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Organisational influence on the co-production of fire science: overcoming challenges and realising opportunities

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ABSTRACT

Addressing the challenges of wildland fire requires that fire science be relevant to management *and* integrated into management decisions. Co-production is often touted as a process that can increase the utility of science for management, by involving scientists and managers in knowledge creation and problem solving. Despite the documented benefits of co-production, these efforts face a number of institutional barriers. Further research is needed on how to institutionalise support and incentivise co-production. To better understand how research organisations enable and constrain co-production, this study examined seven co-produced wildland fire projects associated with the US Department of Agriculture Forest Service Rocky Mountain Research Station (RMRS), through in-depth interviews with scientists, managers and community members. Results provide insights into how organisational structures and cultures influence the co-production of fire science. Research organisations like RMRS may be able to institutionalise co-production by adjusting the way they incentivise and evaluate researchers, increasing investment in science delivery and scientific personnel overall, and supplying long-term funding to support time-intensive collaborations. These sorts of structural changes could help transform the culture of fire science so that co-production is valued alongside more conventional scientific activities and products.

Keywords: actionable science, collaboration, co-production, research organisations, science-management interface, science-policy interface, translation, wildfire social science, wildland fire.

Introduction

In the US, wildland fire is becoming increasingly severe and burned area is growing (Cattau *et al.* 2020). Concerns about loss of life, the health impacts of smoke, the cost of suppression, and the destruction of homes and infrastructure are becoming more acute (Calkin *et al.* 2015). In response, fire scientists are advancing new risk analyses, examining the role of climate in changing fire regimes, and building tools to enable more effective wildfire response. But fire science is often underutilised and the latest research is not always integrated into management decisions (see e.g. Adams *et al.* 2017). The Joint Fire Science Program (JFSP) was established in 1998 to bridge the 'gap' between fire science and management (LeQuire 2011), and has facilitated the use of fire science (Hunter 2016; Maletsky *et al.* 2018). Despite this success, a number of barriers continue to impede the application of fire science in management, including cultural differences between scientists and managers, a lack of trust that impedes communication, institutional and bureaucratic challenges, the inaccessibility of fire science, and the perception that fire science is often not relevant to management concerns (Kocher *et al.* 2012; Hunter 2016). These barriers are similar to the challenge of integrating science into land and environmental management more broadly. But, as Hunter *et al.* (2020) point out, 'relative to other fields (e.g. climate change adaptation), the evaluation of the use of science for the management of wildland fire is immature'. Thus, there is a need for additional research on connecting science and management within fire management specifically (Colavito 2017). The present study examined a set of fire science projects that involved collaborations between researchers, managers and other partners to better understand the benefits and challenges of such work, and more specifically organisational influence on co-production of fire science.

Co-production and the role of research organisations

A number of researchers have called for more interaction between fire researchers and practitioners (Adams *et al.* 2017) and even specifically for 'co-production' to 'bridge the gap between fire science production and application' (Maletsky *et al.* 2018). Hiers (2017) argues that co-production could be transformative for fire science. Co-production is a process that involves collaboration between scientists and managers in knowledge creation and problem solving, and is often assumed to increase the utility of science for management. Co-production of fire science could benefit both managers and scientists, improving the relevance of the research and the ability of managers to solve wildfire problems (Varner and Hiers 2020).

In the broader field of natural resource management, the need for partnerships between scientists and practitioners is increasingly recognised (see e.g. Cook *et al.* 2013; Lawson *et al.* 2017; Carter *et al.* 2020). In a recent review of the use of science in National Forest management, White *et al.* (2019) conclude that natural resource management in the United States will 'likely require increased engagement between managers and scientists' to create actionable knowledge (White *et al.* 2019, p. 13). Increased engagement is often promoted as a solution to the problem of the so-called 'gap' between research and practice, and the incongruence between science and decision-making more broadly (Roux *et al.* 2006; Wyborn *et al.* 2019).

A number of terms have been used to describe processes that bring scientists and managers together to improve the utility of research, including use-inspired research (Colavito 2017), translational ecology (Enquist *et al.* 2017), actionable science (Beier *et al.* 2017) and co-production (Norström *et al.* 2020). We use the term co-production because a recent review of research examining the use of fire science found a growing focus specifically on co-production (Hunter *et al.* 2020). Co-production involves collaboration between scientists, managers and other invested parties in knowledge creation and problem-solving (Wyborn *et al.* 2019; Norström *et al.* 2020). Roux *et al.* (2006) describe co-production as 'a shift from a view of knowledge as a 'thing' that can be transferred to viewing knowledge as a 'process of relating' that involves negotiation of meaning among partners' (Roux *et al.* 2006, p. 16). This 'process of relating' allows for diverse types of expertise to be integrated into a learning experience that reframes a problem and how to address it (Roux *et al.* 2006; Schuttenberg and Guth 2015; Beier *et al.* 2017). When scientists and managers work through this learning process, they are more likely to see the knowledge that they co-produce as legitimate, credible and salient, and the knowledge is more likely to be used in decision-making (Cash *et al.* 2003; Meadow *et al.* 2015; Clark *et al.* 2016). The relevance of research products can be improved by integrating the knowledge of managers and community members into the various stages of the research process, from development of research questions and interpretation of results to dissemination of findings, to ensure that research responds to the concerns of end-users (Cash *et al.* 2003; Dilling and Lemos 2011; Beier *et al.* 2017). Similarly, researchers can describe the limitations of the research, the types of questions the research can answer, and what these answers could be used for (Cash *et al.* 2003; Beier *et al.* 2017). Through this knowledge sharing, the research objectives, methods and products can be negotiated and informed by both scientists and non-scientists, which improves the likelihood that participants will perceive the results as legitimate (Cash *et al.* 2003). Deeper understanding of research processes and scientific uncertainty can also improve participants' perceptions of knowledge as credible (Schuttenberg and Guth 2015; Beier *et al.* 2017).

