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ORIGINAL ARTICLE

Growing convergence research: Coproducing climate projections to inform proactive decisions for managing simultaneous wildfire risk

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Abstract

We apply a convergence research approach to the urgent need for proactive management of long-term risk associated with wildfire in the United States. In this work we define convergence research in accordance with the US National Science Foundation—as a means of addressing a specific and compelling societal problem for which solutions require deep integration across disciplines and engagement of stakeholders. Our research team brings expertise in climate science, fire science, landscape ecology, and decision science to address the risk from simultaneous and impactful fires that compete for management resources, and leverages climate projections for decision support. In order to make progress toward convergence our team bridges spatial and temporal scale divides arising from differences in disciplinary and practice-based norms. We partner with stakeholders representing US governmental, tribal, and local decision contexts to coproduce a robust information base for support of decision making about wildfire preparedness and proactive land/fire management. Our approach ensures that coproduced information will be directly integrated into existing tools for application in operations and policy making. Coproduced visualizations and decision support information provide projections of the change in expected number of fires that compete for resources, the number of fire danger days per year relative to prior norms, and changes in the length and overlap of fire season in multiple US regions. Continuing phases of this work have been initiated both by stakeholder communities and by our research team, a demonstration of impact and value.

KEYWORDS

convergence research, coproduction, wildfire risk and decision support

1 | INTRODUCTION AND BACKGROUND

In the United States and elsewhere, the pressing need for long-term wildfire risk management has intensified over recent decades as costly and damaging wildfire seasons have intensified and become unparalleled in modern history (Abatzoglou et al., 2021; Hessburg et al., 2021). In the face of increasingly severe wildfire seasons (Jolly et al., 2015), convergence research, which is defined as the deep integration of multiple fields to address a pressing societal need on the ground, holds the potential for coproduction of information and solutions with stakeholders to address long term risk (Bremer & Meisch, 2017; McNutt, 2017; Morss et al., 2021; National Science Foundation [NSF], 2021; Peek et al., 2020). In our application, convergence research deeply integrates climate science, fire science, landscape ecology, and social science and supports the coproduction of decision support informed by downscaled climate projections. Our coproduction approach engages decisionmakers at multiple levels of decision making, from local operations to national policy. At all levels decisionmakers must respond to severe, regional wildfire seasons and proactively manage fuels and forests, often in the face of competition for scarce resources including funding, personnel, and equipment. The central question guiding our research is: "how can we best leverage downscaled climate projections related to the potential, intensity, and simultaneity of wildfire danger and occurrence to support decision making and coproduction of risk mitigation solutions?"

In settings where publicly funded science is a critical underpinning of policy and risk management, barriers to disciplinary integration have persisted due to a lack of coproduction between scientists, policymakers, and practitioners to produce usable science that contributes to coordinated and intentional deployment of resources and risk management activities (Bremer & Meisch, 2017; Briley et al., 2015; Buizer et al., 2016; Dilling & Lemos, 2011; Kirchhoff et al., 2013; Lemos et al., 2012; Meadow et al., 2015; Tedim et al., 2021). These barriers have led to what is sometimes referred to as "loading dock science" where research and information are dropped off and never taken up for applications that could give them impact far beyond the academic context (Cash et al., 2006). The NSF Growing Convergence Research Program seeks to overcome these barriers by requiring researchers and practitioners to span boundaries through transformation within and across scientific fields and with a laser focus on solution generation in situations demanding end-to-end analysis (NSF, 2016, 2021).

Although integrated natural hazard risk research has advanced markedly over recent decades (Wong-Parodi & Small, 2019), the gap between research and on-the-ground risk management practices continues to stifle implementation (Gaillard & Mercer, 2012; Gall et al., 2015; Ismail-Zadeh et al., 2017). While the interaction of fire with coupled human-ecological systems shares some elements with risk from natural hazards such as earthquakes, fire occupies a special niche. Fire is a keystone ecological process that is essential for fire-adapted forests and landscapes. More than a century of fire suppression policy in the United States has led to fuel accumulation and substantial risks to fire-dependent ecosystems (Hagmann et al., 2021). A warming climate further predisposes fuels for burning, which increases fire weather danger and creates an even greater potential hazard through longer, often drier wildfire seasons. Proactive management harnessing fire as a risk reduction tool can pay substantial dividends (Ge et al., 2021; Peek et al., 2020; Prichard et al., 2021).

