Making the Transition from Science Delivery to Knowledge Coproduction in Boundary Spanning: A Case Study of the Alaska Fire Science Consortium

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(Manuscript received 16 January 2019, in final form 23 July 2019)

ABSTRACT

Boundary organizations facilitate two-way, sustained interaction and communication between research and practitioner spheres, deliver existing science, and develop new, actionable scientific information to address emerging social–ecological questions applicable to decision-making. There is an increasing emphasis on the role of boundary organizations in facilitating knowledge coproduction, which is collaborative research with end users to develop actionable scientific information for decision-making. However, a deeper understanding of how boundary organizations and knowledge coproduction work in practice is needed. This paper examines the Alaska Fire Science Consortium (AFSC), a boundary organization focused on fire science and management in Alaska that is working to address climate impacts on wildfire. A case study approach was used to assess AFSC activities over time. AFSC's boundary spanning involves a continuum of outputs and activities, but their overall trajectory has involved a deliberate transition from an emphasis on science delivery to knowledge coproduction. Key factors that facilitated this transition included a receptive and engaged audience, built-in evaluation and learning, subject matter expertise and complementarity, and embeddedness in the target audience communities. Recommendations for boundary organizations wishing to develop knowledge coproduction capacity include knowing your audience, employing trusted experts in boundary spanning, and engaging in frequent self-evaluation to inform change over time.

1. Introduction

Climate change is driving rapid changes in social–ecological systems. Land managers are struggling to keep up with these changes while working to integrate the best available science in decision-making. This challenge is especially poignant in fire management—the planning for and fighting of wildland fires—in the United States, where there is a clear link between climate drivers and fires but variability among ecological regions (Littell et al. 2009; Marlon et al. 2009; Marlon et al. 2012; Westerling et al. 2006). The term ''wildland fires'' (hereinafter simply fires) refers to any type of fire that occurs in a vegetated area. Fire managers—the agencies and individuals who deal with the planning for and fighting of fires—are at the forefront of decisions that influence social–ecological systems but often find themselves in a paradox whereby social expectations to suppress fires conflict with scientific evidence that demonstrates the importance of fire as an ecological process (Ingalsbee 2017). This has led to a greater

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Publisher's Note: This article was revised on 22 October 2019 to replace Fig. 5, which contained a misspelling when originally published.

DOI: 10.1175/WCAS-D-19-0009.1

emphasis on adapting to fire and better coexisting with fire in a changing climate to foster social–ecological adaptation and resilience (Chapin et al. 2010; Moritz et al. 2014; Schoennagel et al. 2017).

Boundary organizations—organizations that facilitate two-way, sustained interaction and communication among science and decision-making spheres—are designed to deliver existing science and develop actionable scientific information to address social–ecological questions (Kocher et al. 2012). Actionable science can enhance decision-making, especially for complex problems like climate change (Cash et al. 2003; Clark et al. 2016; Dilling and Lemos 2011; Knapp and Trainor 2013). Knowledge coproduction—a collaborative research approach that incorporates scientists and science users throughout the research process—is increasingly advocated for developing actionable science (Table 1) (Meadow et al. 2015; Wall et al. 2017a). The principles of knowledge coproduction include long-term relationships between scientists and stakeholders, two-way communication, and a focus on actionable science (Meadow et al. 2015). Far less is known, however, about how to make knowledge coproduction work in practice (Djenontin and Meadow 2018). A better understanding of the potential pathways to knowledge coproduction, the role of boundary organizations in knowledge coproduction, and how boundary organizations learn and transition over time to facilitate the development and application of actionable science is needed (McNie 2013; Meadow et al. 2015; Wall et al. 2017b).

This paper uses case study research to assess the Alaska Fire Science Consortium (AFSC)—a boundary organization focused on fire science and management in Alaska—and to develop a deeper understanding of how boundary organizations and knowledge coproduction work in practice. A logic model framework is used to explore how AFSC's historical context, inputs, outputs, and outcomes have changed over time. AFSC's boundary spanning involves a continuum of outputs and activities and has shifted from a focus on science delivery to knowledge coproduction. Key factors supporting this transition are discussed as potential mechanisms to achieve the principles of knowledge coproduction in practice. Recommendations are offered to other boundary organizations seeking to facilitate knowledge coproduction.

2. Literature review

a. Fire and fire management in Alaska

In Alaska, most fire historically occurred in the boreal forests of the interior and the Kenai Peninsula, which experienced large but infrequent lightning-ignited fires. Alaska's fire patterns reflect high interannual variability in close association with climate (Balshi et al. 2009; Markon et al. 2012). Climate change is contributing to altered fire patterns, and models predict increasingly severe fire activity with potential dramatic shifts in vegetation (Chapin et al. 2010; Mann et al. 2012; Johnstone et al. 2011; Joly et al. 2012). Since 2000, the average annual area burned is nearly twice as much as the previous five decades on record, and the total acreage burned is expected to increase in response to warming (Kasischke et al. 2010; Balshi et al. 2009; Calef et al. 2015). The effects of climate change on fire are diverse. For example, the record 2004 and 2005 fire seasons (6.6 million and 4.7 million acres burned respectively) extended into September when normal August rains did not fall. The second largest fire season in 2015 (5.1 million acres) was characterized by warm, dry conditions in May and June that increased fuel availability coupled with numerous lightning ignitions in June. Extreme fire seasons in Alaska like 2015 are 34% to 60% more likely to occur under current conditions due to anthropogenic climate change (Partain et al. 2016).

Fire managers in Alaska face unique challenges due to its large geographic extent and rapid rate of climate change. Fires pose risks for both urban and rural communities (Trainor et al. 2009). Protecting communities from infrastructure loss, disruption of travel corridors, and smoke impacts require substantial economic investment (Melvin et al. 2017). Complicating this is the sheer size of remote, fire-adapted boreal landscapes that surround and occupy these communities.

Fire management in Alaska has operated on a cooperative basis since before World War II. This interagency approach was codified in the Alaska Interagency Wildland Fire Management Plan of 1998 (AWFCG 2016). Agencies involved in fire management in Alaska include the Bureau of Land Management (BLM) Alaska Fire Service, National Park Service, U.S. Fish and Wildlife Service, Bureau of Indian Affairs, U.S. Department of Agriculture (USDA) Forest Service, State of Alaska Department of Natural Resources, Alaska Native Corporations, and Native nongovernmental organizations such as the Tanana Chiefs Conference and Chugachmiut. These organizations coordinate their activities through the Alaska Interagency Coordination Center and the Alaska Wildland Fire Coordinating Group (AWFCG).

Fire managers in Alaska desire actionable fire science to support decision-making (Knapp and Trainor 2013; Knapp and Trainor 2015; Rutherford and Schultz 2019). AWFCG has produced a research needs list for more than 15 years to facilitate collaboration with scientists and meet their needs for actionable information. Climate change has ranked in the top five AWFCG research needs since 2008 (AWFCG 2008). Other key research needs

Table 1. Key modes of science production in boundary organizations as used in this paper.