Despite the numerous benefits of co-production, a number of barriers have been documented. Existing organisational structures and cultures may be unable to accommodate the power-sharing culture that often characterises co-production (Wyborn *et al.* 2019). Incentive systems for many scientists act as barriers to co-production to the extent that they do not reward the usability of science or direct engagement with decision-makers (Dilling and Lemos 2011; Norström *et al.* 2020). In a study on barriers to use of wildfire decision support systems (DSSs), Colavito (2021) identifies the absence of effective strategies to integrate new tools into decision-making processes and a lack of capacity for the development and integration of these tools as two important barriers to use of DSSs by managers. According to Varner and Hiers (2020), fire science suffers from a growing emphasis on disciplinary silos and managers who are sceptical of research that does not integrate management experience, highlighting both the need for and challenges of co-production of fire science.

While the literature abounds with guidelines, principles and recommendations for how to design co-production processes (Dilling and Lemos 2011; Clark *et al.* 2016; Beier *et al.* 2017; Morisette *et al.* 2017; Djenontin and Meadow 2018; Norström *et al.* 2020), there is no single recipe for successful co-production. Rather, each co-production endeavour responds to a specific context that includes different capacities and constraints, power dynamics and decision-making contexts (Littell *et al.* 2012; Van Kerkhoff and Lebel 2015; Norström *et al.* 2020; Turnhout *et al.* 2020). The organisations involved in co-production are an important part of this context because they can enable or constrain co-production processes and subsequent outcomes, but very little empirical research has focused on the organisational context of co-production. In response, Djenontin and Meadow (2018) call for additional research into how organisations can support and incentivise co-production and Wyborn *et al.* (2019) recommend further research into how co-production can be institutionalised at different scales, including at the level of organisations. Two types of organisations are particularly relevant in this context. Research organisations focus on scientific research and include universities, government labs and science agencies, and research-focused non-governmental organisations. Boundary organisations facilitate translation and collaboration across science and decision-making, and support production of use-inspired science (Hunter *et al.* 2020), and similarly include both government and non-governmental organisations. Several studies have examined the role of boundary organisations in facilitating collaborations between fire scientists and managers (e.g. Colavito *et al.* 2019; Hunter *et al.* 2020), but to date, no studies have explored how research organisations influence the co-production of fire science. To address this gap, we studied how the USDA Forest Service Rocky Mountain Research Station (RMRS) as a research organisation influences co-production of fire science, with the goal of identifying institutional changes that research organisations can employ to enable future co-production efforts. To understand organisational influence, we examined how participants in co-production processes view the need for, benefits of and challenges to co-production, including the role of the RMRS in enabling and constraining co-production.

The USDA Forest Service Rocky Mountain Research Station

The USDA Forest Service RMRS is one of six regional research units that constitute the Research and Development (R&D) division of the USDA Forest Service. Forest Service R&D was established by statute as a research organisation in 1928 and amended in 1978 (16 U.S. Code §1642; OLRC 1978). A key provision of these statutes was to promote a comprehensive program of forest and rangeland renewable resources research that operated independently from the rest of the Forest Service and served all forest and rangeland managers regardless of ownership or administration. In addition to this statutory direction, the US Congress appropriates funds separately for management and for research within the Forest Service to ensure that research scientists and managers maintain distinct roles. Despite these separate roles, over time, RMRS has taken on a large portfolio of fire-related research funded by non-R&D appropriations, specifically the hazardous fuels and fire suppression programs designed to improve the agency's mitigation of and response to wildfire. Thus, RMRS was selected for this study because of its outsized role in conducting fire research in the United States. In sum, while RMRS was created primarily as a research organisation with a focus on producing new knowledge related to resource management, similarly to many research organisations it increasingly functions as a boundary organisation in facilitating communications and collaborations between research scientists, land managers and other natural resource stakeholders. Thus, emerging collaboration on wildfire-related research represents an expansion of its statutory role and history of separating management from research and may move RMRS more toward co-production and other research endeavours that involve boundary spanning across science and management.

Study methods

To understand organisational influence on co-production, we studied seven RMRS fire science projects. These projects were selected by RMRS scientists and program managers for inclusion in the study because they all involved research–management partnerships and exhibited many of the features of co-production, specifically collaborations between scientists and managers in knowledge creation and problem solving. For more information on these projects, see Table 1. To protect the confidentiality of the interviewees, we do not identify the specific projects in this paper. The authors of this study were not part of any of these projects.

We conducted in-depth, semi-structured interviews to gain a detailed understanding of how project participants perceived the need for and benefits of co-production as well as organisation support for and barriers to co-production. In-depth interviews are widely utilised in the social sciences, including wildfire social science (see e.g. Olsen and Sharp 2013; McCaffrey *et al.* 2015; Mylek and Schirmer 2016; Rapp *et al.* 2020). We interviewed 33 individuals, with four to seven participants from each project and a similar number of scientists, managers and community members from each project wherever possible. None of the participants were part of more than one project. Of the 33 participants, 14 were scientists (10 from RMRS, 4 from universities and other federal agencies), 9 were managers (all from federal agencies) and 10 were community members (including staff from city and county government and non-governmental organisations). We aimed to interview the individuals who were most involved with each project, including the RMRS scientists working on the projects. Like many research organisations, RMRS employs both scientists who conduct research (known within Forest Service R&D as Research Grade positions) and professional staff who support research activities and help 'deliver' research to managers and otherwise work on science application (known at RMRS as Professional Grade). RMRS scientists (Research Grade and Professional Grade), as well as scientists from universities and other federal agencies are referred to throughout as 'scientists.' Decision-makers in federal agencies and the agency staff who work to implement these decisions are referred to as 'managers' throughout. All participating city and county government staff, representatives

Table 1. Rocky Mountain Research Station Projects.