In this convergence project, we engaged stakeholder communities in coproduction activity focused on reactive and proactive fire wildfire risk mitigation decisions that rely on climate and weather information and forecasting (Corringham et al., 2008). The geospatial distributions of wildfire danger, and of landscapes for which fuel treatment or other management approaches support risk mitigation, are shaped by interactions between climate, weather, vegetation, and human activities. These distributions can inform a range of fire management decisions across spatial and temporal scales. Decisions about the allocation and sharing of fire suppression resources are driven by patterns of fire activity and fire danger, which are in turn influenced by climate and weather (Belval et al., 2017; Cullen et al., 2021). Forecasting potential fire occurrence and behavior to support these decisions must account for seasonal patterns and geographic variability, while requiring an understanding of historic drivers of ignition and spread of wildfire and also projections about future climate and fuels (Prichard et al., 2021; Thompson & Calkin, 2011). For the past 20 years, seasonal forecasts of fire potential have been disseminated in the United States through the predictive services program to geographic area coordinating centers (GACCs). Analysts identify areas and fuel types that may be expected to experience above or below normal fire activity in the coming days to months. The resulting knowledge base informs reactive decisions made on very short-term time scales but leaves a gap regarding proactive decision making for longer time scales.

A characteristic of wildfires that is particularly relevant to both response and planning is simultaneity, defined here as the number of significant fires (defined by size or impact) occurring at the same time. Simultaneity serves as a proxy for competition between fire management resource uses (i.e., incident planning teams, firefighting crews, and equipment). With climate change, the overlap in resource demand across locations has been increasing (Podschwit & Cullen, 2020). This intensification can overwhelm national sharing arrangements and increase the need for international resource sharing for extreme fire years (Robinne et al., 2018; Tymstra et al., 2020). Although trends in annual wildfire occurrence and longer fire seasons have been examined (Dennison et al., 2014; Jolly et al., 2015; Westerling, 2016), co-occurrence of significant fires across biogeographical divisions has only been recently explored, leaving a void in user ready information for decision making (Abatzoglou et al., 2021; Podschwit et al., 2018).

Wildland fire use—through managed, unplanned ignitions or intentional burning—has been shown to be particularly effective at mitigating high severity fire and can also be used to restore fire-adapted ecosystems (Kalies & Kent, 2016; Kolden, 2019; Prichard et al., 2021; Stephens et al., 2020). Even so, increased burning by either prescribed or wildland fire is also accompanied by short-term risks including those associated with smoke (NWCG 2022) and incident escape (Calkin et al., 2013). For these reasons, a convergence of disciplines is needed to better develop the prioritization of landscape strategies to reduce fire risk.

Land managers who share responsibility for managing the risks outlined above are situated within countless local, tribal, state, regional, and national institutions that provide intelligence to manage forests and fuels (NMAC, 2018; USDA Forest Service, 2012). These institutions have varying levels of familiarity and capacity for integrating climate projections into their activities. They share a commitment to established chains of command, accepted information bases deemed defensible, and operational approaches that have been developed under extreme conditions. During wildfire seasons, which now occupy much of the year in locations such as southern California (Frontline Wildfire Defense, 2022), fire managers are deeply aware of the impact of climate change on fire and fuel and thus are invaluable coproduction partners in efforts to leverage climate information.

Within this article, we present our methods for developing research team convergence and for coproducing decision support information with stakeholder practitioners. We share results in the areas of convergence and coproduction, the latter of which is further divided into the identification of coproduction foci and resulting climate and fire information. We offer suggestions for developing capacity for the future of convergence research with early career scholars and scientists. Finally, we identify and communicate a set of policy messages resulting from stakeholder engagement. Although our focus is coproduction of climate projections related to drivers of fire simultaneity and improvements in understanding about sources of uncertainty, this approach is applicable to other complex problems without straightforward solutions, often referred to as "wicked problems".

FIGURE 1 Depiction of the interaction of different layers of convergence in the project. Researchers from disciplinary backgrounds and stakeholders on the ground coproduce policy and science tools, applying these to the pressing societal issue of wildfire risk management decisions

2 | METHODS

Our research effort was designed to scaffold progress toward convergence, starting with team building, including direct communications with our stakeholder community. As we are intentional about integration both across scientific disciplines and also between research and practice, we use multiple metrics to gauge our progress (Figure 1). First, we have moved beyond simply becoming conversant in one another's disciplines—rather, each individual's approach to research has been transformed through our convergence work and development of a new understanding across boundaries. Second, through deep integration of disciplines and decisionmakers that span a range of wildland fire risk activities, we create a community with a shared language and a new paradigm for addressing wildfire risk. Third, successful convergence fosters two-way stakeholder engagement culminating in coproduction of decision support information leveraging climate projections and readily integrated into existing tools for proactive management of wildfire risk (University of Washington, 2022).

