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Lessons learned in knowledge co-production for climate-smart decision-making☆

Alyssa Rosemartin [a,*], Theresa M. Crimmins [a], Katharine L. Gerst [a,b], Erin E. Posthumus [a], Aaron R. Ramirez [c], Cynthia SA Wallace [d], Toni Lyn Morelli [e]

[a] USA National Phenology Network, School of Natural Resources and the Environment, University of Arizona, USA
[b] Bat Conservation International, USA
[c] Environmental Studies & Biology Department, Reed College, USA
[d] US Geological Survey Western Geographic Science, USA
[e] US Geological Survey Northeast Climate Adaptation Science Center, USA

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ABSTRACT

Knowledge co-production, a process that involves both creators and users of information in knowledge generation, is growing in popularity in the conservation and ecology fields. While examples of successful co-production are becoming more common, many barriers and challenges remain in this work. Here, we reflect on our experiences in knowledge co-production from three recent case studies, using a prominent framework to understand and improve our efforts at each phase of the co-production process. Our reflections yield insights that may help other scientists seeking to support decision-making. We found that paying particular attention to the composition of the team and connecting with agency representatives early and often are key to success. Long-term commitment to the project and the people involved are also key. We conclude with suggestions for refining the framework to incorporate our primary lessons learned and include the valuation of a plurality of knowledge systems and empowerment as an ultimate impact of knowledge co-production.

1. Introduction

Unidirectional 'delivery' of science to decision makers often meets with limited success in supporting decision-making (Cash et al., 2006; Lemos et al., 2012). An alternative approach is to engage decision-makers in the co-production of knowledge. Knowledge co-production is the process of producing usable, or actionable, science through collaboration between scientists and those who use science to make management decisions (Arnott et al., 2020; Lemos et al., 2012; Meadow et al., 2015; Wall et al., 2017a). The concept of co-production encompasses a spectrum of engagement approaches suited to a range of contexts and problems (Bamzai-Dodson et al., 2021; Meadow et al., 2015) and has been shown to increase the application of science in decision-making (Arnott et al., 2020; Lemos et al., 2012; Meadow et al., 2015; Wall et al., 2017a).

While examples of successful knowledge co-production (hereafter co-production) are becoming more common (Hallett et al., 2017; Vera, 2018; Wamsler, 2017; Morelli et al., 2021), many barriers and challenges remain in this work. Co-production can be hampered by differences in how scientists and managers approach problems, interact with each other, and invest their time (Hallett et al., 2017). Existing power dynamics within academia and between researcher and management partners limit effective co-production (Vincent et al., 2020). Vincent et al. (2020) propose several strategies to manage these inequities, including equitable control of funding and decision-making, and the establishment of clear expectations and incentives at project initiation. Co-production efforts can falter without skillful convening, listening and translating information from a wide range of perspectives. Co-producers may need to develop new skills, including meeting facilitation, elicitation, effective communication, and evaluation. Researchers' and

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* Correspondence to: 1311 E 4th St, Suite 325, Tucson, AZ 85721, USA.
E-mail addresses: alyssa@usanpn.org (A. Rosemartin), theresa@usanpn.org (T.M. Crimmins), katgerst@email.arizona.edu (K.L. Gerst), erin@usanpn.org (E.E. Posthumus), ramireza@reed.edu (A.R. Ramirez), Centercwallace@usgs.gov (C.S. Wallace), tmorelli@usgs.gov (T.L. Morelli).

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decision makers' incentives, timelines, and research priorities may be mismatched (Hallett et al., 2017). Further, managers often report an excess of available information, or information that is not trustworthy or relevant (Matzek et al., 2014).

Several frameworks have been proposed to overcome these barriers and support effective co-production (Hegger et al., 2012; Howarth and Monasterolo, 2017; Knapp et al., 2019; Bamzai-Dodson et al., 2021; Meadow et al., 2015). Recently, Wall et al. (2017b) created a series of indicators of successful knowledge co-production (hereafter "Indicators"). These Indicators include considerations at every stage of research, from planning to product delivery to impact following the Logic Model, in which intended impacts are used to select inputs, actions, and outputs (Kellogg, 2004). The Indicators represent a promising tool for both planning and achieving actionable science, as they provide a structure for changing research approaches to better support co-production.

1.1. Objectives

We are a team of ecologists engaging in knowledge co-production. Our aim is to reflect on our recent experiences in knowledge co-production to identify insights that may support others in overcoming barriers to co-production. In the present study, we ask:

1) What insights can be gained from recent knowledge co-production endeavors to improve future efforts at the interface of ecology and decision-making?
2) Are the Indicators proposed by (Wall et al., 2017b) a useful tool for researchers to understand and improve knowledge co-production efforts?

Here we present three case studies of knowledge co-production implemented by interdisciplinary teams that represent a range of scales, geographies, topics, and stakeholder groups, and that were sufficiently mature to allow for reflection on outcomes at the time of writing. As the case studies overlapped in time, insights garnered from a given case did not inform the others. We describe and reflect on these projects as they relate to the Indicators. We also provide lessons learned and recommendations for future work emerging from our experience.

1.2. Positionality

We write this article as ecologists and boundary spanners (Safford et al., 2017) with a combined 75 years of experience at the interface of science and society. We work in federal and university positions, where the focus is both on research and the application of information to decision-making. All authors were team members on at least one case study. Although we are not trained as social scientists, we propose that sharing our practical experience in knowledge co-production, structured according to the Indicators, along with our proposed revisions to increase the usability of the Indicators, furthers the conversation in this arena. While we incorporate feedback from agency partners in our reflections, we recognize that as we are embedded in the projects we describe, we are subject to bias.