Project description	RMRS scientists	Non-RMRS scientists	Land managers	Non-profit organisation staff	Local government staff
Community: fuel treatments and hazard mitigation	1		1		2
Community: fire risk regulation and planning	1			2	2
Community: hazard mitigation and education	1	1		3	
Landscape: pre-suppression planning, decision support and fire behaviour modelling	2	1	3		
Landscape: suppression decision support and fire behaviour modeling	1	1	2		
Ecological: impacts of fire and regrowth	1	1	2	1	
Ecological: fire suppression and response planning	1	2	1		

Community projects focused on the community scale and engaged stakeholders and decision-makers at that scale. Landscape projects focused at a larger scale and engaged land managers across multiple jurisdictions. Ecological projects focused on ecological research to support decision-making.

of non-governmental organisations and community members are referred to as 'community members.'

We conducted nearly all of the interviews over the phone, with the exception of a handful that were conducted in person. All of the individuals we contacted participated in an interview, with the exception of one person. We utilised an interview guide (see Appendix A) to provide continuity and comparability across interviews while allowing for follow up questions and emergent phenomena (Patterson and Williams 2002). Interview questions were informed by the co-production literature and preliminary review of documents on RMRS and the seven case studies. Interview questions focused on understanding why participants engaged in these projects, the benefits of these types of collaborations, and the role of the RMRS in enabling and constraining science–management collaboration. We did not use the academic jargon of 'co-production' during the interviews, but rather focused on key features of co-production as outlined in the literature.

Interviews were 45–90 min long, and were recorded, professionally transcribed, proofed and conducted in compliance with the University of Montana Institutional Review Board (IRB Protocol #183-18). Using NVIVO 12 software, each transcript was coded to identify relevant concepts related to the literature on co-production as well as emergent themes not previously addressed in the literature (Patterson and Williams 2002). Interviews were first analysed individually and then comparatively to identify broader patterns between and across individuals. To compare across interviews, the data within each code were analysed in depth to better understand patterns across the sample. Analysis involved an iterative process of reading and re-reading interview transcripts to code for different concepts and themes as larger patterns emerged, as well as comparing and contrasting results with existing theory on co-production. The first author developed the coding scheme, based on preliminary analysis of eight interviews and intensive group discussion (Saldaña 2013) with the full author team. Then, all interviews were coded by the first author. During the analysis, the author group met weekly to discuss the data, the codes and the coding process, and the post-coding cross-interview analysis. The data excerpts below were selected because they either represent a perspective held by a majority of people in the sample or to illustrate the range of views held by people in the sample. Throughout the results, we indicate the number of interviewees who share a particular perspective.

Results

The disconnect between science and management and the need for co-production

Throughout our interviews, scientists, managers and community members described the challenge of working across

Table 2. Additional data on the disconnect between science and management and the need for co-production.

Challenges	Participant responses
The 'gap' between science and management	The Forest Service has a huge chasm between research and management. They have a problem, a big problem… We have a very hard time creating things that the field needs and even a harder time communicating how to use them. (Scientist) I think there's this sort of sense of folks that are in the management side, 'Well, scientists don't get it. They don't get how hard this is' or anything like that, but then on the flip side, a lot of the researchers are saying things like, 'Don't they hear us?' And so I don't quite know how to bridge that gap sometimes. But I feel like where you start with is an olive branch and a relationship. (Manager)
Different epistemologies	The fire management community is very much an experiential community. Basically, you don't get to a decision-making role without having done the job right below you. To really have a say in something, you have to have started with a Pulaski… Fire management has gotten far more complex, and it's a far bigger organisation than it used to be. We're arguing that to really get better we have to use a different approach. We have to bring in analytics. (Scientist)
The need for collaboration	It became very obvious that none of us had all the expertise, nor all the dollars, or the manpower to do this thing on its own, and everybody going their own way, doing their own thing, oftentimes was cross-purposes with one another. (Scientist)

science and management (see Table 2 for additional data on these challenges and the need for collaboration). Approximately half of the participants (15) discussed a 'gap' or separation between scientists and managers, with one scientist explaining that, as a consequence of a 'huge chasm between research and management', scientific products may not be relevant to management concerns or easily understood. Other participants described this disconnect as a lack of understanding that goes both ways: scientists may not understand the difficulty and complexity of management, while scientists may not feel that managers are paying attention to their findings. One manager suggested the need for an 'olive branch', referring to the importance of building relationships and understanding between scientists and managers. The use of the term 'olive branch' indicates that this manager perceived the need for a gesture of goodwill. Participants (11) explained that one of the challenges to effectively connect science and management is that the two efforts often operate based on different epistemologies and ways of knowing, distinguishing between the analytical knowledge of researchers and the experiential knowledge of fire managers. One participant suggested that 'researchers […] are clueless because they don't know what the real world is like.' Participants suggested that some managers may resist using science because they perceive scientists as presenting their knowledge with a kind of authority that managers do not perceive the scientists have. One scientist noted that managers may value their experiential knowledge over research products, again characterising this difference in terms of the epistemologies valued by managers and scientists, and the challenge it posed for collaboration. Despite the challenging relationship between science and management, participants (12) noted that they depend on their partners to meet their broader objectives. Accordingly, the analytical knowledge of science is required alongside the experiential knowledge of managers to address the complexity of wildfire management. Participants suggested that collaboration enables them to achieve much more than they could independently, working solely within the capabilities and expertise of their own organisations.