2.1 | Convergence of the research team

At the outset, our research team encompassed distinct disciplinary strengths, however, each part of the team has built bridges in order to benefit from the strengths of others and to be effective in addressing wildfire risk. Climate scientists contribute downscaled climate projections while seeking connections with stakeholders with whom to coproduce information based on these projections for application on the ground. Forest ecologists bring a focus on individual patches and stands of trees that make up landscapes while seeking spatially generalizable connections to inform policy and operations. Fire climatologists and landscape ecologists bring a perspective rooted in large scale processes and effective strategies across regionally aggregated outcomes, while seeking on the ground applicability in specific contexts occupied by stakeholders. Decision scientists bring frameworks for describing management and policy decisions. These frameworks encompass the available options and paths, the uncertainties that thwart analysis of those options, and the core position of tradeoffs that defy single routes to optimality. Through our convergence work, we seek specific contextual information in order to support stakeholders faced with the reality of a new normal for fire risk and danger.

From the start, in order to make progress toward convergence, our team grappled with the disparate spatial and temporal scales in which our research fields and stakeholders operate. In landscape ecology, spatial scales of meters to a kilometer are meaningful for forests and fire-dependent species, whereas in climate modeling, spatial scales below 25 km are considered to be fine scale (Gutowski et al., 2020). Climate scientists project future scenarios 20–100 years into the future, while forest planning generally occurs on 10–20 year scales, and wildfire response or prescribed burning plans occur on scales of hours to days. In order to bridge these differences, which extend far beyond terminology, we focused on the disparate set of spatial and temporal scales that we use in our individual fields as well as those that stakeholders use in decisions on the ground about prepositioning of resources, fuel treatment tradeoffs, and forest planning.

Other metrics to gauge our team's progress toward convergence include fluency across team disciplines and sustained engagement with our stakeholder community. Many team members are now able to, and have in fact, presented one another's work. In doing so they have enriched those presentations with the integration of their own contributions. This demonstrates a true fluency across disciplines encompassing language, paradigms and methodology. Our team also has experienced substantial success in attracting and sustaining stakeholder interest in coproduction. These long-term partnerships transcend the basic achievement of co-developing improved visualizations that leverage climate projections, although these visualizations are now available and have begun to be introduced in a range of operational settings (University of Washington, 2022). Beyond these concrete and coproduced outputs, new relationships among team members and stakeholders have served as the distinguishing characteristic of our work moving forward. Their strength is demonstrated in the two-way interactions through which new subprojects are initiated and also by the extension of invitations to disseminate policy messages.

Students and early career scientists are a key part of our team and have served in leadership roles, including in stakeholder engagement, public presentations, and policy outreach. Individuals who are at early career stages are sometimes less entrenched in the fields they study and thus less constrained by the boundaries under which some disciplines labor, allowing them to lead more established scientists in the development of convergence (Rhoten and Parker, 2004; Haider et al., 2018). Among these early career scientists, our team includes graduate students pursuing degrees in forestry, public policy, and engineering.

The team meets weekly and shares responsibility for presenting work in progress, as well as strategy sessions. We share an access-controlled Google Drive which serves as a record of our progress and interactions. This directory includes tutorials in methodology and disciplinary approaches, brainstorming exercises, work-in-progress, draft outputs, all aimed to develop communication and shared awareness across disciplines. We also maintain a directory of biographical information about team members' backgrounds, career paths, and skill sets outside of their primary current appointment. Further, the NSF-sponsored Toolbox Dialogue Initiative enriched our understanding of convergence and the approaches of other research teams (Looney et al., 2013; Toolbox Dialogue Initiative, 2021). The Toolbox Dialogue Initiative activities provide structured approaches to breaching communication barriers across disciplinary boundaries.