2. Methods

Many frameworks for evaluating knowledge co-production have been proposed in the past decade (33 such frameworks are reviewed in (Louder et al., 2021). We selected the (Wall et al., 2017b) Indicators as they are influential (according to Google Scholar, the paper has been cited 149 times as of August 2022). However, only six studies have applied the Indicators and all of these studies modify or combine them with other frameworks (Rocha et al., 2020; Kettle, 2019; Meinke, 2017; Treffeisen et al., 2017; Riley, 2021; Wilmer et al., 2021). We chose the Indicators because they are comprehensive, balance process and impacts, are structured following the Logic Model (Kellogg, 2004), thus suited for designing projects, and are contextualized for climate science. In addition, it is logical for us to use these Indicators as we have framed and developed our co-production work using the same research group's typology of co-production modes (Gerst et al., 2022; Meadow et al., 2015). Miller and Wyborn (2020) identify global strands of co-production research, identifying (1) public and business administration, (2) science and technology studies and (3) sustainability science. Both the Indicators and our professional backgrounds and perspectives are located in the "sustainability science" strand of co-production, which seeks to "change how science [is] made and applied to transform the world toward a sustainable future." (Miller and Wyborn, 2020).

The Indicators provide a framework for considering success from each partner's viewpoint and at each stage of a co-produced project. (Wall et al., 2017b) present five categories of Indicators: Input, Process, Output, Outcome, and Impact (see Table 1 for the list of Indicators). The Input Indicators explore dimensions of project planning and time allocation. Process Indicators look at the frequency and nature of communication among team members. Output Indicators focus on the deliverables, such as workshops and reports resulting from the effort. Outcome Indicators address whether the project met its goals and whether the participants perceived the process as legitimate. Impact Indicators provide a typology for the ultimate benefit of co-production efforts, including for example: "Projective'' use of information (agency gained better understanding of possible future scenarios).

Here we examine three case studies through the lens of the Indicators to understand and improve our co-production efforts as well as to test the Indicators in a range of authentic knowledge co-production efforts. All three case studies are in the "Collaborative" mode, following the Meadow et al. (2015) typology. The Indicators were not yet available when we embarked on 2 of the 3 case studies; they were not used to structure or plan our work. Here we apply them after the case studies matured, as a framework for reflection and improvement. We used our knowledge of the efforts, together with reference to reports, publications and web products to review projects relative to the Indicators. We solicited input from agency representatives involved in each case study, on the Indicators. This effort resulted in the Summary of Case Studies Relative to the Indicators (Table 1).

Case Study 1 focuses on an effort carried out by a group of researchers and natural resource managers from National Park Service, US Forest Service, and state wildlife agencies to develop and implement a process for climate change refugia conservation (Morelli et al., 2016). In, (Wall et al. 2017b), US National Park Service (NPS) science staff and USA National Phenology Network (USA-NPN) staff members co-led work with researchers and managers to develop information on historical changes in the timing of spring to inform protected area management at the national scale (Monahan et al., 2016; Waller et al., 2018). For Case Studies 1 and 2, agency representatives were presented with a shared Google spreadsheet with the Indicators and asked to respond (yes/no and/or comment) relative to the case study on which they collaborated.

Case Study 3 describes an effort undertaken by researchers, USA-NPN staff, and federal and state invasive species managers in southern Arizona to predict when and where an invasive grass is most susceptible to herbicide treatment over the course of the summer monsoon season (USA-NPN, 2021a; Wallace et al., 2016)). For Case study 3, agency representatives provided feedback relative to the Indicators via a Google Form structured according to relevant Indicators.

We selected the three studies with consideration to diversity of problem types, geographic scale, maturity, and interdisciplinarity. The problems with which they contend range from new concepts to understanding historical context to informing tactical action. We draw lessons learned from our experience as embedded participants in co-production, an approach which we recognize as subject to bias, but which also enables us to draw on our deep understanding of process and outcomes in the case studies. We are motivated to learn from mistakes as well as

Table 1
Summary Table of Case Studies Relative to the Indicators (Wall et al., 2017b). Categories (eg, Input, Outcome) are bolded as section headers, with the Indicators below abbreviated such that I.1 is Input Indicator 1. Where Indicators were clearly met, the response is Yes, when clearly not met, the response is No. When there is further nuance (discussed in text) the response is Mixed. Agency representative input is denoted as federal (F), state (S), or NGO (N). Blank fields indicate that agency representatives did not respond to this row/question.