The benefits of co-production

To close the 'gap' between science and management, participants were co-producing knowledge through a variety of collaborative processes (see Table 3 for additional data on the benefits of co-production). Participants (17) described co-designing research projects, explaining that dialogue enabled them to refine research questions, methods and analyses to enhance the relevance of the research to management decisions. One RMRS scientist talked about a particular project where, through conversations with managers and community members, they had learned what form of data was easiest for them to use and subsequently adjusted the project to better meet management needs. Participants (18) talked about opportunities for learning and the benefits of building a shared understanding through these projects, which led to adjustments to research questions, methods and management approaches. More specifically, one scientist discussed learning how to communicate across different perspectives to cultivate shared understanding.

Many participants (24) emphasised the importance of valuing different kinds of knowledge in collaborative processes. One scientist described a project to develop maps of wildfire risk that managers could use when responding to a wildfire. The different zones on the maps integrated managers' knowledge about the locations and terrain where they could effectively engage and suppress a fire, manager and community member perceptions of values at risk in that landscape, and scientists' models of fire behaviour. A manager suggested that 'both of those kinds of bodies of knowledge are incredibly important'. A community member

Table 3. Additional data on the benefits of co-production.

Benefits	Participant responses
Improving relevance of research for management through dialogue	By directly having those conversations, we can say, 'If you tweak this just a little bit, maybe this can help answer this question.' Or we can just have a broad question and say, 'This is one of our concerns that we have. Is there any way you can incorporate this into your research?' Or we'll be having a conversation and the researchers may say, 'Well, we can incorporate that in.' Or 'We can help address that question by doing this, or by piggy backing that on to what we're already doing.' Or 'We have already collected data that maybe we can analyse differently to help address that question'… It works both ways where we're enhancing the research and the research is kind of enhancing our ability to make decisions on the ground. (Manager)
Using local, experiential knowledge to improve models	When we first got their product, ground truthing it, I'd say it was 80% inaccurate. I'm just throwing out a number… It didn't provide good planning. [A decision-maker] couldn't look at their map and say, 'Oh, well, that's red,' or 'Oh, that's green', and make a decision off of it. He would have to go out and ground-truth every single one of them because it wasn't reliable enough. What we did was look at some of the parameters that they used, so to go from a yellow to a red we'll say was a 30% slope. Well, okay, 30% slope is pretty steep. In this area where people are building stuff, a 20% might be the more accurate number because we would look at it as practitioners and say, 'That area is a red, not a yellow. Change your parameter from 30% down to 28%. Let's take a look at that.' (Community member)
	Everybody has a different knowledge background… Most of the time, people who are full-time scientists probably aren't going to have the operations background. They're going to know that we need to get fire in this area. They might know this is a tricky area, but they're not going to understand, 'Okay, a hot shot crew that's on full when it's 90 degrees out can build this many lines or this many miles or feet of line in an hour.' That kind of thing… understanding the limitations and abilities of operations is really important for us to understand what's possible on the ground. (Scientist)
Integrating different perspectives into the research process and products	Different perspectives are great, but they've got to be willing to work with people and to see value in those different perspectives. If they don't see that, it's not going to be real – let's just say collaboration is going to be difficult. So they need to be pretty open-minded, and willing to look at things, and try new things. With that approach, I think you end up then having these various perspectives… even if it's not a complete solution – you're going to have a much more robust answer to your questions. (Community member)
	Both of those kinds of bodies of knowledge are incredibly important. To have something that puts them together in a really thoughtful way, that's the goal, is a pretty powerful tool… To have something beforehand that we can utilise to help us inform those decisions that we're making in terms of managing a wildfire is incredibly useful. That we're not only utilising the deep, professional judgment and knowledge of the folks on the ground but also informed by really rigorous peer-reviewed science and methodology is something that will be really useful in terms of being able to describe our thought processes and how we went through looking at risk management when we're managing a wildfire. (Manager)
	It's developing a more nuanced and sophisticated understanding of the problem of wildfire in general. Of how practitioners grapple with it, the complexity of the context. Not just the local context, but the state context, and the federal policy and funding mechanisms in place. But it's also developing shared understanding within the team, shared language, shared history; that is really critical. (Scientist)
Participation by non-scientists increases credibility and legitimacy	We talk a lot with all those groups and try and do problem-driven research. And if you do it that way, then hopefully whatever you find out not only will be more relevant, but also will be more trusted if you've involved the community in the process… I think it's just transparency; they sort of understand how this knowledge didn't just come out of a black box. (Scientist)
	If researcher just showed up and said, 'Hey, we got these cool things we want you guys to try,' chances are they wouldn't pay much attention. If fire leadership showed up and said, 'We want you to do this,' the local [decision-maker] is going to be like, 'What? We're not sure.' That's kind of how we grew to develop our team, so there'd be high-level expertise and credibility in each of those people so that when you showed up somewhere, people were quick to accept because they'd go, 'Oh yeah. I know so-and-so, and they are good at this.' (Manager)

similarly emphasised the need to 'be willing to work with people and to see value in those different perspectives', suggesting that integrating different perspectives into a project means that 'you're going to have a much more robust answer to your questions'.

Many participants (22) suggested that collaborations between scientists and managers can also integrate management knowledge into existing research outputs. One community member described how their experiential knowledge of fire fighting was used to improve the utility of landscape-scale modelling of wildfire behaviour. In this case, managers and community members helped scientists 'ground-truth' and refine how the model characterised the risk of projected wildfire behaviour, based on local knowledge of on-the-ground conditions. One manager suggested that integrating knowledge from management and research 'works both ways where we're enhancing the research and the research is kind of enhancing our ability to make decisions on the ground'.

