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A case-study of wildland fire management knowledge exchange: the barriers and facilitators in the development and integration of the Canadian Forest Fire Danger Rating System in Ontario, Canada

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ABSTRACT

Background. Among the most successful examples of Knowledge Exchange (KE) between researchers and practitioners in Canadian wildland fire management is the development and integration of the Canadian Forest Fire Danger Rating System (CFFDRS) into operational use. **Aims.** Our aim was to identify key factors for this success. **Methods.** Through a case study, we investigated historical KE of two CFFDRS components in Ontario, Canada. We held semi-structured interviews with principal Canadian Forest Service researchers and Ontario fire management practitioners active in development and implementation of CFFDRS from the late 1960s to 2010s. **Key results.** The importance of both formal and informal facilitators to support KE was emphasised. **Conclusion.** Participants were most likely to associate successful implementation with informal facilitators such as personal relationships, shared field-based experiences, and opportunities for dialogue between researchers and practitioners. Critical to success were the credibility and soft skills of the knowledge brokers, early engagement, and consideration of training needs for end users in the design of products. **Implications.** This identification of factors that facilitated or hindered the development and implementation of CFFDRS can enhance the impact of research that will help wildland fire management deal with its present and future challenges.

Keywords: collaboration, fire behaviour, fire danger, forest fire, innovation, technology transfer, wildfire.

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Introduction

Across Canada and much of the world, the impacts of wildland fire are dramatically increasing (Bowman *et al.* 2020). Humans are striving to manage wildland fire under more dynamic fire regimes and with growing complexity (Coogan *et al.* 2019). The many challenges in managing fire and the research needs to help address these are well documented and summarised in the 'Canadian Wildland Fire Strategy – A 10-year Review and Renewed Call to Action' (Canadian Council of Forest Ministers 2016) and the 'Blueprint for wildland fire science in Canada (2019–2029)' (Sankey 2018). As the Canadian Wildland Fire Strategy states, 'the problems of the future will not be resolved by relying on the science of the past…'. The Blueprint (Sankey 2018) further speaks to the requirement for strong science and technological innovation with a priority for Knowledge Exchange (KE).

The process of KE is crucial for the successful development and integration of fire science and fire management. McFayden *et al.* (in press) provides a framework for KE for wildland fire management where KE is described as an overarching process in which knowledge is collaboratively created, shared and transformed through stages of problem

identification, enquiry, synthesis and application (Graham *et al.* 2006; Reed *et al.* 2014). For more details, see McFayden *et al.* (in press) and the references therein. Progressing through these stages is non-linear, with interactions between sub-systems of knowledge transfer, technology transfer, and interface facilitated by knowledge brokers. An important aspect of KE is that researchers and practitioners are recognised as both knowledge producers and users with a bi-directional flow of knowledge between them (Roux *et al.* 2006; Davis *et al.* 2013; Reed *et al.* 2014). Progress and retrogress between the stages of KE is influenced by the research and development cycle but also by Barriers and Facilitators (BF).

An important task of KE is identifying and understanding the significance of BF (Ryan and Cerveny 2011; Davis *et al.* 2013; McGee *et al.* 2016; Hunter *et al.* 2020; Tedim *et al.* 2021). Other disciplines have explored these BFs, such as conservation (e.g. Walsh *et al.* 2019), health practices (e.g. Mitton *et al.* 2007) and forest management (D'eon and MacAfee 2016). Recent studies of KE in wildland fire management have also taken place (e.g. Hunter *et al.* 2020; Tedim *et al.* 2021) with others looking at specific decision support system adoption and perspectives (e.g. Martell 2011; Noble and Paveglio 2020; and Rapp *et al.* 2020).

McFayden *et al.* (in press) provides a summary of nine overarching themes of BFs organised from literature and focused on wildland fire management which include: (1) readiness for innovation; (2) collaboration and networking; (3) communication; (4) capacity; (5) ownership and authority; (6) timing; (7) research motivation; (8) clear objectives and alignment; and (9) trust. However, other studies note that research use (and corresponding BF) is fluid and context-dependent (Nutley *et al.* 2007) making it difficult to identify universal themes.

To improve our understanding of BF in a focused Canadian fire management context, we look at one of the most successful implementations of wildland fire science in Canada – the Canadian Forest Fire Danger Rating System (CFFDRS). This case study focused on the CFFDRS's uptake into operational fire management in the province of Ontario. The aim is to allow us to refine our understanding of the key elements that were part of that successful KE to inform KE strategies for future innovations for Canadian fire management agencies.

Introduction to Canadian Forest Fire Danger Rating System (CFFDRS)

The CFFDRS is the fire danger and behaviour system integrated into Canadian fire management agencies' practices (Taylor and Alexander 2006). The CFFDRS was conceptually designed with four modules: (1) the nationally implemented Fire Weather Index (FWI); (2) the Fire Behaviour Prediction (FBP) System; (3) the incomplete Fire Occurrence Prediction (FOP)[1]; and (4) Accessory Fuel Moisture Systems.