2.2 | Stakeholder engagement

The overarching objective of our stakeholder engagement is to convene fire operations decisionmakers and national-level policymakers together with our team to identify decision contexts in which information about climate and fire danger may help mitigate long-term risk. We seek areas of intersection between climate projections, wildland fire science, and decision needs that are ripe for coproduction. The approach leverages the fundamentals of reflective listening visualization (DeRouen & Smith, 2021). Specifically, we engage stakeholders through in-depth interviews, extracting and coding themes from transcripts of these discussions. For many team members our project represents a first exposure to qualitative research, adding an important tool for future research efforts intended to bring scientific advances into applications. We then design initial visualizations responding to expressed interest and needs, share these for feedback, and then refine and iterate with individuals and in small group workshops. This approach includes a focus on communication that elevates a range of voices and leverages understanding, experience, ideas, and concerns (Bremer & Meisch, 2017; Subedi et al., 2021).

The initial visualizations used to spur discussion and launch coproduction were generated by our research team based on data drawn from multiple sources and were targeted to be applicable and relevant for decisionmakers. Wildfire data from the Monitoring Trends and Burn Severity Project (MTBS, 2022) provide the basis for metrics and information about simultaneous wildfire, following the approach of Podschwit and Cullen (2020). Our focus is significant fires, defined as those exceeding 1000-, 10,000- and 20,000-acre size thresholds, and those exceeding the upper percentiles of local fire size distributions, for example, 75th percentile. Observed climate data come from gridMET, a gridded high-resolution meteorological observation dataset (Abatzoglou, 2013). Projected future climate data come from the NA-CORDEX (North American branch of the Coordinated Regional climate Downscaling Experiment) archive (Mearns et al., 2017) of regional climate model (RCM) simulations covering the period 1950–2100. We use a subset of 13 simulations—10 at 25-km resolution and 3 at 50-km resolution, all driven with Global Climate Model (GCM) simulations using the RCP8.5 emissions trajectory, and bias corrected against gridMET (Bukovsky & Mearns, 2020; McGinnis & Mearns, 2021). From these we generate and interpret seven fire indices: BI (burning index), CFWI (Canadian fire weather index), ERC (energy release component), FM100 (100-hour fuel moisture), FM1000 (1000-hour fuel moisture), KBDI (Keetch-Byram drought index), and mFFWI (Modified Fosberg fire weather index) (Kessenich & Abatzoglou, 2022).

Through existing collaborations and networks within the wildland fire community, we identified an initial pool of expert decisionmaker stakeholders. With stakeholder recommendations, we expanded these connections to ensure inclusion of fire and fuels managers at local, tribal, regional, and national agencies, fire weather forecasters and intelligence providers, and operations specialists (see Table 1).

Our interview and workshop sequence were designed to develop relationships and shared language for effective online engagement as necessitated by COVID-19 (Figure 2). This

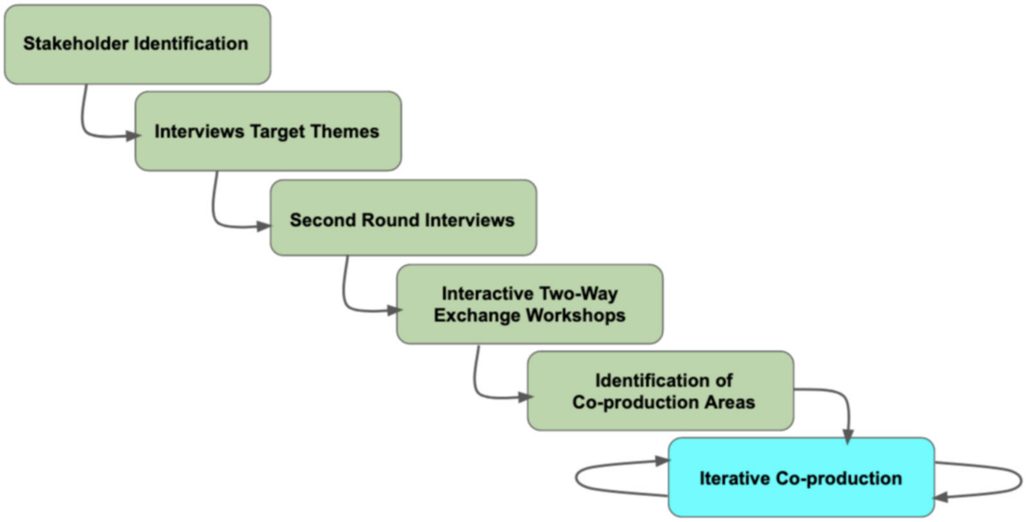

FIGURE 2 Progression of stakeholder engagement sequence including individual interviews and interactive workshops culminating in identification of areas of focus and ultimately iterative coproduction