Participants (15) also described how these collaborations enhanced 'transparency' around research and the way that information is used by managers, noting that this transparency can build support for both the research outputs and the management decisions that are informed by them. One manager explained that the outputs of their project, which integrated professional and scientific knowledge, will be useful for informing decision-making for fire management, as well as explaining how management decisions were made. One scientist suggested that, by incorporating a broad range of participants into the research process and informing communities about the work, the projects and their outputs, gain more 'credibility' and legitimacy because more people understand how they came about, and project outputs 'will be more relevant' and 'will be more trusted'. One manager conveyed that when different kinds of people engage in a process, a broader range of people will see the types of people they trust involved and thus find the outcomes more credible.

Addressing the challenges of co-production

One of the goals of this research was to better understand how research organisations enable and constrain co-production (see Table 4 for additional data on addressing the challenges of co-production). To this end, all participants were asked to reflect on the ways in which their organisation and RMRS specifically supported these projects and their work on them. While participants painted a nuanced picture of the organisational context within which they worked, there was widespread agreement regarding how RMRS might address some of the barriers to collaborative research.

Some participants (10) described RMRS as supportive of collaborations between scientists and managers. One scientist shared that their project was 'well-received' and they were invited to present the project to a variety of audiences. According to another scientist, RMRS is 'very happy about [collaborative work]' and 'they want us to be interacting with managers'. Another scientist conveyed that '[RMRS] has always been very supportive of this work… I've never had anyone not support this work'. Upon further reflection, some participants (15) conveyed that while RMRS values collaborative work, the organisation provided inadequate resources for collaboration or insufficient recognition of this work in job descriptions and performance evaluations.

Many participants (21) explained that these types of collaborations are not part of their normal job duties and entail additional work that is not as easily recognised or valued in their performance evaluations. More specifically, participants (10) argued that Research Grade scientists within RMRS as well as the university scientists who partner with them are evaluated primarily based on research publications. One scientist described the trade-offs between addressing management concerns and working on peer-reviewed publications, explaining that scientists sometimes choose to work collaboratively at the expense of working on publications, or vice versa. When asked about the importance of producing publications from their collaborative work, one scientist commented, 'It's critical. Otherwise, I couldn't be a part of it.' To address this challenge, some participants recommended adjustments to performance evaluations to incentivise and reward both scientists and managers to work collaboratively and to value outputs for applied audiences.

Funding structures were also viewed as a barrier to collaboration. Out of the seven projects studied, only one received additional funding from RMRS specifically for collaboration, including funding for some of their partners. Nearly all of the people who felt they had adequate financial support to engage in collaborative work were part of this project and the project is expected to produce several publications, ensuring that scientists receive 'credit' in performance evaluations. One of the scientists from this project described their program manager, who is their direct supervisor, as 'unbelievably supportive', saying that this supervisor supported them spending time on the project and helped them identify additional collaborators. They shared that they 'have felt so supported by the research station' and are 'lucky to have experienced that'.

Of the other six projects, only one participant described receiving financial incentives or support for engaging in this kind of collaboration, describing the receipt of awards and commenting, 'That's giving a person money and kudos too, so that's a good way to reward someone and incentivise their work.' In contrast, another scientist referenced these types of awards and argued that they do not reflect an incentive appropriate to the amount of investment by the scientists. Most participants regarded funding as largely inadequate to support the large investment of time required for collaborative work. One scientist explained that, because RMRS is unable to provide additional financial resources for collaborative work, scientists depend on external funders to support these time-consuming efforts. Some participants (10) also argued that external funding can make collaboration challenging because it's often short-term and these are 'big efforts' that 'take a while'. As one scientist put it, it is 'hard to develop a program and things that'll last if your money is year to year'. To address funding challenges, some participants (10) suggested that grants should be adjusted to adequately compensate participants for the time investment and to better match the duration of these efforts, which would appropriately incentivise participation.

Beyond the constraints that individual scientists experience to engaging in collaborative processes, some participants (11) also describe that as a team or organisation, they lack the staff capacity to meet the demand for these types of

Table 4. Additional data on addressing the challenges of co-production.