Key concepts	Definition
Science delivery	A one-way delivery of scientific information (McKinley et al. 2012).
Technology transfer	A one-way delivery of scientific information that serves as the basis for the development of new information or tools for use by professionals (McKinley et al. 2012).
Knowledge coproduction	A collaborative research approach that explicitly involves the end users of the research in all stages of knowledge development and dissemination to varying degrees, but which maintains an emphasis on two-way, iterative, and sustained interactions and the production of actionable science (Bremer and Meisch 2017; Meadow et al. 2015; Wall et al. 2017b).
Boundary spanning	An interdisciplinary and transdisciplinary approach for bridging the worlds of scientists and practitioners, which can be accomplished through information brokering, convening, mediating, and translating (Dilling and Lemos 2011; Safford et al. 2017). Boundary spanning can include both one-way and two-way communication and interaction with scientists and practitioners. Bednarek et al. (2018) recently defined it as ''work to enable exchange between the production and use of knowledge to support evidence-informed decision making in a specific context'' (p. 1176). They also describe boundary spanners as the ''individuals or organizations that specifically and actively facilitate this process'' (Bednarek et al. 2018, p. 1176).
Actionable science	Information that ''fulfills stakeholders' value demands'' for a specific situation (McNie 2013, p. 16). Also referred to as ''usable science.'' Scientific information is deemed actionable within the specific context in which it is intended for use.
Boundary organization	Organizations that facilitate two-way, sustained interaction and communication among research and decision-making spheres, deliver existing science, and develop new, actionable scientific information to address emerging social–ecological questions applicable to decision-making (Cash et al. 2003; Gustafsson and Lidskog 2018; Guston 2001; Kocher et al. 2012). Boundary organizations have four key functions: convening, translating, collaborating, and mediating interactions between research and decision-making spheres (Buizer et al. 2016).

include fire behavior, fire danger, and fuel treatments (AWFCG 2017). Use of the phrase ''fire science'' here includes climate science related to fire, like changing fire patterns and fuel characteristics, as well as other scientific disciplines that deal with fire, like social or economic sciences.

b. *Fire Science Exchange Network and Alaska Fire Science Consortium*

Increasingly severe fire seasons across the United States have led to institutional and political support for incorporating fire and climate science into fire management and policy. In 1998, Congress created the Joint Fire Science Program (JFSP) to serve as an interagency partnership between the Departments of Interior (DOI) and Agriculture and better connect federally funded research to practitioner needs (Maletsky et al. 2018). The 2000 National Fire Plan—developed in response to the severe 2000 fire season by the Departments of Agriculture and Interior—called for agencies to manage beyond fire suppression, base fire management activities on the best available science, and encourage timely delivery of usable information (NIFC 2001). Additional collaborative, interagency efforts like the National Cohesive Wildland Fire Management Strategy effort initiated in 2009 have continued to advance science-based fire management.

Several boundary organizations have also emerged to facilitate science-based decision-making, including the JFSP Fire Science Exchange Network (FSEN) and National Oceanic and Atmospheric Administration (NOAA) Regionally Integrated Sciences and Assessments (RISA) (Maletsky et al. 2018; Parris et al. 2016; Prokopy et al. 2015). The FSEN is a national network of regionally focused boundary organizations dedicated to making fire science available and actionable to fire managers (Hunter 2016; Kocher et al. 2012). In September 2009, funding was provided to eight FSENs for one-year pilot grants ''to support regional consortia of fire science providers and managers to enhance fire science delivery and adoption'' (JFSP 2009). AFSC is an FSEN funded in the first group of pilots. Its mission is ''to strengthen the link between fire science research and on-the-ground application by promoting communication between managers and scientists, providing an organized fire science delivery platform, and facilitating collaborative scientist-manager research development'' (AFSC 2018). The FSENs emphasize interdisciplinary work, and AFSC engages with numerous scientific disciplines, including ecology, social science, and economics. AFSC's geographic focus is the State of Alaska. It is collocated at the University of Alaska Fairbanks (UAF) with several climate-related boundary organizations, including the NOAA RISA Alaska Center for Climate Assessment and Policy (ACCAP) and DOI Alaska Climate Adaptation Science Center (AK CASC).

c. *Modes of science production in boundary organizations*

Boundary organizations are one mechanism that can facilitate two-way, iterative engagement between scientists and science users and produce scientific information that is credible, salient, and legitimate for practitioner use (Cash et al. 2003; Gustafsson and Lidskog 2018; Guston 2001; Meadow et al. 2015). Three characteristics have defined boundary organizations: involvement of actors across a science–practice boundary, creation of boundary objects or outputs to facilitate communication, and existence at the nexus of at least two different social worlds (Guston 2001). The activities that boundary organizations sponsor, processes they use, and outputs they produce are relatively distinct but more formalized than social networks (Crona and Parker 2012). There are several key boundary organization functions, including convening, translating, collaborating, and mediating interactions between scientists and practitioners (Buizer et al. 2016). Boundary organizations facilitate boundary spanning, although boundary spanners can be located outside of boundary organizations (Bednarek et al. 2018).

Several terms are related to the different modes of science production in boundary organizations (Table 1). Science delivery and technology transfer are often used to describe one-way delivery of information from scientists to decision-makers (McKinley et al. 2012). Knowledge coproduction involves two-way, iterative engagement between scientists and decision-makers to develop and drive research questions, methodology, analysis, and interpretation in collaborative partnership and to build shared knowledge and trust (Bremer and Meisch 2017; Meadow et al. 2015). Other related terms include "translational ecology," which is the process of knowledge coproduction applied to ecological science (Enquist et al. 2017). Disentangling the multitude of definitions around science production and use is complicated by differences in terminology across sectors and disciplines and changes in meaning over time (Bremer and Meisch 2017; Jacobs 2017).

There is increasing attention to boundary organizations in social science research. Early research focused on linking science and practice in applied research contexts (Agrawala et al. 2001; Keating 2001). More recent efforts have demonstrated the importance of knowledge coproduction and fostering iterative interactions between scientists and decision-makers to increase the usability of information (Lemos et al. 2012; Parker and Crona 2012). Other research has identified how multiple boundary organizations enhance their capacity by networking and leveraging resources and capacities (Lemos et al. 2014).

Research has also begun to investigate the evolution of boundary organizations. Leith et al. (2016) highlight four phases of evolution relating to boundary organization legitimacy: problem definition and framing, early wins, reciprocal commitment among partners, and extending and stabilizing the problem. Parker and Crona (2012) suggest boundary organizations operate within a "landscape of tensions," whereby stakeholder actions, expectations, and orientations influence boundary spanning activities along four continua: basic and applied, disciplinary and interdisciplinary, long-term and real-time, and autonomy and consultancy. Other research has highlighted how boundary organizations have innovated their boundary spanning to increase the usability of climate information (Kettle and Trainor 2015). However, there is limited understanding of how the activities of long-standing boundary organizations shift over time to facilitate coproduction of actionable science.

Evaluating boundary organization effectiveness, including science delivery and knowledge coproduction activities, has also received increasing attention (Fazey et al. 2014; Maletsky et al. 2018; Meadow et al. 2015; Wall et al. 2017b). Multiple evaluation approaches use a logic model framework, which considers the contextual factors, inputs, processes, outputs, outcomes, and impacts of an organization (NRC 2005; Singletary et al. 2015). For example, Wall et al. (2017b) developed 45 indicators within a logic model framework to evaluate the process of coproduction of usable climate science. Logic models and associated indicators (e.g., Wall et al. 2017b) allow for systematic analysis of change over time and facilitate assessment of the outcomes and impacts of boundary organizations.

