of your research. In addition to providing information, an equally important task is to provide clear guidance on appropriate use of that information. Expect managers to challenge your science. Be open about your policy preferences.

This practice is also an important part of all four types of in-person meetings. Managers may have overly optimistic ideas of the quantity and quality of the scientific information available, and may not fully comprehend the implications of key assumptions and the limitations of scientific models when this information is first presented. Once again, breakout groups, repetition by another scientist, working lunches, and other mechanisms can help, and will lead to a better project.

An important activity (and a major focus of the Science Implementation Meeting) is to work with decision makers to develop decision trees or tables describing the most appropriate way to apply the information in each anticipated decision-making context (Nel *et al.* 2016). Because local environmental conditions and social processes affect management decisions, scientists must provide flexible guidance that accommodates local knowledge and stakeholder values.

Scientists should make it easy for resource managers and decision makers to understand key assumptions and the logical chain of analyses. Indeed, scientists should expect managers to challenge assumptions, offer alternative interpretations of analyses, propose alternative approaches, and demand flexible options. Although some scientists might tend to interpret this as pressure to compromise their scientific credibility, in most instances these demands are entirely consistent with the values of science, namely transparency, respect for evidence, logic, and openness to correction. Scientists should embrace these opportunities to improve their science.

Scientists should also freely express their values and policy preferences. All the other partners will have expressed their personal and agency values and preferences, and will not expect or believe that individual scientists are value-free. Scientists increase their credibility by frankly disclosing their preferences and opinions, insisting on transparency and rigor, working to find common ground, respecting the ideas of nonexperts, and being open to all evidence and inferences supported by evidence (Noss 1999; Alagona 2008).

Recommended practice 8. Scientists, funders, boundary organizations: Evaluate coproduction products, processes, and the actionability of the science of individual coproduction projects, and disseminate these findings. As project evaluations accumulate, revise these recommended practices.

Coproduction is still under development, and there is much to be learned to improve the process. Table 2 provides a list of questions that can be used to evaluate a project that attempted to coproduce actionable science. The evaluation should occur after partners have attempted to apply the new science and can provide meaningful answers to these questions. Ideally, evaluation should be embedded into a project from the outset, and budgeted for.

We suggest two ways to evaluate a project. First, a group of key participants, or independent evaluators, can provide a retrospective evaluation, as Nel *et al.* (2016) did 3 years after a major coproduction project. Another option would be to convene a meeting among partners several months or years after the Rollout Meeting (typically the contractual end of the project). In either case, addressing the questions in Table 2 will help determine how well the project delivered actionable science, and how future projects could better produce actionable science. Although the ultimate success or failure of the project (e.g., resilience of biodiversity to changes in climate and land use) may not be evident for decades, the evidence can be considered in a results-chain model (which links actions to desired impact through a series of intermediate steps; CMP 2008). Results of each project evaluation should be disseminated via white papers, peer-reviewed publications, webinars, websites (e.g., www.cakex.org), or scientific and professional meetings such as the biennial National (U.S.) Adaptation Forum (www.nationaladaptationforum.org). Some boundary organizations are beginning to conduct such evaluations, a few of which have been published (e.g., Ferguson *et al.* 2016).

Table 2 Questions to address in evaluating a project to coproduce actionable science

- How well did scientists and managers specify the problem statement at the outset?
- In retrospect, would different scientific information and processes have been more useful? What steps could have better set up the project at the outset?
- Did the project give appropriate priority to process and products? Was the process collaborative, communicative, and positive for both scientists and managers?
- If scientists provided postcontract advice on the appropriate use of the information, was this continuing engagement properly budgeted for?
- Were the scientists appropriately rewarded by their employers, and by the satisfaction of contributing to better decisions?
- What practical steps could have been taken to provide better guidance on appropriate use of the scientific products?
- Did the scientific information and process lead to better decisions (or was it capable of doing so, even if constraints precluded a better decision)? How should future projects be managed to better meet this goal?
- What obstacles to collaboration were encountered in shaping the goals and final results?
- Is the product being used in the way it was envisioned? If not, why not?
- Was a mechanism created to insert new scientific results and learning that occurred by observing the outcomes of decisions made using the products?

As evaluations of individual projects accumulate, systematic reviews or meta-analyses should be used to draw general lessons, and most importantly, to revise this how-to guide. Fazey *et al.* (2013: their table 4) provide 80 questions that can be adapted to evaluate coproduction as a knowledge system. Although a randomized and replicated experiment to evaluate the hypothesis that coproduction is the best route to actionable science may be infeasible, careful grouping of case studies (e.g., Cash *et al.* 2003) could provide meaningful comparisons. Ideally, revision of this how-to guide would be coproduced by scientists, managers, and stakeholders, and subject to peer review.