Challenges	Particpant responses
RMRS supportive of collaborative projects	Because the work was being very well received and was pretty high profile, the individuals were supportive. Part of the support was asking me to give presentations […] to forest service groups, linking me in more directly with various forest or groups that might be interested in learning more about the material. (Scientist)
	So you're asking if RMRS incentivises it? I would say that they get very happy about it. So my boss is happy and if my boss is happy, then I'm going to be happy. And it's incentivised from an expectation of RMRS, they want us to be interacting with managers. (Scientist)
	RMRS has always been very supportive of this work… I've never had anyone not support this work. (Scientist)
	My program manager has been unbelievably supportive. He supports what I do. I mean, they support me spending my time on this. He has actually helped me. I've needed to bring some other people in to help us with the work, and he has had some ideas of people who could help us who turned out to be perfect and spectacular. I'm not trying to be overly effusive, but I have felt so supported by the research station and management at the station. I know I'm really lucky to have experienced that. (Scientist)
Need to address trade-offs between collaborating and publishing	You've got to understand, as a scientist my job position is not graded on how well I address those little things that they ask me. It's graded on how my publications are. My position is not designed to answer their every little science question. My position is supposed to be publishing according to RMRS… There will be times where I have to say, 'No, I don't have time.' Then that could hurt future relationships, not because they're angry or anything, but they'll be like, 'Well they couldn't help me'… So I have to prioritise publications… I have to make a decision. Am I going to invest time and money and travel to go out […] and help them with that? I decided that it's worth that. It's worth that relationship and it's worth getting to see where it goes. So I have to choose that and when I'm doing that, I'm not writing a paper back in my office. (Scientist)
	We basically go and say, 'Here's our body of work,' every few years to a group of our peers. They can look at that and say, 'Yes, you meet the standards of this next level.' That panel process itself is very focused on an old model of research. What did you publish? What's your association within professional societies? How are you considered in your group of science peers? Applied research has typically not been well valued in the panel process, in my opinion. (Scientist)
	I don't mean RMRS hasn't been helpful. They've given me huge independence to do what I do, but there isn't a lot of incentives to do it. It's pretty easy to sit around and write papers and not do all this other work. (Scientist)
	I think they encourage [collaboration]. They would like for that to happen… I guess they just encourage it. I think that's all I could say… I think they support research that might not have as wide of a spread as this for collaboration, just because sometimes that's what comes up with funding. Sometimes you're able to do things that don't have as wide of a collaboration and that's just fine too. (Scientist)
	Different departments [in universities] have different formulations for how they evaluate whether or not somebody is worthy of tenure promotion, or just promotion in general. Those formulas can just look different. Maybe if you need, I don't know, 10 peer-reviewed, high-impact papers, and this is totally just a made-up number, maybe you need eight of that kind and two technical papers that are for an applied audience, providing incentive in that way to publish and to translate academic findings into useful results. (Scientist)
Need for funding that scales to the time investment and duration of collaborative projects	RMRS were able to provide some funding to offset a small portion of my staff time, of my hours to help implement the […] work […] which was hugely beneficial… You have to have some funding to back this kind of work. It's really important. (Community member)
	I mean RMRS's funding covering my time has been a critical piece of us being able to create [the collaborative project] because my research grants don't provide funding to do applied work. (Scientist)
	We never could have participated without that funding… Yes, a grant funding from RMRS definitely helped. Well, it made it possible. (Community member)
	A lot of these efforts, sometimes there's a budget that comes from a national office that will help promote this whole collaborative effort, but, at the same time, these collaborative efforts, they take a while. They're big efforts. So, I would say that a lot of times, the money or funding that they are putting to these efforts upfront, aren't totally thought through in terms of what actually is needed. (Scientist)
	The money is short-term. It's always like a year, there's no long-term soft money commitments, very few. So, the money that they do get, that isn't hardwired for RMRS, it's soft money. It's usually just a year. So it's hard to develop a program and things that'll last if your money is year to year. (Scientist)
	I think long-term funding. We've been cobbling together funding from various sources, always on a wing and a prayer that the next year we'll be able to figure it out. And there are fluctuations in the federal budget that change based on politics, and timing, and fire seasons, and all sorts of things. It means some years we're really scrambling and

(*Continued on next page*)

Table 4. (*Continued*)

Challenges	Particpant responses
	spending a lot of time and energy trying to cobble together resources. Just because you apply for a grant, doesn't mean you get it… sustained funding for these kinds of efforts. (Scientist)
	There may be things that we really want to have some research input or involvement in and if funding is not available to look into that, it may be something that on the ground as a manager you feel is a fairly critical question to get answered, but because the funding isn't available, or there aren't enough – I mean I know our researchers work a ton, and they take on a lot. And so sometimes even trying to find summer help is a challenge, and to be able to collect data. So I think that additional funding could help in providing people and providing the funding to maybe get more researchers on the ground answering more of those questions. (Manager)
Lack of capacity for collaboration	If we had more staff and capacity, we could do it a lot. We have to turn away work because we don't have the personnel. We don't have the permanent positions. (Scientist)
	The collaboration I've been involved with, if you get your external money, you can do things with it. And we're [RMRS] going to allow you to do more things with it once you've really established that that money is solid. But I haven't seen the station pony up its own money. (Scientist)
Need for Professional Grade scientists	I just feel like there's so much science that could be translated and used that we're not taking advantage of, and that the scientists are busy doing their science. The people here, the tech-transfer people are like, 'Hey, we want to take your science and do cool stuff with it.' It's good for their PD [position description]… As much science as we can get out there in their name, it benefits them, and it benefits the user, so I think it's a win–win. I just feel like this buffer of the tech-transfer zone is really important and could be grown. (Scientist)
	What happens is, if you [a Research Grade scientist] create something useful that the field needs, there's no mechanism to be able to have that thing move on and get out of development, and move into operation and maintenance… It's like a teenage kid in your basement that will never leave your house. You have to continue to maintain it, and maintain it, and maintain it. And once you make a couple really useful models or things, then most of your time is going to just maintaining this success or two, and could be throughout the rest of your career… So, instead of saying, okay here's this useful thing, science has got it where it needs to be, let's give it to someone who can then maintain it, and take care of it, and answer the questions from the field, and teach people how to do it, the scientists still have to do all that. (Scientist)
	The research station as a whole, I think, still holds onto the fact that if you're not a PhD research scientist bringing in research dollars, then you're not necessarily worth as much, in a manner, and then the professionals who are actually doing the science application side of things… There's very limited mobility for people like us, so we leave. Eventually people who have these kinds of skills that the research station needs, leave, because […] there's such a limited growth potential for the professional series within the research station. It's like you either become [a Research Grade scientist] or you top out pretty quick… Having a parallel path for the professionals as what the scientists [Research Grade scientists] have, to where you could progress up through different GS [General Schedule] scales, and have a career level GS scale that's a retirement level kind of position. (Scientist)

collaborations. One scientist argued that with more personnel they could do more collaboration, saying, 'If we had more staff and capacity, we could do it a lot', and that they currently have to turn away collaborative opportunities. Another scientist discussed the challenge of securing additional funding for new positions to grow collaborations. One manager argued that important management questions go unanswered because there is limited funding for researchers and too few scientists. To address this challenge, some participants (11) recommended greater investment in scientist positions to build capacity to engage in collaborative research.