	Case Study 1: Refugia		Case Study 2: Spring		Case Study 3: Buffelgrass	
Inputs	Authors	Agency Rep	Authors	Agency Rep	Authors	Agency Rep
I.1. Necessary scientific disciplines are included on research team (research capacity maps to research question).	Yes	N/A	Yes	N/A	Yes	N/A
I.2. Significant research time is devoted to project (% of FTE allocated to the project)	Mixed	N/A	Yes	N/A	Yes	N/A
I.3. Research team works collaboratively among themselves.	Yes	N/A	Yes	N/A	Yes	N/A
I.4. Target agency indicated commitment through contribution of services, funds, time, and a specific point person.	Yes	N/A	Yes	N/A	Yes	N/A
I.5. Target agency representatives on the project can articulate a need for this research (i.e., they have a problem they want to solve through this research project).	Yes	N/A	Yes	N/A	Yes	N/A
I.6. Target agency representative perceives a path to use/application of the research findings (i.e., does manager see barriers to implementation?)	Mixed		Yes	Yes (F)	Yes	
I.7. Proposal includes a clear plan for communication, engagement, and/or collaboration between research and management team	Yes	N/A	Yes	N/A	Mixed	N/A
I.8. Total funding for project compared to total amount allocated for engagement/collaboration activities (if discernable).	Yes	N/A	Mixed	Mixed (F)	N/A	N/A
I.9. Research team has training or experience in collaborative research approaches.	Yes	N/A	Mixed	N/A	Yes	N/A
I.10. Research team's motivations for participating in the project (i.e., their goal is actionable science).	Yes	N/A	Yes	N/A	Yes	N/A
I.11. Research team and agency representative have preexisting working relationship.	Yes	N/A	Mixed	N/A	Mixed	N/A
Process						
P.1. Point at which host/target agency enters or participated in the project: vision, problem definition, research question articulation, research design, data collection, data analysis, knowledge/meaning making, testing, results, dissemination of knowledge, evaluation of project.	Problem Definition	N/A	Vision	N/A	Problem Definition	N/A
P.2. Frequency and medium of communication between research and management teams.	Monthly videocalls, annual meetings	N/A	Monthly video calls	N/A	Monthly emails or calls, initial in person meeting	N/A
P.3. Participants perceive they had equitable opportunities to participate in project meetings, workshops, etc. (observe interactions when possible).	Yes		Yes	Mixed (F)	Yes	Yes (S,N)
P.4. Target agency representative is satisfied with the level of engagement.	Yes		Mixed	Mixed (F)	Mixed	Yes (S,N)
P.5. Researchers are satisfied with the level of engagement.	Yes	N/A	Mixed	N/A	Yes	N/A
P.6. Challenges within project are resolved in mutually agreeable ways.	Yes		Yes	Yes (F)	Yes	
P.7. Researchers are aware of whether/how information was used or not used by agency.	No	N/A	Yes	N/A	Yes	N/A
Outputs						
OP.1. Number of peer-reviewed articles.	12	N/A	2	N/A	1	N/A
OP.2. Number of technical reports/gray literature.	3	N/A	1	N/A	1	N/A
OP.3. Workshops or meetings to disseminate findings.	10	N/A	60	N/A	3	N/A
OP.4. Final report is delivered directly to agency representative(s) or made easily accessible via another format.	Yes		Yes	Yes (F)	Yes	Yes (S,N)
OP.5. Findings are delivered in a timely manner (meet agency's decision calendar or timeline).	No	No	Yes	Yes (F)	Yes	Yes (S,N)
OP.6. Other outputs (media reports, websites, other products created by the project).	20	N/A	5	N/A	1	N/A
Outcomes						
OC.1. Project goals have been achieved (both objective assessment by evaluator and researcher and agency representative perceptions with regard to completion of goals).	Mixed		Mixed	Mixed (F)	Yes	Yes (S,N)
OC.2. Participants perceive science as credible.	Yes	Yes (F)	Mixed	Yes (F)	Mixed	Mixed (S, N)
OC.3. Findings/outputs meet the standard the agency applies to ''usable'' information for action.	Yes	Yes (F)	Yes	Yes (F)	Yes	Yes (S,N)
OC.4. Agency participants perceive the science as salient to their needs/problems.	Yes	Yes (F)	Yes	Yes (F)	Yes	Yes (S)
OC.5. Participants perceive that the process of producing the science was legitimate (i.e., all participants had opportunities to contribute).	Yes	Yes (F)	Yes	Yes (F)	Mixed	Yes (F,S, N)
OC.6. Mutual interest in longer-term collaboration (i.e., both teams express interest in working together again).	Yes		Yes	Yes (F)	Yes	Yes (S,N)
Impacts						
IM.1. ''Enlightenment'' use of information (agency representative perceives self to be better informed about an issue).	Yes		Yes	Yes (F)	Yes	
	Yes		Yes		Yes	Yes (N)

(*continued on next page*)

Table 1 (*continued*)

Inputs	Case Study 1: Refugia		Case Study 2: Spring		Case Study 3: Buffelgrass	
	Authors	Agency Rep	Authors	Agency Rep	Authors	Agency Rep
IM.2. "Problem Understanding'' use of information (more specific than Enlightenment, better comprehension of particular problems).				Mixed (F)		
IM.3. "Instrumental'' use of information (agency representative finds out what to do and how to do something; gained new skills).	Yes		No	No	Yes	Yes (S,N)
IM.4. "Factual'' use of information (provision of precise data, for example).	Yes		No	No	Yes	Yes (F,S, N)
IM.5. "Confirmational'' use of information (previous information was verified).	Yes		Yes	No (F)	Yes	Yes (S)
IM.6. "Projective'' use of information (agency gained better understanding of possible future scenarios).	Yes		No	No (F)	No	No (F,S, N)
IM.7. "Motivational'' use of information (encouraged someone to keep going (or not) on search for information).	Yes		Yes	No (F)	Yes	Yes (F)
IM.8. "Personal or Political'' use of information (helped a person gain control of a situation or avoid a bad situation).	Yes		No		No	
IM.9. Findings from study are explicitly used in agency planning, resource allocation, or policy decision.	Yes	Mixed (F)	No	Mixed (F)	No	
IM.10. Findings contribute to successful climate change adaptation action.	No	No	Mixed	Mixed (F)	No	

successes and improve the practice of co-production.