3. Methods

This analysis of AFSC uses a logic model framework. A logic model is a graphical representation of an organization's program theory, "an explicit theory or model of how an intervention contributes to a set of specific outcomes through a series of intermediate results" (Funnell and Rogers 2011, p. 31). The logic model framework was selected for multiple reasons. AFSC's activities were already organized in a logic model framework because JFSP has been requiring their use in all FSENs since 2012 in order to evaluate program effectiveness. Research on FSEN's has highlighted the importance of regular surveys to inform program effectiveness evaluation and the iterative, ongoing use of logic models to incorporate evaluation into planning (Maletsky et al. 2018; Singletary et al. 2015). A logic model framework is also proposed by Wall et al. (2017b) as a way to evaluate knowledge coproduction with the use of consistent indicators. Logic models typically include consideration of an organization's context and situation, inputs (assets or resources), processes (activities), outputs (what they produce), outcomes, and impacts (Funnell and Rogers 2011). Logic models project desired short-, medium-, and long-term outcomes. For the FSENs, short-term outcomes represent planned "change in knowledge or the participants actually learn"; medium-term outcomes represent "change in behavior or the participants act upon what they've learned"; and long-term outcomes occur when "societal condition is improved due to a participant's action" (Singletary et al. 2015). The logic model framework used here includes historical context, inputs and assets, outputs and activities, and outcomes. AFSC's impacts were not analyzed, as they are longer-term and more difficult to measure (Ferguson et al. 2016).

Multiple methods anchored in modified grounded theory—a research approach that begins inductively with questions to generate data and subsequent themes and patterns—were used, including semistructured interviews, group interview, participant observation, and document analysis (Miles and Huberman 1994; Strauss and Corbin 1990). These methods were selected in order to gain a comprehensive understanding of AFSC's activities over time. Data were collected between March 2016 and April 2017. This research was undertaken using the principles of knowledge coproduction and involved the AFSC core team, which included the principal investigator (PI), program coordinator, and subject matter experts, in research design, data collection, analysis, and interpretation. The AFSC PI (a social scientist) and program coordinator are coauthors on this paper.

A purposive sample was developed with the AFSC core team to target respondents who had past or present involvement with AFSC (Table 2) (Bernard and Ryan 2010). In this research, involvement includes past and present AFSC core team members, past and present AFSC Advisory Board members, ACCAP staff, AFSC event participants, users of AFSC outputs, and fire management leadership. One individual declined to participate in an interview. Interviewees (n = 30) were asked open-ended questions about their involvement with AFSC, involvement with fire science, perceptions of AFSC's effects on their work, and thoughts for improving AFSC and the connections between fire science and management (Dunn 2008). Interviews were conducted in-person or by phone and recorded for transcription. A historical scan—a form of group interview—was conducted with four past and present AFSC core team members to develop a chronology of AFSC's history, achievements, and key influencing events (Earl et al. 2001).

The individual and group interviews were transcribed and coded three times by a single coder using NVivo qualitative data analysis software. Initial coding was

TABLE 2. Respondent demographics: science refers to respondents who primarily conduct research, management refers to respondents who primarily work for state and federal land management agencies, and boundary spanner refers to respondents who work for or directly with boundary organizations. For respondents with more than one affiliation, their current affiliation or the affiliation of the organization in which they are employed was used for classification.

Affiliation	Science	Management	Boundary spanner
University	7	—	7
Federal agency	3	6	2
State agency	—	3	—
Other	1	1	—
Totals	11	10	9

conducted during transcription, detailed analytical notes were taken, and participants were consulted throughout coding to verify single coder reliability (Saldaña 2016). A preliminary codebook was developed with categories from the logic model framework and descriptive categories from the literature on knowledge coproduction and boundary spanning (e.g., the code boundary organization had the subcodes of convening, translating, collaborating, and mediating) (Buizer et al. 2016). The preliminary codebook was reviewed and revised by two AFSC core team members. The interviews were then iteratively coded by first assigning codes from the codebook and then adding additional emergent, inductive codes based on content (Bernard and Ryan 2010; Strauss and Corbin 1990). The codebook was reviewed and revised again by AFSC core team members, and a final round of coding was conducted to derive main codes and descriptive categories.

Participant observation of AFSC's workshops, meetings, webinars, internal meetings, and other events was conducted in Fairbanks and Anchorage, Alaska, to examine interactions between AFSC core team members and AFSC participants (Kearns 2008). These data were supplemented by observations of video recordings of AFSC workshops and webinars. Observational data were recorded but not coded.

All written and oral outputs produced by AFSC between 2009 and 2016 were compiled. These outputs were classified by category (e.g., workshops, webinars, field trips, newsletters, research briefs) through systematic review of AFSC webpages, server folders, and hardcopy documents. They were then tallied to examine how output production has evolved over time (Funnell and Rogers 2011). Letters of support written by AFSC staff for research proposals and collaborative proposals with AFSC participation were compiled and classified into four categories by AFSC core team members. The AFSC activities database—an ongoing database of all AFSC activities and outputs used for reporting to JFSP—was

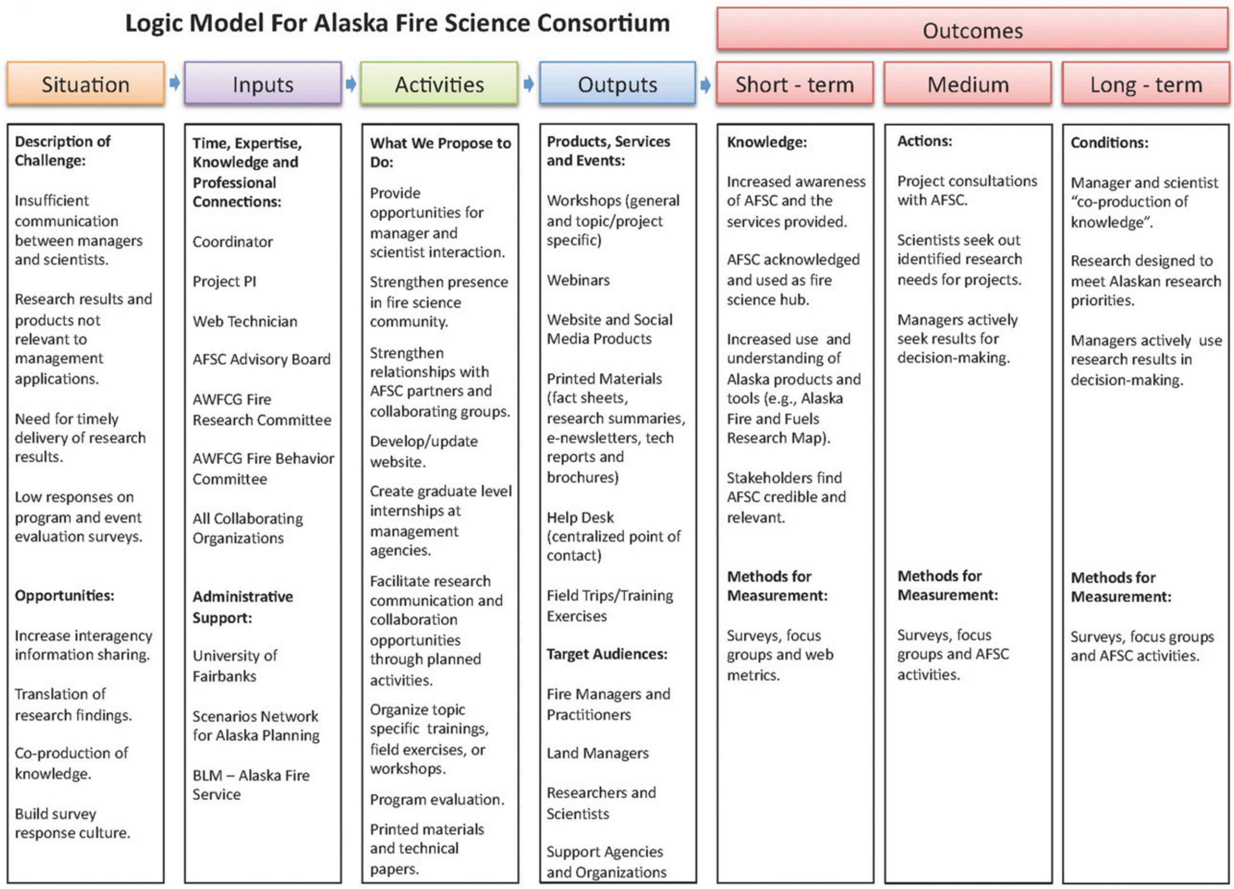

FIG. 1. AFSC logic model 2012. This example of an AFSC logic model was created as part of their 2012 renewal proposal to JFSP. It illustrates a vision by AFSC to build coproduction as part of long-term outcomes.