TABLE 1 Organizations tapped for stakeholder engagement

US Department of the Interior (DOI) DOI, Office of the Secretary DOI, Bureau of Land Management (BLM) DOI, Bureau of Indian Affairs (BIA)
US Forest Service (USFS) Fire & Aviation Management, USFS Fire Sciences Laboratory, USFS Wildland Fire Management Research, Development, and Adaptation, USFS Okanogan—Wenatchee National Forests, USFS
US National Interagency Coordination/Fire Center (NIFC)
Northwest Interagency Coordination Center (NWCC)
Washington State Department of Natural Resources (WA DNR)
California Department of Forestry and Fire Protection (CALFIRE)
The Nature Conservancy (TNC)

format allowed intense engagement with a shorter time commitment for stakeholders. We note that given the multiple rounds of iteration, the time commitment by the research team far exceeded that of an in-person, 2-day workshop.

We interviewed 12 decisionmakers in spring 2021, using a structured protocol (Appendix A) probing their involvement in decisions about fire response, landscape, and fuels treatment, the sources of information they rely on in the form of historic observations and/or projections, the gaps in the information base, the decision support tools available, and barriers to using new information. In addition, we asked them what policy suggestions they wished to communicate to national agency policymakers, a stakeholder group that we also engage. Our goal was to identify points at which climate information and historic fire weather observations could enter a decision process—and thus to identify potential coproduction opportunities.

To prompt interaction, we shared illustrative decision tree structures with stakeholders during our workshops. These were developed in response to stakeholder expressions of interests and needs during the interview process. One such structure centers on the decision about the appropriate level of fire response resources to preposition in a region in advance of the fire season (Figure 3). The decision is treated as the starting point in a cascading sequence of events. Working from left to right, a decisionmaker must choose between prepositioning a higher or lower level of resources, based on prior beliefs about what the season will hold. This decision is followed by a probabilistic uncertainty node, representing the intensity of the season with two possibilities: "High Impact Season—Many Synchronous Significant Wildfires" or "Not High Impact Season". In reality this and other chance nodes can encompass any distribution of probability, and any number of possible outcomes, that a decisionmaker desires. The implication of a high impact fire season is that the prepositioned resources may not be adequate for suppression to manage risk. The decisionmaker faces further decisions such as whether to request additional resources from other GACCs, further uncertain events such as whether any such request will be fulfilled, and ultimately the chance that the resources will be adequate and effective in handling the fire season or not. The terminus of each sequence of branches is the point at which the consequences accrue to the decisionmaker, that is, any costs or benefits from the decisions made and uncertainties resolved, which here would include the cost of suppression, impacts to health and property, and any other gains or losses.

The uncertain events in the tree represent points in the decision sequence where new coproduced information could help to inform the probabilities upon which the decisionmaker is reliant (labeled A through C). A second tree structure, centering decisions about fuel treatment and the tradeoff between