Guiding principle #3: Build connections across disciplines and organizations, and among scientists, decision makers, and stakeholders

Decisions on complex issues can require combining information on available technological and policy options at different scales of decision making, and information on the likely ecological, economic, and societal costs and benefits of those options. This requires integration across disciplines, sectors, and scales. Linking information producers and information users is especially challenging because the cultures and incentives of science and practice are different, and those differences need to be respected (NRC 2009). All partners must invest goodwill, respect, commitment, time, and resources to develop the interpersonal interactions that are critical to coproduction (Cheruvelil *et al.* 2014).

Recommended practice 9. Funders, universities, and governments: Create and grow the capacity of boundary organizations dedicated to coproduction of actionable science.

A boundary organization is an entity that serves as a convener of science producers, science users, and other affected parties, and as a translator and a facilitator of productive tension among these groups (Guston 2001; Cash *et al.* 2003; NRC 2009). Boundary organizations related to conservation and climate adaptation include the Intergovernmental Panel on Climate Change, International Platform on Biodiversity and Ecosystem Services, Regional Integrated Sciences and Assessments Program, CSC, Landscape Conservation Cooperatives, U.S. State Agricultural Extension Programs, and NGOs such as EcoAdapt, Conservation Biology Institute, and Geos Institute. Many universities also sponsor boundary organizations.

We recommend support for boundary organizations dedicated to coproduction of actionable science, because such enterprises incur extraordinary expenses to build and maintain good relationships across disciplines and sectors. Support for coproduction activities must be built into the base funding of boundary organizations because these activities extend beyond the normal 2- or 3-year duration of individual projects. Boundary organizations with broad geographic scope will find it challenging to develop long-term relationships with partners, especially with leadership turnover in partner entities. Accordingly, the budgets of boundary organizations should be structured to minimize turnover in key personnel within the boundary organization, train staff to serve as facilitators, conveners, and communicators, support staff travel, and provide high-quality virtual-meeting facilities. These investments are necessary to build a regional community of researchers and science users, to support individual projects, and to generate the political support that will sustain the boundary organization.

Recommended practice 10. Funders, managers, universities, agencies, and NGOs: Create incentives for academic scientists to consider coproduction of actionable science as a rewarding line of work.

Table 3 Questions to be used by funders to evaluate a proposal to coproduce actionable science

- What decisions will the project inform? Does the proposal explain how the research will inform multiple, specific decision-making contexts?
- Has the need been articulated by managers or other users? Does the research team include managers?
- How well does the proposal incorporate the recommended practices for coproduction?
- Does the budget include adequate funding for collaborative activities?
- Does the proposal provide flexibility to modify goals and activities in response to stakeholder input?
- What mechanisms are in place to ensure collaboration between those who will use this research and the researchers conducting the project?
- Does the project team have the appropriate expertise, or is there a plan to procure it?
- What outreach is planned to disseminate the product to those who need it? Will users be trained on how to use the product? Will appropriate staff be assigned to make the products user-friendly?
- How will the project be evaluated for both process and product?

A straightforward incentive would be for a funder to issue a request for proposals to generate competing proposals to coproduce science to address important management decisions. The request for proposals should encourage academic applicants to recruit managers as coprincipal investigators, and advise applicants that the questions in Table 3 will be used to evaluate proposals for funding.

Universities and research laboratories should modify promotion and tenure criteria to consider a peer-reviewed publication focused on coproduction of actionable science as equivalent to more than one "pure science" publication. Considering the extra effort involved, time lag from project inception to publication, and benefits to society, a multiplier of at least two seems reasonable.

Regardless of how their employers reward coproduction, many academic scientists may find coproduction of actionable science personally satisfying and professionally rewarding (Brugger *et al.* 2016). For example, Beier (2008) felt that a coproduction effort that led to a conserved wildlife corridor that included a highway crossing structure was a more satisfying legacy than any increase in h-index that might have occurred from avoiding the time-demanding coproduction process. Coproduction can also be professionally rewarding. For example, participation in multiple coproduction efforts resulted in two well-cited peer-reviewed papers that summarized the lessons from those efforts (Beier *et al.* 2008, 2011). Although the same amount of time invested in traditional research would have yielded more papers, coproduction was not a professional black hole, and can be part of a diversified portfolio of professional activities.

Conclusion

The actionability of science depends on how well the knowledge system carries out four functions, namely convening, translating, collaborating, and mediating (Cash *et al.* 2003, 2006). Coproduction is not the only route to actionable science; alternatives include the loading dock model, contractual research, knowledge exchange, user-inspired basic research, boundary organizations, research scientists embedded in management agencies, training scientists to communicate to managers, and social learning (Cash *et al.* 2003, 2006, Kirchhoff *et al.* 2011, Cook *et al.* 2013; Meadow *et al.* 2015). Because coproduction and boundary organizations are the only approaches that deliberately target all four critical functions, we argue that these two closely allied approaches should be more widely used. We believe coproduction is especially appropriate for problems involving multiple spatial and temporal scales, problems where neither scientists nor managers can specify needed science products in advance or situations in which managers need ongoing guidance on proper use of science in a variety of decision-making contexts.