also chronologically tallied by activity categories to understand AFSC staff interactions with the AFSC audience over time. These analyses were reviewed for accuracy by AFSC core team members.

Desired program outcomes as stated in the 2012 and 2015 AFSC logic models were compared to actual program activities and achievements to assess the extent to which AFSC achieved its goals (see Fig. 1). Analysis of the 2017 logic model was omitted as it is too recent to assess outcomes. Results from the JFSP biennial FSEN surveys were reviewed but were excluded from analysis as their major themes and results are published elsewhere (Maletsky et al. 2018).

4. Findings

Findings are organized with the logic model framework: historical context (factors that contributed to AFSC's development), past and present inputs and assets (resources available to AFSC over time), outputs and activities (what AFSC does and what it produces), and outcomes (AFSC's contributions to change). AFSC's trajectory over time is also mapped to three key periods.

a. *Historical context*

Interviews and the historical scan found that a foundation had been laid for interagency collaboration between fire science and management prior to AFSC's establishment. The USDA Forest Service Institute of Northern Forestry (INF), established in 1963 but closed in 1996 due to budget cuts, facilitated collaboration between boreal forest managers and scientists, such as those at the Bonanza Creek Long Term Ecological Research Program, which addresses ecological questions at long time scales (Viereck 1995). In response to INF's closure, agency staff organized mechanisms to maintain fire science capacity in Alaska, including the AWFCG Fire Effects Task Group and a reference database and research clearinghouse funded by JFSP.

Collaborative efforts among fire managers and scientists ramped up in 1999 when a collaborative team of scientists and managers designed and analyzed an experimental burn near Fairbanks. Collaboration was further advanced in 2002, with the creation of an ecosystem model that simulates boreal vegetation and fire responses to climate change (Rupp et al. 2000a,b), which was funded by a JFSP grant through the Alaska Fire Service. As one scientist said about the model, ''The fire management community had gotten to a place and time where they were starting to think critically about how the fire regime might be changing.'' Meanwhile, fire managers began to identify, prioritize, and communicate their research needs via the AWFCG Fire Effects Task Group, which produced the first official Research Needs List in 2003 (AWFCG 2003). In 2006, scientists and manaers collaborated to implement an experimental fuel treatment and subsequent prescribed fire in 2009 at Nenana Ridge with JFSP funding.

The extreme fire seasons of 2004 and 2005 contributed to the 2006 interagency decision to move the official start date of the Alaska fire season from 1 May to 1 April, illustrating a policy response to seasonal changes in fire patterns (Trainor et al. 2017). Research on fire weather and climate quickly emerged as high-priority science needs for fire managers. Climate change research has been on each AWFCG Research Needs List since 2003 and in the top five since 2008 (AWFCG 2003, 2008). Thus, when AFSC was established in 2009, there was already ongoing collaboration among scientists and managers focused on climate impacts on fire.

b. *Inputs and assets*

AFSC's inputs and assets include funding, evaluation results, core team staff, and relationships and contributions from the scientific and management communities. JFSP has been a key input by providing consistent funding for the core office staff, evaluation resources, and opportunities for collaboration with other FSENs. The first AFSC proposal in 2009 was developed in partnership between UAF scientists and fire managers and highlighted AWFCG's interest in science, the need to formalize science delivery and two-way communication, and fire management challenges related to climate change. As one boundary spanner said about the pilot proposal, ''We just collectively felt like we needed a better platform for cooperation and collaboration.'' JFSP funding for AFSC has continued with four subsequent successful renewal proposals.

Results from internal and external evaluations are important inputs that help with long-term planning to meet audience needs. JFSP contracts with an external evaluation team that conducts annual national evaluation surveys, compiles web metrics, and provides resource guides and advice on evaluation. JFSP also requires that FSENs conduct program and event evaluation at the regional level. Thus, AFSC has consistently solicited feedback from its audience, and this user input is deliberately used to refine AFSC activities and develop its future trajectory.

AFSC staff, with their diversity of expertise and experience in science delivery and collaboration, are another key input. During AFSC's early years, the core team consisted of co-principal investigators (CoPIs), an ecologist and a social scientist at UAF, and a coordinator, who was supported through a two-year intergovernmental agreement with BLM Alaska Fire Service. Over time, the social scientist has taken the lead as PI and director of the program while the former CoPI ecologist remains on the Advisory Board. A new coordinator was hired in 2013 with deep roots in the scientific community. Staff capacities expanded over time, including hiring part-time subject matter experts, a fire ecologist in 2013, and a fire behavior analyst in 2016, both of whom are former fire managers and serve as liaisons between the fire management and science communities.

AFSC also receives inputs from a well-organized and engaged fire science and management community. The AFSC Advisory Board, whose members represent all federal and state fire management agencies in Alaska, advises AFSC in setting its course of action, works to maintain connections with its audience, ensures AFSC's activities are relevant, and participates in AFSC activities. AFSC engagement with AWFCG further ensures that its activities meet management research needs. In addition to its partnership with ACCAP and other boundary organizations, AFSC participates in national Arctic and wildfire-related research initiatives, such as the National Aeronautics and Space Administration (NASA) Arctic Boreal Vulnerability Experiment. AFSC staff also participate in scientific meetings and engage with visiting scientists.

c. *Outputs and activities*

AFSC contributes to science delivery and knowledge coproduction by hosting webinars and workshops, producing written products, and engaging in proposal writing. Webinars are especially effective at encouraging dialog among managers and scientists (Trainor et al. 2016). As another boundary spanner stated, ''I think the webinars are probably attended at least half by scientists.'' AFSC leverages ACCAP's expertise and enhanced webinar delivery capacity to reach a larger, geographically dispersed audience on fire-climate topics (Kettle and Trainor 2015; Kettle et al. 2017). These shared webinars have initiated new opportunities for AFSC. For example, one webinar on climate change and fire in Alaska hosted by ACCAP precipitated multiple presentations to the DOI, including the Secretary of the