3. Results

We provide a summary of each project relative to the Indicators in Table 1; for each case the authors assessed the case study relative to the Indicator; agency representative input is included in a second column for each case. Below we highlight dimensions of the case studies relative to the Indicators.

3.1. Case Study 1: climate change refugia conservation

For a problem as complex as reducing the impacts of anthropogenic climate change, collaboration between researchers and resource managers is key. The identification, protection, and management of climate change refugia – areas relatively buffered from contemporary climate change that enable persistence of valued resources – has increasingly been proposed as a focus of climate adaptation actions (Keppel et al., 2015; Morelli et al., 2016, 2020). With funding originally provided by the boundary-spanning California Landscape Conservation Cooperative and later from the Northwest Climate Adaptation Science Center to formalize the group as the Refugia Research Coalition (RRC), an interdisciplinary collaboration was formed that included federal and state resource agency representatives, federal and academic scientists, and conservation organizations (https://www.climaterefugia.org/). Project leader TLM designed the refugia conservation teams to be diverse and interdisciplinary, with expertise from the physical and biological sciences as well as resource management (I.1, see Table 1 for the Indicator numbering system). Researchers came to the table with the specific goal of actionable science (I.10) and built on preexisting relationships with stakeholders (I.11). Notably, there was not significant funding for the effort committed by the target agencies originally (I.4); that has begun to change as successes become more evident. Although many of the researchers, apart from the project leader, were only able to devote time intermittently to these efforts (I.2), we have found that a large team can compensate for lack of intensive individual attention.

The refugia conservation process brought together practitioners and resource management agency staff (e.g., National Park Service superintendent, wildlife biologist), as well as academic scientists, in local or regional workshops, where the participants identified the resources (e.g., species or ecosystems) to be the focus of conservation plans. The target agency representatives were brought in early, often at the first meeting (P.1). Subsequent video conferences and in-person meetings were used to maintain connections with RRC participants and to continue synthesis efforts and develop new science that could directly inform on-the-ground actions (P.2). Notably, similar activities, including lengthy workshops, have continued despite Covid19 restrictions; video conferencing and web tools including instant polling enable continued cohesion and effective two-way communication. Participants perceived they had equitable opportunities to participate (P.3) and seem satisfied with the level of engagement from the point of view of the project leaders (P.4 and P.5).

An early achievement of the project was an open access journal article that included a functional definition of climate change refugia and a model for incorporating refugia into existing management structures through the Climate Change Refugia Conservation Cycle (Morelli et al., 2016). Later, the RRC and the efforts of its core members acted as a unifying platform to bring people and ideas together around a shared goal. The RRC published a number of peer-reviewed papers, reports and fact sheets, including the June 2020 Special Issue in *Frontiers in Ecology and the Environment* (OP.1, O.P.2), which were organized with investments from the boundary spanning organizations (primarily, the Climate Adaptation Science Centers). A dozen workshops and symposia (OP.3) have focused on bringing local knowledge to ecological modeling efforts to identify climate change refugia to be prioritized for management action by federal and state agencies and NGOs (e.g., https://www.cal-ipc.org/project/sierra-nevada-meadows/).

Over the last five years, the collaborative refugia work of scientists and managers has expanded from a small regional effort to include most regions in the US and Canada, including a new national scale effort. This has deepened connections among original members and resulted in collaborators working together on numerous additional projects (OC.5, OC.6). The RRC website has had over 5000 unique visitors since 2018. The press has published a variety of articles on the topic. The Morelli et al. (2016) paper was in the top 1% (out of over 22,000) of downloaded research articles in PLOS ONE.

This case has achieved many of the Impact Indicators. The climate change refugia work described here, along with work by others on this topic (Keppel et al., 2015), has moved the idea of climate change refugia conservation from theoretical obscurity to actionable science. For both the National Park Service (NPS) and the Environmental Protection Agency, findings have generated sufficient interest and demonstrated value that continued research funding has been approved (IM.7). Indeed, refugial meadow maps have been used by NGO staff, in partnership with federal and state agencies, to prioritize sites for restoration (Vernon, 2019; IM.9).

3.2. Case Study 2: spring onset in protected areas

While protected areas have good information about changing climatic patterns, there is little information to translate those climatic changes into impacts on priority species or systems (Monahan and Fisichelli, 2014). Staff members of the USA-NPN, the NPS and the US Fish and Wildlife Service (FWS), the US Geological Survey (USGS), and two universities co-produced information characterizing historical changes in the timing of spring within resource management units (I.1 and I.4). The goals of the project were to improve NPS and FWS understanding of historical changes in the timing of spring and to better anticipate the impact that these changes have on priority species and systems, as well as communicate climate change impacts to visitors. In addition, information about how spring onset was changing across the latitudinal gradient of migratory flyways provided FWS with a landscape-scale context and information regarding potential threats to species that migrate outside the boundaries of their individual refuge, as well as provided information to the FWS Migratory Birds program that manages at a regional to national scale (Waller et al., 2018; I.5).

For the analysis of NPS units, staff of the USA-NPN and the NPS Climate Change Response Program together with two university faculty defined the question and method for documenting changes in the timing of spring. Project leadership shifted from USA-NPN to NPS staff early in the process (P.1). For the analysis of FWS units, a need for the study was expressed by the Inventory and Monitoring (I&M) Initiative of the National Wildlife Refuge System (P.1). During production, we consulted with I&M, refuge managers, biologists, and visitor services staff (for example, to determine the size of refuge buffers; P.2). We also consulted with these groups on how to present results on the collaboration website fws.usanpn.org.