Participants (16) also described a pressing need for translation of research into products that are useful to managers. Some participants specifically emphasised the need for more Professional Grade scientists who are not incentivised to publish, but instead focus primarily on translation. One scientist discussed the importance of 'tech-transfer' activities like adjusting tools to be more easily usable, training individuals on how the tools work, maintaining them over time, and providing feedback to scientists on any problems that users are experiencing. Another scientist explained that tech-transfer work can help translate and maintain research products for management use, and enable researchers to continue creating new tools, instead of spending their energy maintaining their successful products. In addition to building capacity to translate research into products that are useful to managers, one scientist argued that Professional Grade scientists need career ladders that value and incentivise their work to address frequent turnover in these positions due to lack of upward mobility.

Discussion

Participants in this study suggested that fire science may not always be relevant to managers, and that differences in organisational culture can cause difficulties in communication and manifest as different epistemologies. By integrating different forms of knowledge, participants argued that they had enhanced the relevance of fire science for specific contexts, incorporating decision contexts, financial resources, community values and diverse goals into research products. They also suggested that the on-going learning involved with co-production can build trust and improve transparency, thereby increasing the credibility, salience and legitimacy of fire science. It is important to note that this research examined seven wildland fire projects that were characterised as co-production, and thus these results may be biased toward participants who have been more successful at overcoming organisational barriers to co-production. Despite this success, however, participants in this study still experienced important organisational constraints. As Colavito (2021) points out, the 'disconnect between science and management' is not unique to fire science, but rather 'pervades many complex natural resource issues that seek to integrate scientific information into decision-making'. Thus, even though this study focused on a specific research organisation, RMRS, the incentives and barriers described in this paper may apply to co-production more broadly, given the similar cultures and incentive systems that are present in many research organisations, from government labs to universities.

Like previous research, we found that support and incentives for co-production are vital (Dilling and Lemos 2011; Meadow *et al.* 2015; Clark *et al.* 2016; Beier *et al.* 2017), and many institutional structures continue to limit this type of engagement (Djenontin and Meadow 2018; Wyborn *et al.* 2019; Turnhout *et al.* 2020). As a research organisation whose mission includes producing science to assist Forest Service managers, co-production is aligned with the RMRS mission. However, RMRS still exists within a broader science culture and structure that values, conducts, rewards and funds science in particular ways. As such, RMRS provides a window into both the benefits of co-production as well as the ways that co-production challenges conventional models of science. Our results suggest a number of institutional changes that can improve the ability of research organisations to support co-production, within fire science and beyond.

Adjustments to performance evaluations could help incentivise co-production, and better connect fire science and management. More specifically, participants in this study argued that performance evaluations for scientists tend to value peer-reviewed scientific publications more than engagement in co-production. Previous research has found that incentive structures for scientists that focus on peer review publications can discourage participation in co-production (Dilling and Lemos 2011; Beier *et al.* 2017). Furman *et al.* (2018) recommend that performance evaluations in academia consider relationship-building on par with outputs and recognise the long-term nature of collaborative research processes (Furman *et al.* 2018). These kinds of structural adjustments to performance evaluations could prompt a broader cultural shift within the scientific community toward valuing direct engagement with decision-makers (Clark *et al.* 2016).

The Forest Service guide for evaluation of Research Grade scientists was recently revised to emphasise impact and collaboration. The guide states that 'information and technology transfer (ITT) is an important aspect of disseminating research results' and that 'research accomplishments have no ultimate effect until someone uses the scientist's findings, or puts new information into the hands of those that can apply the results' (USDA Forest Service 2019, p. 45). The revision also specifically recognised the value of 'conducting joint research with potential end users or research results' and noted 'much Forest Service research is also the result of collaborative relationships with research partners and land management' (p. 45). These changes had not yet been formally adopted at the time the interviews for this study were conducted, and it may take time to shift organisational structure and culture toward valuing and rewarding impact and collaboration alongside other scientific work.

In addition to changes to performance evaluations, greater investment in positions specifically designed to facilitate dialogue across science and end-users (often called science application or science delivery positions) is needed. These positions often focus on translating research into products that meet the needs of end-users and helping scientists better understand the needs of managers. In recognition that this work requires spanning the needs and cultures of both science and management, these individuals are increasing called 'boundary spanners' (Cash *et al.* 2003; Bednarek *et al.* 2018). Colavito (2021) describes boundary spanners as individuals who 'bridge the spheres of science and management' and 'provide communication and translation functions that help to facilitate the exchange of knowledge to co-develop' science, decision support tools and other knowledge for fire management. Matso and Becker (2015) recommend that projects build in capacity for integration through dedicated resources for boundary spanning to improve the utility of science for decision-making. Note that boundary spanners do not need to be employed by boundary organisations and can reside in research organisations. But regardless of location, career ladders and compensation that adequately value the work of boundary spanners are needed (Bednarek *et al.* 2018).

While investments in boundary spanning positions could help integrate manager knowledge and needs into existing research products, if designed as one-way science delivery, these investments could further separate managers and scientists from directly engaging with one another. This highlights an important trade-off, because many of the benefits of co-production come from iterative engagement between scientists and managers throughout the process, such as shared learning and relationship building (Sarkki *et al.* 2015; Schuttenberg and Guth 2015; Van Kerkhoff and Lebel 2015; Norström *et al.* 2020). Thus, to improve the ability of research organisations to create science that is useful for management and addresses the management questions that go unasked, it may be necessary to build capacity for boundary spanning *and* better incentivise scientists to engage with managers.