The FWI System accounts for the wetting and drying of fuel and produces three fuel moisture codes, namely the Fine Fuel Moisture Code, the Duff Moisture Code, and the Drought Code. These codes relate to the actual fuel moisture (i.e. the higher the code the drier the fuel). There are also three indices that reflect aspects of fire behaviour in a mature Pine fuel type, these are the Initial Spread Index, the Build Up Index, and the Fire Weather Index (Van Wagner 1987).

The FBP System builds on elements of the FWI System and provides quantitative outputs of various aspects of fire behaviour (e.g. fuel consumption, fire spread rate, fire intensity) in a number of major Canadian fuel types (Forestry Canada Fire Danger Group 1992). These two Systems (the FWI and FBP) form the core of the CFFDRS.

Background on CFFDRS development

The CFFDRS development was led by the Canadian Forest Service (CFS) with roots in field-based fuel moisture and ignition studies that began in the 1930s at the Petawawa Forest Experiment Station in Ontario (Wright 1933). Canada's fire hazard and danger rating methods developed over the decades (Wright 1933; Wright and Beall 1938; Beall 1948; Canadian Department of Northern Affairs and Natural Resources Forestry Branch 1957) the first edition of the FWI System, designed to be a single system used universally across Canada (Muraro 1968), released for fire management agencies in 1969–1970 (Van Wagner 1974).

From the 1960s to the 1990s, the CFS fire research program carried out a large-plot experimental burning program collaboratively with local fire management agencies, which focused on collecting the observations that formed the foundation of fuel type specific models of fire behaviour. Most of these experimental burns occurred in Ontario, Alberta, and British Columbia. The resulting models were assembled within what became the FBP System, which was released in 1992 (Forestry Canada Fire Danger Group 1992).

The importance of assessing day-to-day changes in fire potential has led other jurisdictions to also develop similar fire danger rating tools (e.g. the National Fire Danger Rating system (NFDRS; Deeming *et al.* 1972) in the United States (Deeming *et al.* 1972), and the Australian Forest Fire Danger Index (McArthur 1967) and Grass Fire Danger Index (McArthur 1966). The CFFDRS has been used by all Canadian fire management agencies in Canada for more than five decades and has been adopted and adapted into other countries to aid in wildfire planning and prevention activities (e.g. New Zealand, Argentina, Indonesia, Malaysia). Taylor and Alexander (2006) outline a more detailed history

[1]It is important to note that the FOP System has had independent research and been implemented regionally. For example, Woolford *et al.* (2021) document the development of human-caused FOP along with Wotton and Martell (2005) lightning-caused FOP models for Ontario.

of the development and use of CFFDRS nationally and internationally.

Ontario's fire management agency's decades long collaboration with the CFS' Great Lakes Forestry Centre and involvement in the large plot experimental fire burn program (which supported FBP System development) make it an ideal location for a case study where there was dedicated practitioner and researcher collaboration to explore the factors that led to the successful development and implementation of CFFDRS.

Methods and analysis

To capture the complexity of the case study, interviews were held with 14 participants who were identified through Ontario Ministry of Natural Resources and Forestry (MNRF[2]) and CFS networks. Participants were selected because of their involvement in the development or implementation of the FWI or FBP Systems in Ontario. Participants were comprised of those who had, during their career, been either researchers at CFS or in leadership and influential roles at the Ministry. Participants represent a period in FWI and FBP System development and implementation from the late 1960s to 2010s. A social constructivist lens (Creswell and Creswell 2018) was applied to develop research methods that effectively collected the complex views of participants and allowed them to connect their experiences to understandings of KE. An exploratory sequential mixed method approach (Creswell and Creswell 2018) was used to offer a KE framework to participants that they could evaluate and relate back to when describing their experiences.

All participants completed a short questionnaire prior to their interview that introduced them to the purpose of the project and the deductive overarching themes of BF summarised in McFayden *et al.* (in press), which they also ranked on a five-option Likert scale (Joshi *et al.* 2015) of overall importance in the development and implementation of CFFDRS in Ontario.

Interviews with each participant were guided by two of the authors who represent current CFS research and Ministry practice. The interviews were used to gain perspectives of the participants' views on KE, to understand each participants role in KE; characterise the state of CFFDRS during their time of involvement; and understand to what degree KE took place. The interviews were semi-structured (described in Given 2008) to promote informal and genuine conversations and participants were encouraged to speak openly to capture and explore new and emerging themes. The use of interview elicitation is common for many topics in fire management (e.g. Hirsch and Martell, 1996; Brummel *et al.* 2010; Thomas *et al.* 2015; McFayden *et al.* 2019; Noble and Paveglio 2020; Rapp *et al.* 2020).

All interviews were held virtually because of COVID-19 health restrictions. With informed consent and permission, interviews were recorded and transcribed through voice-to-text software. Transcripts were reviewed and edited to clarify transcription errors and uploaded to qualitative software for analysis. Interviews were planned for 1 h; however, there was no restriction on time and interviews ranged from 1 h to 1.75 h.