The team published two papers that characterize changes in the timing of spring in parks (Monahan et al., 2016) and refuges (Waller et al., 2018), respectively. We also developed an NPS Resource Brief and web page; further communications and briefs were planned but not completed (NPS, 2021; OP.1, OP.2). The Secretary of the Interior announced the findings of the NPS effort with a press release at a public event. The results of the National Wildlife Refuge work are available dynamically in a web tool and were picked up by multiple news outlets, blogs, as well as the Fish and Wildlife News, a quarterly newsletter for the National Wildlife Refuge System (USA-NPN, 2021b; OP.6). In total, our team members and collaborators presented project findings on earlier springs at protected areas at over 60 climate change planning workshops, webinars and conferences. In addition, the National Parks Conservation Association leveraged project results in a report that summarizes climate change impacts on parks (National Parks Conservation Association, 2019, OP.3).

The majority of participants in both projects reported satisfaction with regard to process and project goals via in person conversations and contributions to the Indicator spreadsheet. All partners have interest in continued collaborations (OC.1, OC.4, OC.6). The work was perceived as usable by agency representatives (OC.2).

NPS collaborators reported impacts in terms of Enlightenment, Problem Understanding, and use in planning policy (IM.1, IM.2 and IM.9). Researchers have observed additional Confirmational and Motivational uses of information; results have been used by parks to better convey within and beyond park staff that indeed, spring is coming earlier, and to motivate additional monitoring of priority species' phenology (IM.5, IM.7). In response to Impact Indicator 10 (Findings contribute to successful climate change adaptation action), the project team member with the NPS Climate Change Response Program noted: "Yes. Capacity building and education are core to adaptation, and this has clearly contributed to that. Results have been used to support scenario development at 80 workshops, reaching 1600 NPS unit staff." The scenarios developed with this information are used to guide management, for instance, planning for earlier visitation for wildflower viewing. As it is a more recent project, the FWS project does not yet have documented impacts.

3.3. Case Study 3: forecasts of buffelgrass green up

Staff at the USA-NPN and a scientist from USGS worked together to produce maps forecasting green-up in buffelgrass (*Pennisetum ciliare)*. At a listening session with Tucson, Arizona area land managers and decision-makers, we learned that one of the biggest challenges in the Southern Arizona region was managing the invasive plant buffelgrass, which promotes fire and damages native plant communities. As buffelgrass is best controlled by herbicide treatment once it has greened up and prior to seed set, this management challenge is a clear example of where phenological information can support decision making. The team therefore opted to co-produce and deliver daily maps predicting buffelgrass green-up across Arizona.

USA-NPN staff members, the USGS scientist, and a small group of protected area managers collaborated on this project. The USGS scientist and USA-NPN staff had previously created models and tools that could be replicated or modified to forecast buffelgrass green up (Wallace et al., 2016). The managers described their needs and gave advice at project initiation and throughout the process. To garner broader input on product features, twenty-four participants from the Sonoran Desert Cooperative Weed Management Area, a large regional invasive species working group, contributed feedback via an online survey, mid-way through the project and prior to release; these survey results substantially influenced and improved the final product.

Representatives of NPS, Arizona Department of Transportation, a non-profit land conservancy, and a private landscape services company shared input on the development of the Buffelgrass forecasts. Four representatives were satisfied by the level of engagement with the USA-NPN during the map development process, one was not, and one felt they were not involved enough to comment (P.4). Six representatives were satisfied with the level of communication, including weekly map notifications (P.2).

After the maps were publicly released, USA-NPN staff have shared the product with hundreds of potential users via weekly notifications, web pages, an information sheet, email newsletters, and five regional conference presentations (USA-NPN, 2021a; OP.3, OP.5, OP.6).

Two representatives found the science to be credible while two did not (OC.2). Input indicated that managers plan to act on the information provided, underscoring the relevance of these forecasts to manager needs (OC.4). While two managers indicated they would have preferred to give more input prior to map delivery, four were satisfied and perceived the process to be legitimate (OC.5). It is clear that ongoing collaborative work is needed to improve the models and maps to better inform the timing of treatment by accurately predicting green-up. All partners in this project have expressed an interest in longer-term collaboration (OC.6).

The maps helped four representatives plan for their treatment activities (IM.3) and helped two representatives gain a better understanding of what triggers green-up in buffelgrass (IM.2). One representative shared that the maps helped motivate them to monitor buffelgrass (IM.7). Another representative used the maps to confirm suspected green-up derived from other methods (IM.5).

4. Discussion

We described the process of conducting and communicating actionable science through knowledge co-production using three case studies. We found a great deal of value in applying the Indicators to our work as a framework for reflection. Case Study impacts included instrumental information on climate change refugia that turned theory into practice, "enlightenment" information on the timing of spring that supported climate change adaptation, and factual information on real-time phenology that supported invasive species management. We faced some limitations, and have identified areas where we can improve

our practice of co-production.