To the best of our knowledge, this is the first attempt to provide a set of coherent recommended practices that scientists, managers, funders, and institutions can use as a recipe to coproduce actionable science for resource management. Our terse statements gloss over many of the complexities. For example, the recommendation that universities modify promotion criteria would involve major cultural shifts in some institutions. Similarly, some natural scientists may require training in facilitation, needs assessment, or social science (although many "fall into" these skills by persistent engagement in issues they care about; Brugger *et al.* 2016).

Although it is unlikely that any recipe produces perfect results every time, this set of recommendations fills an urgent need for practical guidance. Coproduction is expensive, time-consuming, difficult, and ambitious, and it will sometimes fall short of achieving actionable science, especially in the initial attempts (Lovbrand 2011). Nonetheless, even partial success is better than not having tried at all, especially if rigorous evaluations provide lessons to guide future attempts.

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References

ACCCNRS [Advisory Committee on Climate Change and Natural Resource Science]. (2015). *Report to the Secretary of the Interior*. Washington DC. https://nccwsc.usgs.gov/sites/default/files/files/ACCCNRS_Report_2015.pdf (visited Mar. 31, 2015).

Alagona, P. (2008). Credibility. *Conserv. Biol.*, **22**, 1365-1367.

Beier, P. 2008. Learning like a mountain. *Wildlife Pro.*, Winter, 26-29.

Beier, P., Majka, D. & Spencer, W.D. (2008). Forks in the road: choices in procedures for designing wildlife linkages. *Conserv. Biol.*, **22**, 836-851.

Beier, P., Spencer, W.D., Baldwin, R. & McRae, B.H. (2011). Toward best practices for developing regional connectivity maps. *Conserv. Biol.*, **25**, 879-892.

Beier, P., Behar, D., Hansen, L. *et al.* (Actionable Science Workgroup of the Advisory Committee on Climate Change and Natural Resource Science). (2015). *Guiding principles and recommended practices for co-producing actionable science: a How-To Guide for DOI Climate Science Centers and the National Climate Change and Wildlife Science Center*. *Report to the Secretary of the Interior: Advisory Committee on Climate Change and Natural Resource Science*, Washington, DC.

Beier, P., Hunter, M.L. & Anderson, M.G. (2015). Conserving nature's stage. *Conserv. Biol.*, **29**, 613-617.

Bowen, K., Miller, F. & Graham, S. (2015). The relevance of a coproductive capacity framework to climate change adaptation: investigating the health and water sectors in Cambodia. *Ecol. Soc.*, **20**(1), 13. http://dx.doi.org/10.5751/ES-06864-200113.

Brugger, J., Meadow, A. & Horangic, A. (2016). Lessons from first generation climate science integrators. *B. Am. Meteorol. Soc.*, March **2016**, 355-365.

Cash, D.W., Clark, W.C., Alcock, F. *et al.* (2003). Knowledge systems for sustainable development. *P. Natl. Acad. Sci. USA*, **100**, 8086-8091.

Cash, D.W., Borck, J.C. & Patt, AG. (2006). Countering the loading-dock approach to linking science and decision making: comparative analysis of El Niño/Southern Oscillation (ENSO) forecasting systems. *Sci. Technol. Hum. Values*, **31**, 465-494.

Cheruvelil, K.S., Soranno, P.A., Weathers, K.C. *et al.* (2014). Creating and maintaining high-performing collaborative research teams: the importance of diversity and interpersonal skills. *Front. Ecol. Environ.*, **12**, 31-38.

CMP [Conservation Measures Partnership]. (2008). Open standards for the practice of conservation. http://cmp-openstandards.org/, accessed 5 July 2016.

Cook, C.N., Mascia, M.B., Schwartz, M.W., Possingham, H.P. & Fuller, R.A. (2013). Achieving conservation science that bridges the knowledge-action boundary. *Conserv. Biol.*, **27**, 669-678.

Dilling, L. & Lemos, M.C. (2011). Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environ. Chang.*, **21**, 680-689.

Fazey, I., Evely, A.C., Reed, M.S. *et al.* (2013). Knowledge exchange: a review and research agenda for environmental management. *Environ. Conserv.*, **40**, 19-36.