Analysis

Using NVivo qualitative analysis software, a content analysis >was performed through a hybrid approach of mixed inductive–deductive coding to organise data and compare responses. Interview transcripts were first coded deductively and themes derived from an analysis of the pre-existing literature (see McFayden *et al.* in press) were matched to sentiments expressed by participants during their interviews. Next, interview transcripts were explored inductively to determine emerging themes and ideas participants described that were not emphasised through our literature review. The resulting BFs were refined through careful reading and re-reading of the data to gain a holistic understanding of what participants were saying, recognise emerging patterns, and ensure all vital aspects of the data were captured (similar to coding described in Azungah 2018). The first round of coding was completed by an author who is a social scientist with iterations between fire science researcher and fire management practitioner authors. The perspectives for each BF were derived by the authors recalling the literature review, the interviews, and quotes identified through the coding.

Results

In total, 14 respondents (100%) completed the pre-interview questionnaire, with three identifying as researchers and 11 identifying as practitioners. Each participant generally put similar weighting to each of the overarching BF themes (from McFayden *et al.* in press). The order of importance of the themes determined through the Likert survey responses were: (1) communication; (2) capacity; (3) collaboration; (4) readiness for innovation; (5) trust; (6) clear objectives and alignment; (7) timing; (8) research motivation; and (9) ownership and authority (Fig. 1). However, as one survey respondent commented in the follow-up interview,

> I probably could have marked everything as "very important". I think what was effective in developing and implementing the CFFDRS in Ontario was the willingness of the Ontario Fire Management program to support the developmental research and to have the internal capacity

[2]The Ministry of Natural Resources and Forestry (MNRF) had several names through our study period including Ministry of Natural Resources (MNR) and Department of Lands and Forests. For consistency in the paper we use 'Ministry'.

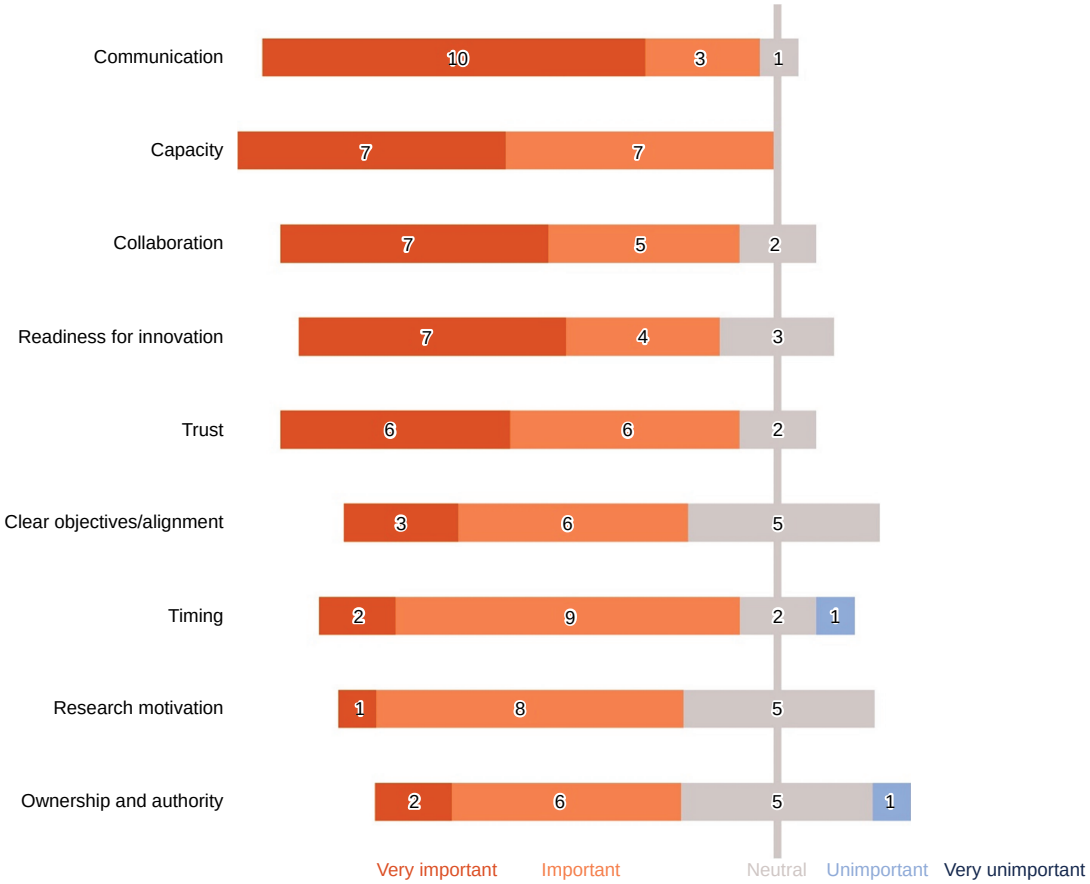

Fig. 1. Perceived importance of overarching themes of facilitators of knowledge exchange elicited from the introductory survey completed by 14 respondents. The facilitators are ordered from most to least important top to bottom as indicated by the responses.