Here we discuss each category of Indicator, share our reflections on improvements we could have made, and provide our lessons learned and recommendations to enhance the Input, Outcome, and Impact Indicators (we had no recommendations for the Process and Output Indicators). Our refined Indicators are summarized in Fig. 1. We emphasize Input Indicators because project leaders have many choices to make during this phase and, when executed well, this foundation creates the conditions for success across the other Indicators. We suggest carefully planning a project around the Input Indicators and the first Process Indicator (the point at which agency representatives are brought into the project). From there, the work evolves more organically, responding to the context and needs of project team members (Owen et al., 2019). The project benefits if, early on, the full team shares a vision of the Outputs, Outcomes, and Impacts of the work, with a recognition that these may change as the project evolves. Shifts in focus can be a good sign, and only become a problem if a shared vision is lost.

4.1. Input indicators

4.1.1. Scientific disciplines and agency representation (I.1 & I.4)

In Case Study 1, working across disciplines and perspectives was critical to developing ideas. Managers and scientists shaped definitions, actions, and priorities with both practical and theoretical perspectives. For example, the definition of climate change refugia, now widely used (Morelli et al., 2016 has been cited 327 times according to Google Scholar), includes a focus on conserving "valued" resources, an idea that came from a management perspective that recognizes the subjectivity in prioritization based on people's interests. Multiple researchers have shown that the strengths of diverse teams will not be realized on their own; rather, meaningful engagement and thoughtful facilitation enables engagement among diverse perspectives (Hemming et al., 2018; Lencioni, 2010). Carefully considering who is invited to these efforts can increase the diversity of representation. Remote workshops and webinars, proven effective out of necessity in 2020, can reduce barriers to participation.

Revising *I.1 Necessary scientific disciplines are included on research team* as follows would acknowledge the need for diversity in expertise and background among team members: "The team is composed of agency representatives, researchers and others with the appropriate knowledge, motivation and perspective to address the problem. Team includes members with skill in facilitation and project management. Team is balanced in terms of race, gender, career stage and/or other dimensions of identity that may be relevant to achieving equity in the context where the work takes place." There are important considerations of who is at the table beyond scientific disciplines. A stakeholder analysis can assist in identifying people who will influence the product, shine light on the degree of conflict that might exist between team members, and establish team member roles and how they will interact (Hermans and Richard, 2006). All three case studies benefited from the close collaboration of people with different expertise, discipline, and perspective based on their professional role, affirming the key role of transdisciplinarity in knowledge co-production (Polk, 2015; Thompson et al., 2017).

Resource management agencies are hierarchically organized, and it can be difficult to know which "level" of agency representative to include in a project (e.g., national climate change advisor, regional manager, or unit manager). If the person is focused on local management for a single unit, they likely do not have the power to institutionalize ideas across their organization. If they are working at a top administrative level, they may lack the local knowledge or the practical expertise to know what can and should be done at the scale of the management unit. Ideally, a project will involve both the on-the-ground manager and the higher-level administrative official from the outset of the project. Case Study 1 team members were primarily field researchers and natural resource managers that were close to where the decisions were being made. Case Study 2 would have benefited from involvement of on-the-ground managers who were the intended audience for the information. If this is not feasible, an alternative is for scientists within the management agency to be working as boundary spanners, ensuring two-way communication both within their agency and with the external researcher. Case Study 3 benefited from strong involvement from on-the-ground managers.

Our case studies do not represent contested spaces (in contrast with Kettle, 2019), however we recognize that power relationships, and the perceived value of certain kinds of expertise over others, are commonly present in our work and affect team dynamics. There are multiple legitimate ways of building knowledge and pluralism is increasingly acknowledged as a key principle of co-production (Norström et al., 2020). This presents a challenge to the foundational assumptions of academia, but through conversation and reflection, space can be made even within an academic context. For example, through relationships with Indigenous partners and the emergence of work at the intersection of knowledge systems, the USA National Phenology Network recently modified its mission statement to acknowledge multiple approaches to the study of phenology (Chisholm Hatfield et al., 2018; Team and Tribal Adaptation, 2019). The mission now reads (addition in italics): "The USA-NPN collects, organizes, and shares phenological data and information to aid decision-making, scientific discovery, *and a broader understanding of phenology from a diversity of perspectives.*"

If co-production teams do not attend directly to knowledge systems, race, gender, ability, and other forms of diversity, it is likely that existing

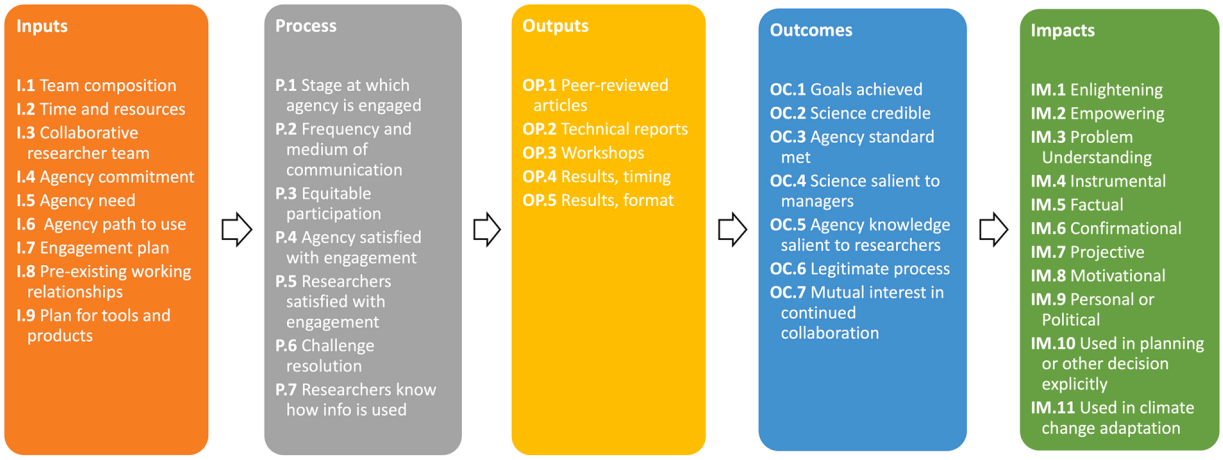

Fig. 1. Summary of the refined (Wall et al., 2017a) Indicators; for full text version of refined Indicators, see S1.