It is important to recognise, as Cash *et al.* (2003) have noted, that perceptions of the salience, credibility and legitimacy of knowledge are subjective, and efforts to increase these characteristics for some can often decrease them for others. When research organisations make a shift to provide more salient outputs for managers, they may jeopardise the credibility of their research within the scientific community, which currently assigns more value to questions and knowledge that builds from and contributes to the scientific literature. Further, many policies require that federal agencies like the Forest Service integrate the 'best available science' into their decisions and 'best available science' is typically defined as peer-reviewed science. This presents a conundrum for researchers whose work is relevant to natural resource management, especially if increased investments in co-production come at the expense of publishing. Thus, research organisations need to enable scientists to engage with managers to ensure that their research is actionable *and* to publish their results so that management decisions are legally defensible.

Funders also play an important role in encouraging research processes that connect science with action (Arnott *et al.* 2020). According to Matso and Becker (2014, 2015), funders can support actionable science by modifying the review process to place more emphasis on science that is connected to decisions, requiring that scientists and end-users engage throughout the research, and dedicating funding to support this engagement. Including decision-makers on review panels and conducting impact analysis can also help advance research that meets the needs of end-users (Nyboer *et al.* 2021). Echoing these calls, Varner and Hiers (2020) recommend that fire science funders require that proposals demonstrate how projects will meet the needs of managers and outline how managers will be involved in all stages of the research. Longer-duration grants and dedicated funding can enable science–management partnerships that are focused on the problems that managers face (Carter *et al.* 2020; Nyboer *et al.* 2021). To the extent that fire science funders provide training and resources on co-production, as recommended by Varner and Hiers (2020), funders can help build the capacity for co-production.

Hunter *et al.* (2020) point out that co-production processes are time-consuming and potentially prohibitive. Boundary organisations can help address these barriers by facilitating ongoing interactions between fire scientists and managers, to advance fire science that is relevant to decision-makers (Kocher *et al.* 2012; Colavito *et al.* 2019; Hunter *et al.* 2020). For example, Maletsky *et al.* (2018) found that the JFSP Fire Science Exchange Network facilitated the use of fire science in management decisions. In the present study, several of the projects included external partnerships with local government, NGOs, or other federal agencies, but none of these partners play the role of a boundary organisation. Research organisations do not necessarily need to evolve into boundary organisations. However, research organisations can enhance their capacity to engage in boundary-spanning work, and leverage their resources and skills to support co-production to improve the utility of science, including fire science, for management.

Conclusion

Our results suggest that research organisations can make adjustments to better support the co-production of actionable science, and thus help agencies respond more effectively to the ever-growing risk of wildfires. The growing body of research on the benefits of co-production, including this study, indicates that collaborative engagements between scientists and decision-makers increase the relevance and utility of research products. But because co-production means doing science differently, these efforts require institutional support. Research organisations, from government agencies to universities, are uniquely positioned to incentivise collaborations that create more useful and useable science through investments in co-production via modified funding arrangements, performance evaluations, career laddersa and resources for translation.

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Appendix A. Interview guide

Individual context

1. I'd like to begin by learning a bit about you, could you tell me about your current position?
   Probe: Who do you work for? How long have you worked where you do now?
   Probe: Is this the same position you held during the [project name]? (If not) Could you tell me about that position?
2. How did you become involved in the [project name]?
   Probe: What was your role in the [project name]?

Roles, process and barriers

3. Who participated in the [project name]?
4. Could you walk me through the [project name] process from the start to finish?
5. What role did the different organisations play in this project?
6. Could you describe how the main objectives of the [project name] were established?
7. How do those objectives relate to the goals of [participant's organisation]?
8. Do you feel like the [project name] adequately met those objectives?
   a. If not, why?
   b. If so, how?
9. What were some of the challenges and barriers that the project faced?
   Probe: Are there things that the different organisations involved could do to alleviate those challenges or barriers?

Their participation

So we started out talking a bit about your work, and the project itself, and now I'd like to transition more into your participation during the project.

10. Was your participation in [project name] encouraged by RMRS or did you participate of your own initiative?
    a. If discouraged, how/why?
    b. If encouraged, how/why?
    Probe: Was your involvement in the project incentivised by RMRS?
11. What are some of the barriers you faced to participating in a collaboration like this [project name]?
12. Has your experience with collaboration in the [project name] changed how you may approach your work in the future?

a. If so, how?
b. If not, why not?

Their organisation

I'd like to transition now to focus more on your organisation.

13. Do collaborations like this, where scientists, managers, and other stakeholders work together, change the work of [participant's organisation]?

14. Do collaborations like this between scientists, managers, and other stakeholders change the usefulness of the new knowledge that's created?

15. What role do you think these kinds of collaborations should play in [participant's organisation] in the future?

16. Are there ways [participant's organisation] could better support these kinds of collaborations in the future?

Probe: What things might need to change about your organisation to support these kinds of collaborations?

For non-RMRS scientists: Are there changes that RMRS could make to better support these kinds of collaborations going forward?

Wrap-up

17. That's the end of my questions; is there anything you'd like to describe about the [project name] that I haven't asked about?

I'd like to hear more about this collaboration from other scientists, managers or stakeholders who were highly involved; are there any people you may recommend I speak with?

Thank you for your time today, I appreciate the opportunity to hear from you. If you have any additional questions or comments, please let me know.