Ferguson, D.B., Rice, J. & Woodhouse, C.A. (2014). *Linking environmental research and practice: lessons from the integration of climate science and water management in the Western United States*. Climate Assessment for the Southwest, Tucson, AZ. http://www.climas.arizona.edu/publication/report/linking-environmental-research-and-practice, accessed 8 July 2016.

Ferguson, D.B., Finucane, M.L., Keener, V.W. & Owen, G. (2016). Evaluation to advance science policy: lessons from Pacific RISA and CLIMAS. Pages 215-234 in A. Parris, G. Garfin, K. Dow, R. Meyer, S. Close, editors, *Climate in context: science and society partnering for adaptation*. Wiley, New York.

Guston, D.H. (2001). Boundary organizations in environmental policy and science: an introduction. *Sci. Technol. Hum. Values*, **26**, 399-408.

Jacobs, K. (2002). *Connecting science, policy, and decision-making: a handbook for researchers and science agencies*. National Oceanic and Atmospheric Administration Office of Global Programs, Silver Spring, MD.

Kirchhoff, C.J., Lemos, M.C. & Dessai, S. (2013). Actionable knowledge for environmental decision making: broadening the usability of climate science. *Annu. Rev. Environ. Resourc.*, **38**, 3.1-3.22.

Lebel, L., Wattana, S & Talerngsri, P. 2015. Assessments of ecosystem services and human well-being in Thailand build and create demand for coproductive capacity. *Ecol. Soc.*, **20**(1), 12. http://dx.doi.org/10.5751/ES-06527-200112.

Lemos, M.C. & Morehouse, B.J. 2005. The co-production of science and policy in integrated climate assessments. *Global Environ. Chang.*, **15**, 57-68.

Lovbrand, E. (2011). Co-producing European climate science and policy: a cautionary note on the making of useful knowledge. *Sci. Publ. Pol.*, **38**, 225-236.

Meadow, A.M., Ferguson, D.B., Guido, Z., Horangic, A., Owen, G. & Wall, T. (2015). Moving toward the deliberate coproduction of climate science knowledge. *Weath. Clim. Soc.*, **7**, 179-191.

Meadow, A.M., Guido, Z., Crimmins, M.A. & Mcleod, J. (2016). From principles to action: applying the National Research Council's principles for effective decision support to the Federal Emergency Management Agency's Watch Office. *Clim. Serv.*, **1**, 12-23. doi: 10.1016/j.cliser.2016.02.002

Mukhopadhyay, P., Nepal, M. & Shyamsundar, P. (2014). Building skills for sustainability: a role for regional research networks. *Ecol. Soc.*, **19**(4), 45. http://dx.doi.org/10.5751/ES-07105-190445.

National Research Council (NRC). (2009). *Informing decisions in a changing climate*. Panel on Strategies and Methods for Climate-Related Decision Support, Committee on the Human Dimensions of Global Change. *Division of Behavioral and Social Sciences and Education*. National Academies Press, Washington, DC.

Nel, J.L., Roux, D.J., Driver, A. *et al.* (2016). Knowledge co-production and boundary work to promote implementation of conservation plans. *Conserv. Biol.*, **50**, 176-188.

Noss, R. (1999). Is there a special conservation biology? *Ecography*, **22**, 113-122.

Reed, M.S., Graves, A., Dandy, N. *et al.* (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *J. Environ. Manage.*, **90**, 1933-1949.

Reed, M.S., Stringer, L.C., Fazey, I., Evely, A.C. & Kruijsen, J.H.J.. (2014). Five principles for the practice of knowledge exchange in environmental management. *J. Environ. Manage.*, **146**, 337-345.

Salazar, K. (2009). Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources, Secretarial Executive Order 3289. available at https://www.doi.gov/sites/doi.gov/files/migrated/whatwedo/climate/cop15/upload/SecOrder3289.pdf, accessed 3 October 2016.

Schuttenberg, H.Z. & Guth, H.K. (2015). Seeking our shared wisdom: a framework for understanding knowledge co-production and coproductive capacities. *Ecol. Soc.*, **20**(1), 15. http://dx.doi.org/10.5751/ES-07038-200115.

Spencer, W.D., Beier, P., Penrod, K. *et al.* (2010). California Essential Habitat Connectivity Project: a strategy for conserving a connected California. Report prepared for California Department of Transportation and California Department of Fish & Game. https://www.wildlife.ca.gov/Conservation/Planning/Connectivity/CEHC, accessed 5 July 2016.

USGS. (2016). CRAVe: the climate registry for the assessment of vulnerability. https://nccwsc.usgs.gov/crave/ (visited Feb. 20, 2016).

Wyborn, C.A. (2015). Connecting knowledge with action through coproductive capacities: adaptive governance and connectivity conservation. *Ecol. Soc.*, **20**(1), 11. http://dx.doi.org/10.5751/ES-06510-200111.