patterns of systemic exclusion will continue (e.g., Pandya, 2012). This work begins with a consideration of who is invited to participate, from the perspective of race and other identities. It takes additional time and effort to build a team that is truly representative of the country or the region's diversity, but benefits the team in terms of new perspectives and ensures the work's broader relevance. There are many resources available to support this work (e.g., racialequitytools.org; Independent Community-based Organizations, 2019). We recognize that we did not explicitly consider racial equity when developing these case studies. We have revised this Indicator to ameliorate this serious limitation in our current and future projects.

4.1.2. Planning for communication (I.7)

Case Study 2 could have benefited from a more detailed plan for dissemination of the information to the agency staff. While the NPS Climate Change Response Program office has strong capacity for communications, plans for communication and engagement were developed at a late stage. The lack of planning for communication in this case resulted in a reduced number of communication products, and project team members feeling overextended toward the end of the project. Additionally, the relevant application of the product to support management activity was not apparent to FWS users and they requested further translation of the information into a usable format.

4.1.3. Funding (I.8)

In all three case studies, adequate time was given to collaborative activities, though this was more a result of the base funding for staff, and the latitude that staff had in allocating their time, than due to dedicated project funding. Each case study operated beyond a single funded grant, which is key for sustaining relationships and meeting research and management timelines. The FWS component of case study 2 was funded by the agency, which clarified the agency's view of the importance of the effort.

4.1.4. Pre-existing relationships (I.11)

Case Studies 1 and 2 were initiated by team members with established working relationships. These pre-existing relationships made it easier to clearly outline roles and ensure an efficient work process. While Case Study 3 did not build on pre-existing relationships, the smaller geographic scope and the proximity of the agency representatives to the USA-NPN's national office allowed for regular in-person meetings to build relationships and motivate all team members. Building relationships with key regional and subject area players can be a good approach over greater geographic regions.

We recommend revising *I.11, Research team and agency representative have preexisting working relationship*, to acknowledge the need for diversity in expertise and background among team members. We suggest this modification: "Research team and agency representatives have preexisting working relationships, or sufficient time is built into the project to develop relationships." We agree with the premise that existing relationships increase likelihood of project success, and that the short timeline for writing a grant, followed by one-to-two-year performance periods focused on outcomes, presents challenges to partnership building. We have also noticed that leveraging existing relationships can work against diversity. As a solution to these challenges, we recommend thinking of teams as existing beyond individual funded projects and seeking funding sources that are longer term or explicitly support partnership building such as the Haury Program in Environment and Social Justice (Arnott et al., 2020a).

We recommend adding an Input Indicator: "*Project includes a clear plan and resources appropriate for hosting and maintenance of any tools or products developed.*" Dependably hosted and updated tools help ameliorate the mismatch in the timing of information delivery and build trust in the tool.

4.2. Process indicators

4.2.1. Manager satisfaction with engagement (P.4)

Engaging with agency representatives "early and often" is a central tenet of knowledge co-production, and we found this to be necessary for success. Academic researchers may be tempted to wait until they have the ideal product or solution before providing information to agencies (Hallett et al., 2017). In contrast, in Case Study 3, we found that agency representatives were enthusiastic to engage with us and work to improve imperfect information. Across our three case studies, the managers most satisfied with the engagement were those who participated in more well-defined teams, with more ongoing interpersonal communication. We also noted that, given manager priorities and constraints, there is a wide range of what a manager may perceive as an appropriate level of engagement, thus calibrating expectations on engagement throughout the process is important.

4.2.2. Resolving challenges (P.6)

When challenges arose, they were resolved in mutually agreeable ways. In Case Study 1, the team iterated frequently as the ideas evolved, and found they came closer to a shared vision over time. In Case Study 2, there was initially a lack of a shared understanding about appropriate geographic scale and analytical approach. Through discussion and responding to each other's conceptual diagrams, the authors came to support the agency representative's approach. This modified approach improved the way the authors analyze and deliver phenological information beyond the scope of the project.

4.2.3. Output indicators

These indicators were the most straightforward, as they are commonly collected and reported by researchers (e.g., articles published [OP.1], workshops held [OP.3]). While it is necessary to allocate resources to completing and tracking outputs, we learned more as we extended our thinking through to the outcomes and impacts of the efforts.

4.4. Outcome indicators

4.4.1. Participants perceive science as credible (OC2)

In Case Study 3, a few survey participants indicated they did not perceive the science as credible. In follow up conversations, we learned that this perception was due to a desire for models to be more complex and incorporate additional environmental variables. We see this concern as an opportunity to bring these participants into future collaborations to improve and iterate on the models, demonstrating that this is the merely beginning of a long-term process that shows their input to be valuable.