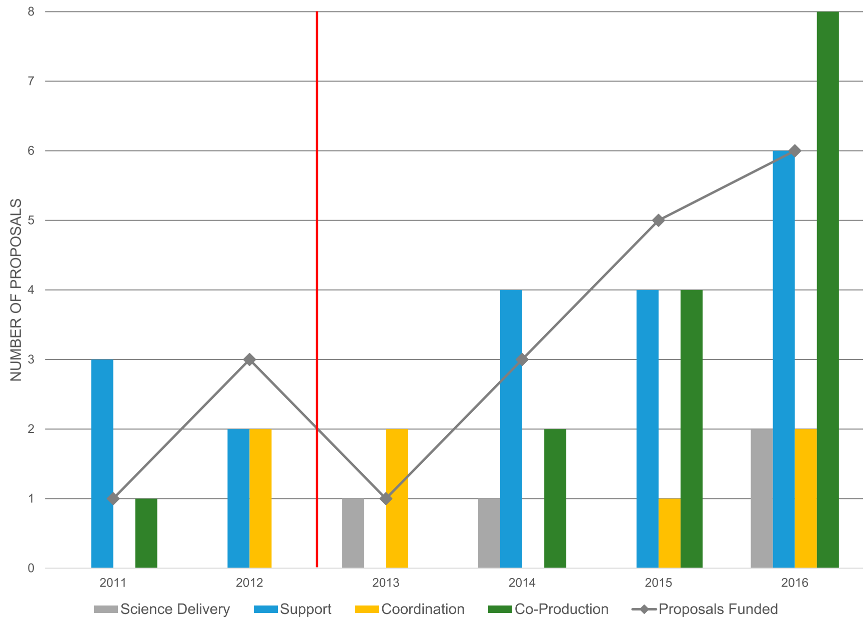

FIG. 2. AFSC involvement in research proposals. AFSC staff identified four levels of involvement in research proposals, classified by the level of coproduction in proposal development. Science delivery: AFSC was involved only in science delivery; Support: AFSC provided a letter of support for the proposal; Coordination: AFSC coordinated with the proposal's primary investigators and/or participated in writing proposal content but was not formally named on the proposal; Coproduction: AFSC staff were formally named on the proposal to provide support for their added capacity to the proposed research. All levels assume AFSC was involved in science delivery. The vertical red line represents the transition from the reactionary/awareness period to the proactive/research facilitation period (Table 4). This figure does not include AFSC renewal proposals to JFSP. There was no evidence of AFSC involvement in collaborative proposals prior to 2011. The 2011 proposal categorized as coproduction was submitted to JFSP for the ''In a Time of Change: The Art of Fire'' exhibition. This proposal is unique because it resulted in a highly coproduced art exhibition, but unlike the other proposals classified as ''coproduction'' it did not include funding to support AFSC staff (AFSC 2015).

Interior in 2016, and expanded AFSC's connections to national-level fire managers.

AFSC workshops occur in conjunction with semiannual interagency meetings and are codesigned with managers to deliver science, provide in-person engagement, and facilitate relationship building. AFSC's coordinator partners closely with the fire management community to organize and plan these meetings such that AFSC workshops have been integrated into the interagency meetings since 2014. One manager stated, ''the workshops that we've been able to have in conjunction with our spring and fall meetings, I think, do . . . not just provide information to the people who are going to use it immediately, but allow people who aren't at that level yet to kind of get some exposure to fire science.'' AFSC also hosts topical workshops to meet specific information needs. For example, the 2014 Canadian Forest Fire Danger Rating System (CFFDRS) Summit was coordinated by AFSC in response to requests by managers for more analysis regarding the application of CFFDRS in Alaska. AFSC conducts evaluations of all their events and uses the responses in future planning.

In addition to written outputs such as research briefs and blog posts, AFSC facilitates science delivery through the development of peer-reviewed articles. For example, in 2016, AFSC collaborated with ACCAP and AK CASC, fire and climate scientists, and fire managers on a paper for the *Bulletin of the American Meteorological Society*, which utilized attribution science to determine the extent to which the exceptional fire year of 2015 was due to climate change (Partain et al. 2016). AFSC coordinated the production of the paper by convening authors, facilitating collaboration, and contributing content.

AFSC also participates in collaborative research proposals in a range of modes, including convening scientists and managers in dialogue about new research,

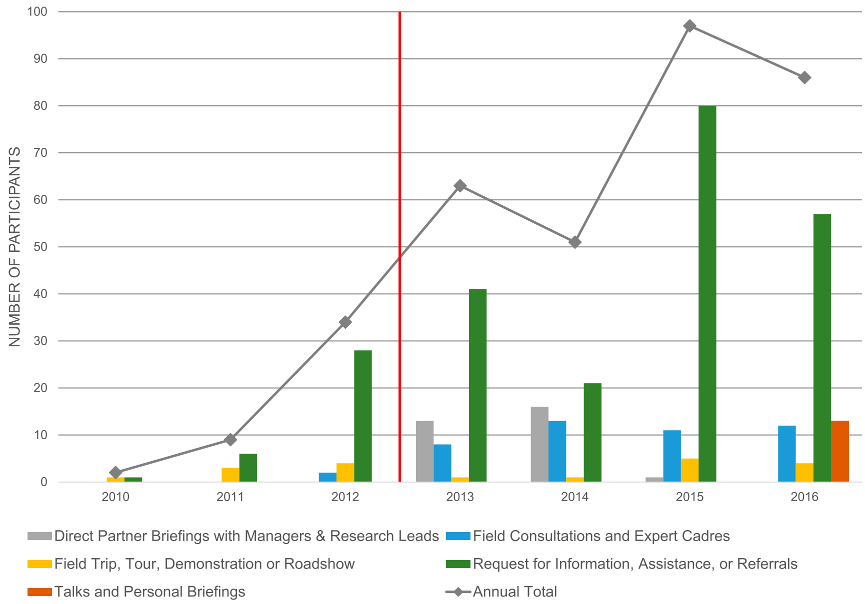

FIG. 3. AFSC staff interactions with their audience. Data in this figure are from the AFSC activities log, which is kept by staff members, include all AFSC activities, and are used for reporting to JFSP. This figure only includes activities representative of AFSC staff time spent in interactions with participants. These categories were established by the JFSP core office in 2010 and definitions have evolved over time. AFSC reporting was also imperfect. Nonetheless, the figure demonstrates an increase in staff interactions with participants in 2013. The vertical red line represents the transition from the reactionary/awareness period to the proactive/research facilitation period (Table 4).

writing letters of support, and serving as CoPI on proposals (Fig. 2). One manager said about collaborative proposals, "the opportunity to kind of help direct whatever project proposals and making sure that they're actually things that can be used by . . . people in the field . . . you're getting the links in the chain to make it meaningful." The number of funded proposals for which AFSC has been a PI or formal collaborator has increased since 2014. Since 2015, AFSC's proposal involvement has expanded beyond JFSP as funding agency to include NOAA, NASA, and the National Science Foundation (NSF). In 2016, a JFSP Task Statement highlighted Alaska as a regional focus, which led to AFSC's involvement in eight proposals. It is too early to assess the outcomes of these coproduced proposals, as much of the research is ongoing.

The relative frequency of AFSC's engagement with its audience and its activities has also shifted over time (Figs. 3 and 4). Initially, AFSC's focus was science delivery to build awareness of and interest in existing research. This is reflected in the emphasis on outputs like fact sheets, research briefs, and webinars. For example, the total number of research briefs grew steadily from 2009 to 2013 before declining (Fig. 4). This decline coincides with an increase in the number of collaborative proposals and the 2014 CFFDRS Summit, both of which required significant staff capacity. Direct engagement with fire managers and scientists shows a marked increase in 2013 (Fig. 3). AFSC's on-going production of outputs such as webinars and fact sheets and briefs demonstrate the ongoing work needed to maintain awareness of existing research even when shifting to more time-consuming activities like collaborative proposal development and workshops (Fig. 4).

d. Outcomes

As required by JFSP, AFSC created logic models for their renewal proposals after 2012. The logic models were created with input from the JFSP external evaluation team, AFSC's regular evaluations, and discussions with the AFSC advisory board. The 2012 (Fig. 1) and 2015 logic models were analyzed with a focus on outcomes related to behavior and societal conditions that provide evidence for the established elements of knowledge coproduction (Table 3) (Meadow et al. 2015). There were also desired outcomes related to behavior and conditions in 2012 and 2015 for which evidence of achievement has not yet been collected.