> to carry out the technology transfer for the system components (FWI System, FBP System, etc.). I think also the collaboration and the trust between the operational [fire management] agency and the research people was key…

The following section will outline the key BFs emerging from the interviews organised under the nine overarching themes, which are summarised in Fig. 2. We include a perspective for each theme with detailed perspectives and select quotes for the individual BF in the Supplementary Material Part A (available online). We recognise that in our identification of the BFs there are dynamic interactions between them (Nutley *et al.* 2007), which is inherent across all the themes which can lead to duplication and overlap of ideas (for example, factors that support communication can support trust and visa versa).

Theme 1 – communication

Through the surveys, communication was identified as the most important theme by project participants, with 10 participants identifying communication as 'very important', three identifying it as 'important' and one 'neutral'. During the interviews, the importance of regular informal communication was a recurring theme, with participants saying that they benefitted from building 'close working relationships' and being able to call [colleagues] up by telephone or say, 'I'm coming up… can I pop in and talk with you?'. Although many participants acknowledged that there was value in formal meetings and collaborative agreements, several said these were second in importance to the informal communication.

Time is required to develop the relationships needed to support ongoing informal communications. In the case of researchers working on the FWI and FBP Systems, they were given significant fire management agency support to engage in developing those relationships; for example, travelling to different Ministry offices and participating in Ministry-led initiatives. The relationships that developed allowed Ministry field personnel the confidence to informally call up a lead researcher and discuss some aspect of the FWI and FBP Systems, or similarly for a researcher to ask about some aspect of fire management. Participants noted that this type of inter-personal communication improves the relationship and

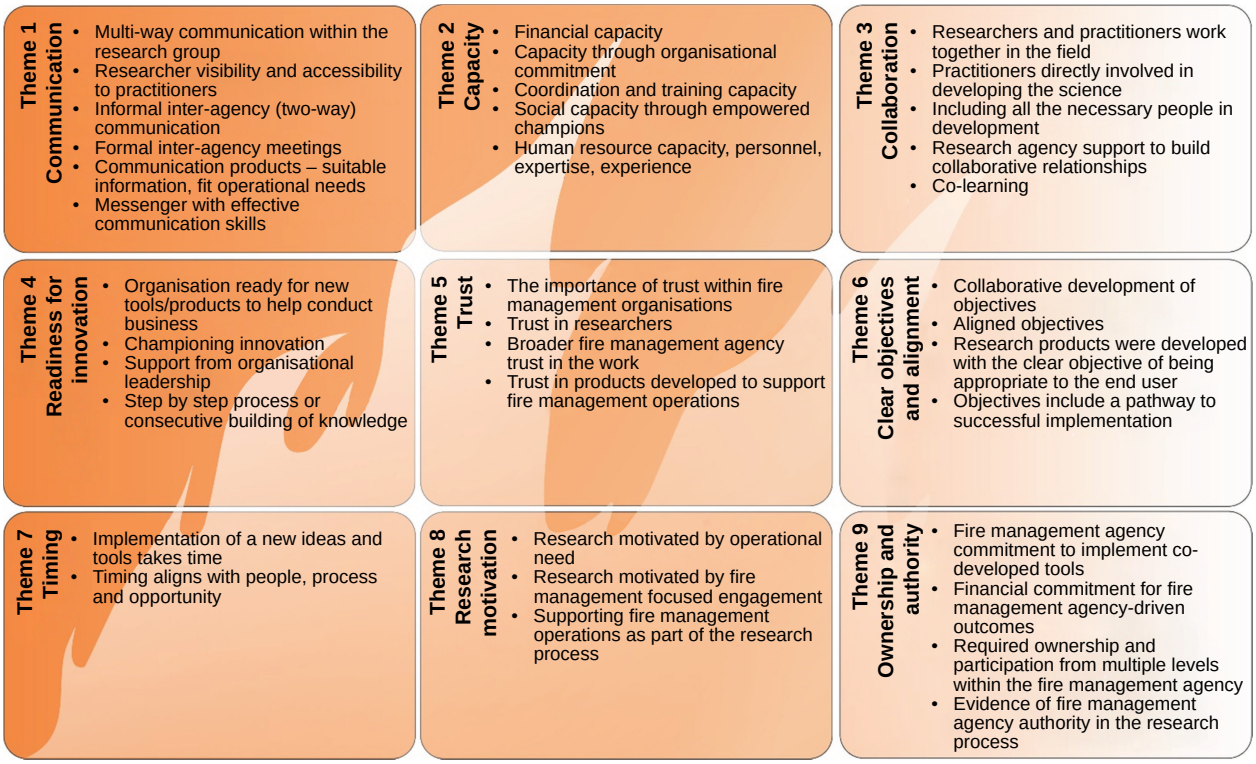

Fig. 2. Summary of the overarching themes from McFayden *et al.* (in press) and those barriers/facilitators identified through the participant responses.

ultimately engenders the trust needed to share their thoughts openly. It was also noted that those with the personal attributes to communicate and act as intermediaries between researchers and practitioners, were important. As one participated noted: 'I don't think that everybody can do it. [Those leading the KE] need to deliver it using language that colleagues [can understand]…'. Researchers working on the FWI and FBP Systems dedicated a significant amount of time to fieldwork and prioritised in-person communication with those involved in fire management operations.