4.4.2. Long-term commitment (O6)

Our experiences with these case studies verified the need for long-term commitment to increase the likelihood that a partnership and project will be successful. The interest among partners to continue collaborating is both indicative of the success of the collaboration and also necessary given the duration needed to address the complex and changing problems faced by natural resource managers. This commitment also supports the continued evaluation of the outcomes of the project, beyond the funded period.

Adding an Indicator to complement OC.4 (*Agency representatives perceive the science as salient to their needs and problems*) would highlight the two-way knowledge exchange: has the process led to researchers perceiving agency knowledge to be salient? If co-production is envisioned as an equitable process, and a pluralism of knowledge systems is recognized, then local, manager and traditional knowledge would be seen as valuable by all participants in the process.

4.5. Impact Indicators

The impacts of co-production efforts take years or decades to develop, and we recognize that the impacts and lessons learned that we identify here will continue to change and emerge over time. We found that some of the impact Indicators, like the Projective and Factual use of findings were part of our discussions and plans; we aimed for these impacts. Other Indicators, such as Motivational and Problem Understanding were identified by agency collaborators. If we hadn't used this typology to reflect on these projects, we wouldn't have known about these uses of findings. We suggest using the full typology in at least one early discussion for project planning to better understand the breadth of and context of information use. We also found that paying close attention to I.6 (*Agency representative perceives path to use*) was key to resolving barriers that might limit the ultimate impacts.

We recommend adding an Indicator to describe empowerment of participants, as follows: "*Empowering use of information (agency representative perceives self to be more capable of solving future problems or achieving future goals)*." We see this impact as related to, but broader than, the motivational and personal or political Indicators. An effort might have an impact on empowerment through the elevation of local or traditional knowledge (as in the Indigenous level of community participation in David-Chavez and Gavin 2018), through increased capacity within an agency to integrate local knowledge and academic research methods to solve future problems (as in the Collegial mode of co-production, Meadow et al., 2015), or through social capital (e.g., being connected with managers in adjacent states lending legitimacy to a management approach) or use of tools like Structured Decision Making (Hammond, Keeney, and Raiffa, 2015) enabling a manager to defend management decisions to stakeholders or supervisors. There is some conceptual overlap between our proposed Empowerment indicator and the Empower approach to co-production described in Bamzai-Dodson et al. (2021), which "considers stakeholder input and decisions to be co-equal to the rest of the research team." We propose empowerment as occurring when the locus of power is shifted to the stakeholder.

In addition to the revisions described above, we propose rewriting several of the Indicators as full sentences to allow the features of successful co-production to be marked as present or absent. This change may this improve the usability of the Indicators, framing each one as a feature that should be present, rather than a topic to consider (e.g., "frequency of communication" becomes "adequate frequency of communication, to achieve goals, according to participants"). Our 'Revised Indicators' incorporate the above suggestions and the rewriting for presence/absence (see *S1*).

5. Further reflections

We came to this work as ecologists and boundary-spanners, not as social scientists. We collectively invested several hundred hours of staff time in reading, attending webinars, executing, and reflecting on knowledge co-production projects, building on our prior foundation of stakeholder-centered work. We relied on co-production skill sets including communication, facilitation, and reflective practice (Schwartz et al., 2017). While there would be many advantages to engaging in this work with social science expertise, including study design and avoidance of common pitfalls, we recognize that there are many professional pathways to developing actionable science and a hunger for more information as well as examples of how to grow and engage in this arena in the field of ecology. By articulating our experience, we hope to inspire increasingly robust examples of knowledge co-production.

We found the Indicators to be a powerful and useful framework for considering past efforts as well as for shaping future conservation efforts. The practice of shifting from attending primarily to the end product to attending to both process and product has transformed our work and increased our learning. This process improved our understanding of how to build effective teams, including composition by role and background, as well as how power and conflict are negotiated among team members. We learned that there is a wide range of opinions among managers regarding what constitutes an appropriate level of communication, and now work to differentiate communication based on preferences. We found great value, especially, in the Indicators' impact typology for understanding how information is put to use. We have seen improvements in manager engagement and satisfaction among agency representatives and expect to see further improvements as these necessarily long-term investments pay off. Our proposed revisions to the Indicators increase their clarity and completeness. We expect that future efforts will benefit from use of the refined Indicators, enabling the avoidance of certain missteps (for example, lack of planning for long-term tool and product hosting) as well as promoting the engagement of diverse teams, with more attention to the locus of power. We see the combination of new and evolving frameworks for knowledge co-production, such as Bamzai-Dodson et al. (2021), together with the refined Indicators as a powerful platform for creating actionable science.

Both the Indicators and this work are centered in the researcher perspective on the process of co-production. We recognize that we had incomplete information collected formally from managers to inform our assessment and reflection. An important next step is to review and improve the Indicators from the perspective of agency representative partners. A review of this kind might also change key features of the Indicator language; for instance, "target agency representative" may not represent how our partners think of themselves. Co-production efforts stand to benefit if researchers, managers, funders and policy-makers continue to seek ways to better align incentives and timeframes between the research and management communities to facilitate knowledge co-production (Hallett et al., 2017). We see the value of co-production in the problems resolved by our agency partners and in our teams' interest in continued collaboration. We look forward to participating in the continued development of this mode of collaborative science.

Author contributions

AHR, TLM, KLG, EEP, TMC and conceptualized the idea and contributed to the manuscript text and edits. AHR led the development of the manuscript and contributed to Case Study 2. TLM and ARR contributed to Case Study 1. KLG and CSAW contributed to Case Study 3. EEP contributed to Case Study 2.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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government.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2023.01.010.

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