The logic models reveal that AFSC set knowledge coproduction as a deliberate and clearly articulated goal

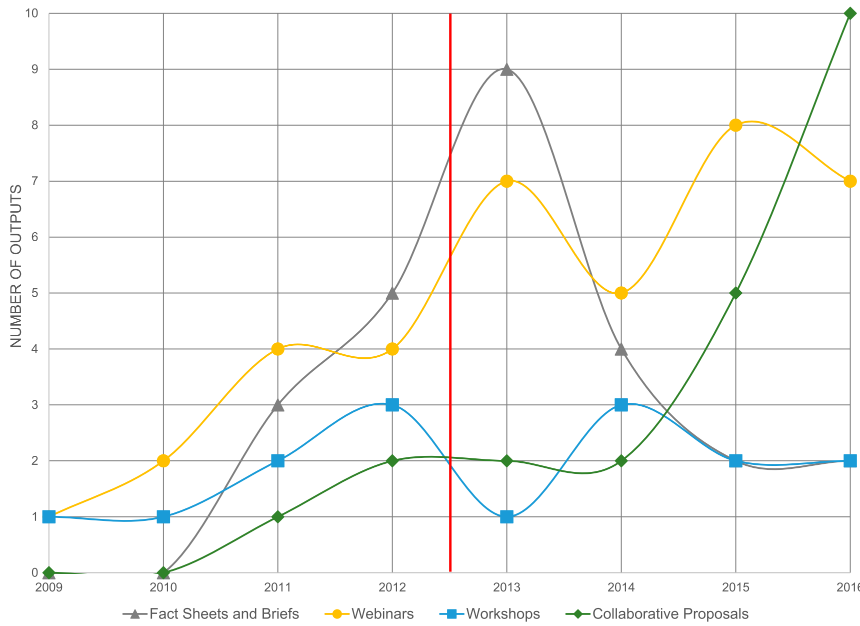

FIG. 4. Changes in select AFSC outputs and activities from 2009 to 2016. The vertical red line represents the transition from the reactionary/awareness period to the proactive/research facilitation period (Table 4). Collaborative proposals include those in the coordination and coproduction categories in Fig. 2.

in both 2012 (Fig. 1) and 2015. While it can be difficult to trace causality from logic model outputs and activities directly to outcomes (Funnell and Rogers 2011), data collected and analyzed here (Figs. 2, 3, and 4) provide evidence that numerous desired outcomes related to knowledge coproduction were accomplished. Table 3 presents the desired outcomes as stated in the AFSC logic models together with the evidence of achievement of these outcomes as reported in Figs. 2, 3, and 4.

e. *AFSC's historical periods*

AFSC's historical trajectory can be characterized by three key periods: the foundational period, the awareness-building (reactionary) period, and the research facilitation (proactive) period (Table 4).

In the foundational period, multiple preconditioning factors contributed to AFSC's emergence (Ferguson et al. 2014). Prior to AFSC's creation, existing relationships, ongoing interactions, and receptivity to the use of science in management set the stage for AFSC's initial focus on science delivery, including emerging science from Alaska. In the reactionary period, AFSC's activities focused on developing audience recognition, increasing awareness of existing science, and building relationships (Figs. 3 and 4). Although AFSC's staff were limited during this period, their preexisting relationships with the fire management and science communities allowed them to leverage existing networks (Lemos et al. 2014). During this period, AFSC's workshops served a convening function to create a forum for engagement between the management and science communities (Buizer et al. 2016). The webinars and fact sheets reflect a one-way information push model (Cash et al. 2006). Partly due to limited staff capacity and focus on science delivery, time spent engaged with participants was relatively low compared to later periods (Fig. 3).

The transition to the proactive period was initiated by shifting staff inputs, including the hiring of a new coordinator with experience in science facilitation and subject matter experts from the fire management community. New AFSC staff inputs created capacity that was vital to a new focus on knowledge coproduction (Bednarek et al. 2018; Brugger et al. 2016). This enhanced capacity allowed AFSC staff to spend more time building relationships with their participants (Fig. 3), as well as developing collaborative research proposals designed to coproduce new knowledge, while continuing to deliver existing science through webinars, workshops, and research briefs (Fig. 4). The transition between the reactionary and proactive periods is illustrated in the following quote by a past member of the AFSC core team, "We were almost kind of reactionary. . .we were trying to catch up to what everyone wanted. . .versus now, the Consortium has built their stakeholders, had these meetings, had these conversations, that allows you [i.e., AFSC] guys to be more proactive."

TABLE 3. AFSC achieved outcomes relevant to knowledge coproduction as articulated in the 2012 and 2015 logic models.

Logic model year	Outcome stated in logic model	Evidence of achievement
2012	Project consultations with AFSC	Activities log
	Scientists seek out identified research needs for projects	Proposal meetings
	Manager and scientist "coproduction of knowledge"	Submitted and funded coproduced proposals
	Research designed to meet regionally identified management research priorities	Submitted and funded coordinated and coproduced proposals
2015	Increased collaborative proposal submissions	Submitted coordinated and coproduced proposals
	Scientists are better prepared to extend their research to management application	Special topic workshops, coordinated and coproduced proposals
	Increased collaborative proposal success	Funded coproduced proposals
	Development of science/management partnership, functioning and productive "co-production of knowledge"	AFSC role in organizing fall and spring fire management meetings, submitted and funded coordinated and coproduced proposals
	Research designed to meet regional management priorities	Submitted and funded coordinated and coproduced proposals

5. Discussion

a. AFSC transition from science delivery to knowledge coproduction

AFSC's focus has deliberately shifted over time from a focus on science delivery to a focus on knowledge coproduction (Fig. 1). The trajectory of AFSC's activities and outputs in the proactive, research facilitation period demonstrates their shifting emphasis to knowledge coproduction. First, AFSC's involvement in collaborative proposals increased fivefold between 2014 and 2016 (Fig. 2). AFSC leveraged their trusted relationships to facilitate dialog, as well as establish and foster new relationships for collaborative proposal development (Brugger et al. 2016). Second, AFSC's outputs and activities began to place greater emphasis on iterative, two-way interactions (Meadow et al. 2015). AFSC's production of outputs like fact sheets and briefs peaked in 2013 (Fig. 4). This can be attributed to the considerable time investment needed for knowledge coproduction activities like collaborative proposals (Fig. 5) (Wall et al. 2017a). AFSC continued hosting workshops, which allowed for one-way science delivery, as well as relationship-building, and also became embedded in the fire management community's existing gatherings (Djenontin and Meadow 2018; Ferguson et al. 2014). Third, AFSC's facilitation of webinars increased (Fig. 4). These webinars increasingly fostered

TABLE 4. Key periods in AFSC's history as identified by AFSC staff during the historical scan and corresponding inputs from fire and scientific communities and AFSC staff. Each of these periods can be characterized by different inputs and characteristics. Inputs from the advisory board have remained relatively constant and are not included in this table.