The BF identified for this theme include: (1) multi-way communication within the research group; (2) researcher visibility and accessibility to practitioners; (3) informal inter-agency (two-way) communication; (4) formal inter-agency meetings; (5) communication products – suitable information, fit operational needs; and (6) messenger with effective communication skills. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A1 (available online). Early, interactive, and ongoing communications are important and support by relationships as one participant noted:

> You need to have involved the people that you hope to use [the research outcomes] in the end involved early on. And you need to give them some kind of information along the way. … You need to use some tool that brings the practitioners and the researchers together. Just so the people in the field don't think that everything's going on in a void and they're just going to get this thing dumped on their lap someday … because that means it's not it's probably not going to work.

Theme 2 – capacity

Survey results for capacity were evenly split between 'very important' and 'important', with seven respondents each. Capacity was described by one interview participant:

> I have an expression that I've used for a long time that there's the three C's you need; cash, commitment and capacity, to get anything done. You've got to put some money on the table to make things happen; you have to have a commitment to go through [with] it…and, you've got to have people ready for it when the science comes together.

The research programs that developed the FWI and FBP Systems were described by study participants as being well-funded and well-supported as a high priority at the organisational level, in both CFS and the fire management agency. Researchers leading the projects were well established, had credibility within fire management circles, and a network of support. There was also commitment for coordination and training capacity associated with the FWI and FBP Systems.

The KE and subsequent buy-in on the operational side was successful partially because of the number of knowledge brokers (as defined in McFayden *et al.* in press) associated with the development and implementation of the systems and their personal capacities to share information effectively. The BF identified for this theme include: (1) financial capacity; (2) capacity through organisational commitment; (3) coordination and training capacity; (4) social capacity through empowered champions; and (5) human resource capacity, personnel, expertise, experience. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A2 (available online).

Theme 3 – collaboration

The importance of collaboration ranked relatively high, with seven survey respondents identifying it as 'very important', five participants identifying it as 'important', and two indicating they were 'neutral' to the importance of collaboration. The 'collaborative spirit' of the work to build the FWI and FBP Systems was a common theme in the interviews. Supporting collaboration throughout the research process resulted in more effective KE and buy-in as research products were released. During the development of the FBP System, CFS researchers were very engaged in Ontario's fire program and visited, learned, and established priorities based on feedback from the Ministry.

Collaboration was often brought up in the interviews around the joint field work such as the fire behaviour data collection that would eventually contribute to the FBP System. Fire management agency collaboration in the research process created broad acceptance among operational users and belief that the science that underlined the models in FBP System was sound and could be relied upon to inform operational decision-making. The collaboration extended beyond operations staff to research coordinators and managers. There was support from both the CFS and the Ministry to build the research programs and work collaboratively to achieve meaningful outcomes. The collaboration from both agencies extended to the dissemination and training associated with the research products. This collaboration came in many forms, as indicated by one interviewee:

> CFS fire researchers collaborated with each other and directly with fire management agencies, especially agency fire management leads, while keeping research managers informed. Agencies were involved in research planning and prioritization, facilitated data collection (including monitoring of large wildfires), and funded and helped carry out the large experimental burning program essential to the development of the FBP System.

The BF identified for this theme include: (1) researchers and practitioners work together in the field; (2) practitioners directly involved in developing the science; (3) including all the necessary people in development; (4) research agency support to build collaborative relationships; and (5) co-learning. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A3 (available online).

Theme 4 – readiness for innovation

Seven participants evaluated readiness for innovation as 'very important', four evaluated it as 'important', and three participants listed readiness for innovation as 'neutral' for facilitating KE. From the interviews, organisational readiness was highlighted as an important precursor to KE and supporting innovative changes. In the case of the FWI and FBP Systems, interviewees often mentioned that these systems filled a need to better assess operational safety for fire management. These innovations were not just incremental improvements, multiple participants mentioned they were addressing a clear 'void' where there largely was no existing system. For example, the FBP System (as delivered in 1992) addressed a well-accepted need that was pre-identified by its user community. The Systems shaped through eager partnership with the end-user community, whose readiness to use the Systems developed alongside the development of the Systems. Research outcomes were produced incrementally, and the end users were able to follow along with the development with interim products, supporting better knowledge and technical transfer and therefore trust in the products. Technology posed both opportunities and challenges for innovation, but, because products were developed incrementally (e.g. from simple printed material to computers software), practitioners were more willing to adopt with technology. As one participant noted:

> There was a staged implementation of a simple methodology that grew into a more complex methodology and people could see the progression. In the first implementation, the rough rates of spread, people said, 'oh, they can figure out rates of spread,' and then that evolved into a very simple system and they said, 'okay, this makes sense, we can apply it in a broader range.' People can apply it… it just makes sense how it all falls together; it's very logical. … If you just come out with the final system … I think it would have been a lot less successful. People would have been very intimidated by it and just set it aside and said, 'later, maybe.' But the staged implementation, I think facilitated its overall acceptance.

The BF identified for this theme include: (1) organisation ready for new tools/products to help conduct business; (2) championing innovation; (3) support from organisational leadership; and (4) step-by-step process or consecutive building of knowledge. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A4 (available online).

Theme 5 – trust

Trust was evaluated by participants as being important, with six respondents identifying it was 'very important', six identifying it was 'important' and two respondents being 'neutral' to the importance of trust. Recalling the interactions in BF, 'trust' is arguably a function for and requirement of many factors (e.g. collaboration, communication). For example, the importance given to informal communications is a way of saying relationships are key, which implicitly covers trust. This could explain why trust was weighted as a lower importance, because it permeates many of the themes ranked higher. During the interviews, the theme of trust was repeatedly emphasised as important for KE. Several interviewees highlighted that trust is vital in a fire management organisation where the health and safety of operational personnel and the public are of critical importance. The pace and high stakes nature of the fire program requires trust in the information and tools being used to support decision-making. Participants not only highlighted the importance of trust within fire operations, but how that trust needed to extend to research, researchers and the associated products produced. Trust had to be gained at key organisational levels, including operations and management. Similarly, in the case of the development of the FWI and FBP Systems, trust in individual researchers also had to be earned and not bestowed by their organisational affiliation. This grew out of three key components: (1) their extensive experience on wildland fires; (2) their extended interactions and reputation with working-level Ministry fire practitioners; and (3) their engagement in a process that sought practitioner feedback, insight and advice during the development and testing of research products. In the case of the FWI and FBP System work, it was important that tools were used to help practitioners to work through the methodologies themselves to gain trust. Examples include the FWI System workbook tables (Canadian Forestry Service 1984) and the tables in the 'Red Book,' a Field Guide to the Canadian Forest Fire Behaviour Prediction System (Taylor *et al.* 1996). The following quote by one of the participants sums up trust well:

> There needs to be that trust with the organization that developed [the product] and in the person who's in the program who has to deliver it and explain it. And they have to be able to say, "This is credible research; I know the people who did it. They based it on X, Y and Z, and I really think this will help." It just helps bring the masses up to speed … and [builds] that trust.

The BF identified for this theme include: (1) the importance of trust within fire management organisations; (2) trust in researchers; (3) broader fire management agency trust in the work; and (4) trust in products developed to support fire management operations. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A5 (available online).

Theme 6 – clear objectives and alignment

In the questionnaire, three participants identified clear objectives and alignment to be 'very important', six identified it as 'important', and five were 'neutral' to the importance of clear objectives. Although alignment between fire management agencies and research organisation was important in terms of establishing a set of common research priorities, it was clear from the interviews that pre-defined final deliverables, at least initially, was not as important. Researchers worked iteratively, to develop a responsive research program with beneficial outcomes to fire management overall. This iterative process relied heavily on ongoing interaction with fire management field staff, which was supported by their respective higher-level management. From the interviews, it was apparent that the principle objectives of the CFFDRS, research programs were focused on appropriately reflecting the needs of fire management practitioners and ensuring effective KE. Ministry fire management practitioners were engaged in and informed that research process. There was also significant time and effort invested in KE among researchers, facilitators, and trainers among the multiple agencies and within the Ministry to ensure the FWI and FBP Systems were adopted. As identified by one participant, a truer understanding by both parties (which forms objectives) is needed to be successful.

> I think you understand the need to bring the people along on both sides of the table and bring them together and get them talking so that things work. … [Researchers] have thought they had the greatest model and the greatest analytical tools, but it is important to develop it in a way that it is what the [end user] wants to use it and it's in a format that they can use.

The BF identified for this theme include: (1) collaborative development of objectives; (2) aligned objectives; (3) research products were developed with the clear objective of being appropriate to the end user; and (4) objectives include a pathway to successful implementation. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A6 (available online).

Theme 7 – timing

Although timing was thought to be important, it was less important than some of the other themes for ensuring successful KE. Overall, two participants identify that it was 'very important', nine participants responding it was 'important', two participants 'neutral' to its importance, and one respondent identifying that it is 'not important'. From the interviews, it was understood that the process for the integration of new ideas and products into sustained operational use takes a significant amount of time even where there is a clear need. Two key elements of the timely uptake of new science-based products appear to be the personal readiness

of the staff who are potentially adopting it into their day-to-day fire management activities and the organisation's technological readiness to apply the innovation. The lack of either of these elements in an organisation can result in diminished early adoption, inhibiting the innovations spread to most users. The FBP System research program offered early outputs for interim evaluation (and to motivate feedback), which succeeded in creating a foundation of readiness (and a core of local champions) for the organisation to get new products and tools out to a wider audience.