Period	Community and staff inputs	Characteristics
Foundational (1990s–2008)	Fire management community members engaged in science	Strong historical context for science and management integration
	University staff engaged in management-relevant research	
Reactionary, awareness building (2009–12)	AFSC coordinator on intergovernmental agreement from BLM	Focus on building awareness and recognition of the program
		Relationship building
	AFSC principal investigator with expertise in knowledge coproduction	Delivery of existing scientific information
Proactive, research facilitation (2013–present)	New AFSC program coordinator with experience in scientific community	Focus on increasing scientist/practitioner relationships
	New AFSC fire ecology subject matter expert from fire management community	Increase in collaborative proposals to address new research needs and coproduce new knowledge
	New AFSC fire behavior subject matter expert from fire management community	Continued science delivery
	AFSC principal investigator with expertise in knowledge coproduction	

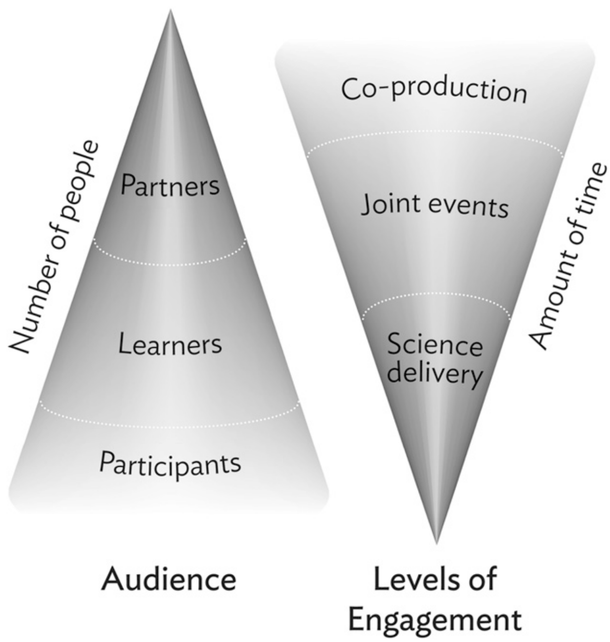

FIG. 5. Continuum of boundary spanning activities. There are multiple factors in this continuum: (left cone) audience type and degree of engagement and (right cone) types of activities together with time required. As you move along continuum from the bottom to the top of the diagram there are tradeoffs associated with the number of individuals served, level of engagement, type of activity, and time required. Thus, engaging partners in knowledge coproduction requires a larger time commitment and reaches fewer people than science delivery. (Source: AFSC subject matter expert.)

two-way dialog and featured managers. They also allowed AFSC to leverage trusted climate science knowledge from other boundary organizations like ACCAP to facilitate knowledge coproduction (Kettle and Trainor 2015; Lemos et al. 2014). Fourth, AFSC's involvement in the development of peer-reviewed articles illustrates their growing emphasis on knowledge coproduction (Knapp and Trainor 2015). The production of the Partain et al. (2016) paper on attribution of the 2015 fire season to climate change is illustrative of this. Fifth, AFSC staff spent increasing time engaging with managers and scientists (Fig. 3). This engagement was largely in person, which is critical for maintaining relationships and facilitating the iterative, two-way communication critical to knowledge coproduction (Colavito 2017; Meadow et al. 2015).

b. Continuum of boundary spanning activities

Analysis of AFSC's transition from science delivery to knowledge coproduction revealed a continuum of boundary spanning activities, including translation and communication of science, as well as building social capital, with activities and processes commonly used to support actionable science (McNie 2013). AFSC's activities included both one-way modes of engagement, such as science delivery that targeted a large audience and required minimal time to implement, as well as two-way engagement strategies that targeted smaller audiences and required higher time investments (Dilling and Lemos 2011; Djenontin and Meadow 2018).

Transitions in the frequency of specific boundary spanning activities across the continuum of engagement highlight multiple tradeoffs among the number of individuals served, level of engagement, and time required to support engagement activities (Fig. 5). Figure 5 was created by an AFSC subject matter expert in 2013 to facilitate discussion of proposed AFSC activities. It illustrates an explicit awareness of the trade-off between the number of people reached and the time investment required as the degree of engagement increases. The decrease in AFSC production of fact sheets and briefs and increase in collaborative proposals around 2013 illustrates this trade-off and an effort to increase knowledge coproduction activities (Fig. 4). The participant engagement and boundary spanning activities depicted in Fig. 5 are represented as a continuum, as there are often blurred boundaries among participant types and modes of engagement (Leith et al. 2018).

c. Barriers and challenges

AFSC has experienced challenges in their transition to knowledge coproduction especially due to their limited part-time staff capacity and a fire management audience who simultaneously wear multiple hats and are often stretched thin (Wall et al. 2017a). Other research has also documented that boundary organizations face a range of institutional challenges in developing and applying actionable science (Lemos et al. 2014). For example, reasons that scientific information is not used in management may not be due to intent on the part of managers but rather bureaucratic structures that make it difficult for managers to effectively articulate what kinds of information would be most actionable in decision-making (Esch et al. 2018; Owen et al. 2012; Wright 2010). Another core challenge in the evaluation of boundary spanning and use of logic models is the difficulty attributing identified societal impacts to any given activity or outcome or identifying causality (Funnell and Rogers 2011; Maletsky et al. 2018). Additional evaluation challenges include tracking longer-term impacts and identifying and understanding the use of science in decision-making (Ferguson et al. 2016; Hunter 2016).

d. Key factors in the transition from science delivery to coproduction

Knowledge coproduction requires several important elements including understanding the knowledge and decision-context of the user community, building trusted relationships, and remaining flexible and responsive to new opportunities and user needs (Djenontin and Meadow 2018; Kettle 2019; Lemos et al. 2012). Institutional support, funding availability and priorities, and changes in management also influence science delivery and knowledge coproduction (Leith et al. 2018; NOAA 2017). In this section, four interrelated key factors that facilitated development of these elements and the transition from science delivery to a focus on the coproduction of new knowledge in AFSC are summarized.

1) Receptive and engaged audience

AFSC emerged in the context of a fire management community that was aware of the importance of science for decision-making—often because they could not rely on information developed for the contiguous United States—and receptive to actionable science (AWFCG 2003; AWFCG 2008; Knapp and Trainor 2015). This receptive and engaged audience was an important preconditioning factor in AFSC's ability to transition from science delivery to knowledge coproduction (Ferguson et al. 2014). AFSC's emergence created a formal, agency-neutral structure that serves the convening, moderating, and facilitating functions of a boundary organization within this existing, receptive practitioner environment. The receptive and engaged audience enabled AFSC to work with AWFCG to advance manager-identified research needs. For example, research on the attribution of climate change to the 2015 fire season (Partain et al. 2016) contributed to understanding the climate linkages to past and present fire patterns, which was identified in the 2014 Research Needs List (AWFCG 2014). This receptive and engaged audience provided partners eager to participate in research opportunities, enabling AFSC to shift its focus from science delivery to knowledge coproduction.