Another consistent comment from the interviews related to timing with the FWI and FBP Systems was the impression that the 'stars aligned' – that the timing was perfect. CFS researchers were encouraged to work on Ontario-specific research questions, there was a capable and credible group of researchers working on the projects. Those researchers had well-established, interpersonal relationships with provincial fire managers, and collectively were engaged in each other's work and committed to sharing ideas and innovations. It may have taken much longer had any of those elements not occurred or been available within the same period.

The BF identified for this theme include: (1) implementation of new ideas and tools takes time; and (2) timing aligns with people, process and opportunity. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A7 (available online).

Theme 8 – research motivation

Although evaluated as important, research motivation was determined to be the eighth most important theme for KE in the survey; just one respondent characterising it as 'very important', eight evaluating it as 'important' and five respondents describing it of 'neutral' importance to KE. During the interviews, however, participants described several themes that relate to research motivation as a mechanism to ensure the success of research products and KE. With both the FWI and FBP Systems, alignment between research objectives and operational objectives was critically important to the success of the KE for these products. Researchers who were motivated to build collaboration with fire management staff into their research process, consequently built the credibility within fire management circles. The accessibility of researchers and supporting fire management practitioners during the research process was highlighted as a very important factor. Participants also discussed the fire management agency's role in driving research motivation by incentivising it through appropriate funding and support and the interactions to ensure their research products are applicable and appropriate for implementation, for example one participant stated:

> [As a researcher,] I think really if you're collaborating with each other with the idea that the sum is more than the parts you'll get something out of it collectively that makes it better. I think that's the important way to go at it and it requires trust… [As a researcher,] you're not collaborating on something …because you're going to get a paper out of it; you're collaborating because you have common interests there and usually what that generates are some different ways of looking at things.

Several study participants highlighted that, over time, research motivation had changed causing the research to become less fire management operations focused. The BF identified for this theme include: (1) research motivated by operational need; (2) research motivated by fire management focused engagement; and (3) supporting fire management operations as part of the research process. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A8 (available online).

Theme 9 – ownership and authority

Overall, participants suggested that ownership and authority is important for KE, although it was not as important as the other criteria; two participants responded that is was 'very important', six responded that it was 'important', five respondents were 'neutral' to the importance of ownership and authority, and one stated it was 'unimportant'. During the interviews, participants identified several themes suggesting that ownership and authority was important for KE. The importance of commitment to develop tools to support decision-making was described and the feelings of ownership in the research. To develop the FWI and FBP System products, the CFS and the Ministry committed significant time and resources to collecting data used in that research and consequently had authority and ownership.

The BF identified for this theme include: (1) fire management agency commitment to implement co-developed tools; (2) financial commitment for fire management agency-driven outcomes; (3) required ownership and participation from multiple levels within the fire management agency; and (4) evidence of fire management agency authority in the research process. For detailed perspectives on each BF and select attributed quotes, see Supplementary Material Part A9 (available online).

Discussion

There are some key similarities and differences from the BFs presented in the literature, and those from the case study. Communication challenges associated with traditional academic language and jargon are described in the fire management literature (e.g. Ryan and Cerveny 2011; Davis *et al.* 2013) and beyond (e.g. Mitton *et al.* 2007). In the FWI and FBP system case, participants identified that communication products need to be developed with the practitioner (end user) in mind and therefore, the knowledge and technical transfer challenge is broader than the language used. It

includes the types of products developed and how they are shared with practitioners. While others (e.g. Davis *et al.* 2013; McGee *et al.* 2016; Noble and Paveglio 2020) describe the importance of face-to-face exchanges and in-person engagement, results from the FWI and FBP case suggest these in-person communications need to extend to operational and field-based activities where researchers engage with fire management practitioners during their day-to-day operations. Participants also described the importance of having a messenger with effective communication skills, which was also identified to be important by Mitton *et al.* (2007).

As in the FWI and FBP case, the importance of sufficient resources to support KE is widely identified in the literature (e.g. Ryan and Cerveny 2011; Davis *et al.* 2013; McGee *et al.* 2016). The importance of training capacity was also evident in the FWI and FBP case and literature (Noble and Paveglio 2020; Rapp *et al.* 2020). The importance of champions for facilitating the KE process was well described by study participants but not as well described in the fire management literature to-date. Champions were identified by participants as vital to KE as well as the successful implementation of both the FWI and FBP systems.

While other studies describing KE discussed the importance of a network and the development of collaborative research partnerships (e.g. Mitton *et al.* 2007; McGee *et al.* 2016), responses from participants in the FWI and FBP case focused more on the informal aspects of collaboration, including ensuring that the right people are included, they can work together and co-learn, with many participants suggesting that informal communication and collaboration may be more important than formal networks and collaborative agreements. Research related to the FWI and FBP Systems was motivated by operational needs and providing relevant new knowledge to practitioners. As suggested by others (Ryan and Cerveny 2011; Davis *et al.* 2013), this is an essential facilitator to KE in wildland fire management. The issue of various reward systems creating misaligned goals for researchers and practitioners has also been identified in the literature (Ryan and Cerveny 2011; McGee *et al.* 2016) as potential BF to KE. At the time of the development of the FWI and FBP systems, researchers and practitioners were encouraged to work together to address operational challenges in wildland fire management as mutual incentive.

However, as study participants have suggested, these mutual incentives can diverge over time if the conditions are not maintained. Participants emphasised the importance of trust within a fire management organisation to adopt or implement science generally because of the fast pace and high-stakes decision making that takes place within the organisation. This organisational environment demands a high-level of trust and credibility from researchers and products developed based on the research. Those involved in fire management organisations commonly want to be able to verify the information from a researcher or tool, and only through doing this will new innovations be implemented. Although high-level agency support, high user involvement (Noble and Paveglio 2020) and readiness for change (Mitton *et al.* 2007) are important facilitators for innovation, study participants highlighted the importance of an incremental step-by-step process to implementation to ensure practitioners understand and appreciate the new information and tools developed. This was identified as a key facilitator in the broad adoption of the FWI and FBP Systems.

While formal, higher-level ownership and authority, including collaborative research agreements, memorandums of understanding, and formal funding agreements, were described by case study participants as important for facilitating KE, many participants also identified the importance of the sense of ownership which extends from those researchers and practitioners working together to develop new innovations on the ground. In the FWI and FBP systems, the feeling of ownership supported the development of system champions and supported operational buy-in for the research and associated products.

Although other papers have emphasised the importance of clear objectives and goals to support knowledge and technical transfer (e.g. Noble and Paveglio 2020), the importance of maintaining an open and iterative dialogue between researchers and practitioners throughout the initiative from problem identification to implementation, was described by participants as being even more important. This means that objectives may change over time, but all parties had to be involved as the projects evolved. Transparency and alignment with the needs of the end user were described by participants as best fostering KE.

Enhancing future fire management innovation can be supported through a sound KE approach. For example, the efforts to update the core components of the CFFDRS (Canadian Forest Service Fire Danger Group 2021) and to support the WildFireSat initiative (Jackson and Johnston 2020; Johnston *et al.* 2020; Government of Canada 2022). These two initiatives recognise the importance of KE, which are outlined further in the Supplementary Material, Part B (available online). KE strategies tailored to collaborative teams have been successful in Canada in similar areas such as forest management (e.g. D'Eon and MacAfee 2016).

This retrospective case study investigated the development and implementation of the FWI and FBP Systems in Ontario to focus a Canadian lens on the nature of barriers and facilitators to KE in fire management from both the researchers and practitioners involved. We believe these observations are generally applicable across Canada since Canadian fire management agencies have similarities and have the shared experience of implementing the national FWI and FBP Systems at the same time. However, we also recognise that each of the fire management agencies across Canada have varying mandates, policies, strategies, and practices (see Tymstra *et al.* 2020) and consequently, there may be

important differences and BFs introduced through the different fire management agency organisational structures (Damanpour and Gopalakrishnan 1998). Furthermore, we have not directly discussed the interactions between organisational and individual factors, which have been variously shown to predict attitudes towards and actual use of technological innovations (Devaraj *et al.* 2008). Workplace cultures are not static and evolve over time, people leave or change roles and technology changes which may not be reflected by a retrospective look at KE. As noted by the following quote:

> Computerization brought, and still brings, the ability to quickly get real data from somewhere. So now [fire managers] are talking about satellite information. We're in the information age and what we're seeing with the Internet is the ability to get information from a distant place. … [Decision-makers in the past] wouldn't have made a decision without one of the [Technicians] flying over [a fire], and looking at it…That's changed right, so [the technology is] giving you the ability to make decisions in different ways. … Now, the computer gives [fire management staff] so much information… and the most of them [grew up in the information age], so handling multiple streams of information isn't unusual to them…

When interpreting some of the observations highlighted here, it is important to consider the changing information landscape (the technology, tools and ways people interact with information) that occurred over the case study period and how that might influence the future decision making. For example, recent research has explored the impact of the changing digital landscape relative to KE as a result of the COVID-19 pandemic (Nguyen *et al.* 2021). With the ongoing advances in fire science and continued technological innovation, there is a need for ongoing discussion, continued research, and as the workplace continues to change, continued observation and adaptation of KE strategies.

Overall, results from this case study of KE for the CFFDRS in Ontario, emphasise the importance of both formal and informal facilitators to support KE. Participants were more likely to describe the value of informal facilitators, including interpersonal relationships, common field-based settings experiences, and opportunities for informal dialogue as these support trust, buy-in, and eventually, implementation of research products. The credibility and soft skills of the FWI and FBP System champions and embedding them within respective agencies were also key facilitators to the success. Thinking through the knowledge transfer aspect of research ahead of time, including the appropriate people and developing products and training for end-users was also of critical importance. By adapting the perspectives and lessons learned on KE from the past, future KE in wildland fire management and science may be more successful.

Supplementary material

Supplementary Material is available online. Part A, Perspectives and supporting quotes for barriers and facilitators; and Part B, Examples of potential applications.

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