2) Built-in evaluation and learning

AFSC's shift from science delivery to knowledge coproduction has been further supported by external evaluation and internal activities assessments, which have provided regular, iterative feedback from its audience since the beginning of the program (Maletsky et al. 2018; Singletary et al. 2015). The external evaluation team contracted with JFSP to work with the FSENs has assisted AFSC in building skills in evaluation delivery and analysis. AFSC's internal evaluations have provided a way for the AFSC audience to provide input and feedback on the value of AFSC programming. Informal, one-on-one conversations also allowed audience input on activities and programming (Fig. 3). AFSC used results from these evaluations to plan future activities, remaining flexible and responsive to audience needs. For example, numerous AFSC activities were a direct result of needs expressed in the evaluations (e.g., CFFDRS Summit, webinars and speakers for workshops, and the cultivation of coproduced proposals) (Figs. 2 and 4). This ongoing evaluation and communication provided AFSC's already receptive and engaged audience opportunities to contribute to AFSC's processes and outputs. It has also allowed AFSC's audience to better understand and describe their scientific information needs through regular feedback. The continuity of the evaluation structure has allowed AFSC to longitudinally track its outcomes over time.

3) Subject matter expertise and complementarity

Since its inception, the experience and expertise of AFSC core team members have spanned management and interdisciplinary science communities (Bednarek et al. 2018; Brugger et al. 2016). The fields of science that AFSC engages on behalf of meeting managers' needs span a range of disciplinary fields, including fire ecology, fire behavior, smoke modeling, climate science, and economics (see, e.g., Little et al. 2018; Rutherford and Schultz 2019). Social science research on the process of boundary spanning, such as this project, also informs AFSC activities and boundary spanning strategies. AFSC's first coordinator and current subject matter experts come from fire management careers, and the current coordinator previously worked in science administration. This experience conveys the necessary legitimacy to build trust with the management community (Pinkerton 2018). They have worked as a team, with each contributing their respective expertise and learning from each other. The AFSC core team's complementarity of experience in both the fire science and management communities in Alaska has been a significant factor in facilitating knowledge coproduction through a boundary organization (Evans 1996; Kettle et al. 2017).

4) Embeddedness in the target audience communities

With complementary experience, AFSC has become increasingly embedded in the fire science and management communities. The fire management community has included AFSC in the planning of their spring and fall interagency meetings, offering opportunities to integrate fire science presentations and dialog.

AFSC's Advisory Board members have also routinely suggested topics and presented in AFSC webinars. AFSC has served a ''secretariat'' role, meaning they are entrusted with administrative duties toward maintaining agency-neutral science–management partnerships (Buizer et al. 2016). With the increase in coproduced proposals, this secretariat role has expanded to bridge the science and management realms. AFSC's collocation with key players in the fire and climate science community has facilitated sustained, in-person interaction and contributed to embeddedness through science–manager relationships (Colavito 2017). Both complementarity and embeddedness have been identified as important elements of knowledge coproduction (Evans 1996).

e. Research limitations and suggested future research

Because AFSC is just one example of a boundary organization, a key study limitation is that it cannot assess the range of conditions under which boundary organizations operate. For example, AFSC operates in a stakeholder context with a receptive and engaged audience. Therefore, this study cannot analyze how a boundary organization that lacks this initial condition can work to promote knowledge coproduction. As such, the single case study approach used allows for rich contextual detail but cannot support broader generalizations across multiple boundary organizations or other natural resource sectors or regions. Furthermore, evidence of AFSC's shifting activities partly relies on a self-reported activity log that is inherently prone to human error.

Based on work to date, future research that seeks to understand how boundary organizations transition over time, range over varied contexts, or address boundary spanning when the key factors that facilitated AFSC's transition are not present is recommended. For example, additional case studies that compare boundary organizations working in fire management across regions can identify regional conditions such as audience receptivity, existing stakeholder networks, the constellation of land ownership, and ecological factors that may facilitate or impede knowledge coproduction. Conversely, future research that explores the activities of different boundary organizations working in the same region yet addressing different resource management areas such as fisheries, wildlife, or coastal management with associated climate impacts would elucidate how the awareness, assumptions, and institutional configuration of stakeholders, resource managers, and scientists vary by resource. This may shed light on how to build more integrated, interdisciplinary knowledge coproduction to address the spectrum of impacts of climate change.

Due to the difficulty of attributing causality from an organization's activities (Funnell and Rogers 2011; Maletsky et al. 2018), better methods are needed to identify and measure causal factors that lead to societal outcomes. Additional research is also needed to better understand knowledge coproduction across different epistemological boundaries, such as between scientists and Indigenous peoples (Kettle 2019; Trainor 2013).

6. Conclusions

This case study highlights the continuum of boundary spanning activities ranging from one-way science delivery through two-way knowledge coproduction. This analysis shows that boundary organizations are capable of simultaneously engaging in multiple activities along this spectrum, yet doing so involves trade-offs in time required for engagement and number of audience members reached (Fig. 5). The AFSC case study demonstrates that boundary organizations are capable of deliberately shifting their emphasis along this continuum over time to transition from a portfolio comprising primarily science delivery to one weighted toward knowledge coproduction. Key factors contributing to this transition were a receptive and engaged audience, built-in evaluation and learning, subject matter expertise and complementarity, and embeddedness in the target audience.

Based on the AFSC case study, three interrelated recommendations are proposed for boundary organizations or boundary spanners who intend to shift from science delivery to knowledge coproduction in their activities.

1) Know your audiences. Building trusted relationships is critical to successful boundary spanning (Bednarek et al. 2018). Having these trusted relationships in both the science and practitioner communities is critical for knowledge coproduction (Brugger et al. 2016; Safford et al. 2017). Knowing the specific decision contexts of the user community is a core prerequisite for knowledge coproduction (Trainor et al. 2019; Parris et al. 2016). Developing trusted relationships can facilitate the development of a receptive and engaged audience in instances where they do not already exist but does require a significant time investment (Wall et al. 2017a) (Fig. 5).
2) Employ trusted experts, rather than view boundary spanning as entry-level work. Successful knowledge coproduction requires expertise in both the subject matter and in the realities of practitioner demands and decision-contexts (Brugger et al. 2016; Djenontin and Meadow 2018). While it is critical to train early-career scientists and entry-level workers in knowledge coproduction, employing later-career or retired

individuals with considerable experience in practitioner realms can be an enormous asset.

3) Engage in frequent self-evaluation and adjust activities accordingly. Evaluation is a systematic process that requires a program to set goals, identify practices to achieve those goals, monitor and evaluate outcomes over time, and adjust to ensure goals are being met, with periodic re-evaluation of goals (Ferguson et al. 2016, Funnell and Rogers 2011; Maletsky et al. 2018; Singletary et al. 2015; Wall et al. 2017b). Frequent evaluation provides an awareness and a deliberate decision-context within which to situate boundary spanning activities along the spectrum of science delivery to knowledge coproduction. Soliciting audience input and acting on their recommendations is critical, and feedback should be solicited in multiple venues (Fazey et al. 2014). Audience feedback should be taken seriously and used as a guide for strategic planning.

Acknowledgments. This research was supported by the Alaska Center for Climate Assessment and Policy (ACCAP), a Regional Integrated Sciences and Assessments Team of the National Oceanic and Atmospheric Administration, Awards NA16OAR4310162 and NA11OAR4310141. Support was also received from Alaska EPSCoR NSF Award OIA-1208927 and the State of Alaska. We thank Randi Jandt, Tina Buxbaum, and Heather McFarland for their assistance with this research and manuscript, as well as the individuals in fire science and management in Alaska who participated in this study. We also thank the Joint Fire Science Program and the Alaska Fire Science Consortium for providing information for this research. Finally, we thank the anonymous reviewers for their thoughtful and constructive feedback.

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