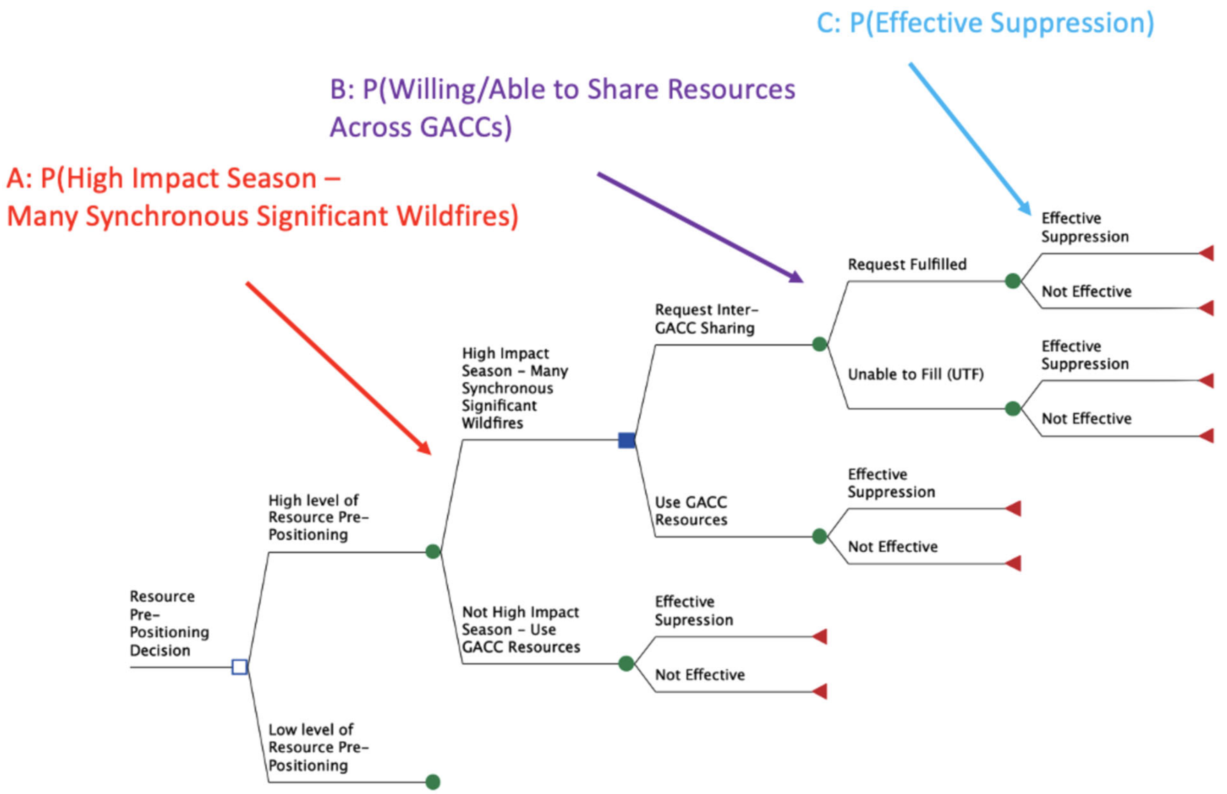

FIGURE 3 The tree structure represents the sequence of events in a decision about the level of prepositioning of fire suppression resources in advance of the fire season. It is a flexible structure that can be customized to evaluate a set of decision paths and their interaction with a series of future uncertain events. Decisions are represented by square nodes and uncertain chance events are represented by circular nodes. Each uncertain event is associated with discrete probabilities for each branch (or a continuous distribution) which could be based on the historic record or augmented with coproduced climate and fire projections. Locations for the incorporation of new information into the decision are marked by the colored arrows and identified by a letter from A through C. Ultimately each sequence of decision and uncertain chance nodes leads to one of a set of consequences or outcomes representing tradeoffs between multiple objectives of the decisionmaker. Every decision option can be evaluated in terms of the ultimate consequences and weighted by the probability of chance events along the path

short term and long-term impacts of wildfire on humans and ecosystem was also shared.

Interview transcripts for each stakeholder were coded for:

- Use of historic weather observations, use of climate projections, and interest in leveraging additional climate projections in decision making.
- Awareness or application of information regarding simultaneity of fires and fires that compete for resources.
- Perceptions of gaps in the information base upon which decisions about risk management and/or policy rest, for example, resource allocation, fuel treatment, and forest and operations management including suppression, budgeting, and hiring.
- Experiences from the most recent fire seasons and impactful fires that serve as specific examples of the above categories.

The 2020 wildfire season, which was notable in the number of simultaneous impactful wildfires across the western United States, offered a recent and highly relevant context.

2.3 | Initial visualizations to stimulate idea generation for coproduction

Stakeholders who participated in the first round of interviews were invited to take part in a second round of interviews, followed by small group workshops to delve into visualizations and to identify promising areas for coproduction. To prepare for these workshops we shared a set of graphical visualizations tailored to each of our stakeholders at the second-round interviews. These visualizations highlighted aspects of co-occurring (i.e., simultaneous) fire over time and into the future, changes in fire danger indices over time, and changes in fire weather across the year and over decades for specific locations (e.g., the site of the 2020 East Troublesome Fire in Colorado and the 2020 Creek Fire in California).

After these initial interactions we held two online workshops, each of which included our research team and six stakeholder practitioners. The stakeholders presented lightning remarks related to their responsibilities, approaches to decision making, and relative strengths and weaknesses of currently available decision support tools. Plenary and breakout sessions focused on a set of illustrative climate and fire projections developed by the team, some updated and refined from those presented above, with new additions generated in response to feedback. Participants considered which information and presentation formats had the greatest potential value for decision support, which might benefit from changes, and which were less promising.

As outlined above, interview transcripts and workshop notes were coded to identify key gaps and unmet needs in decision-support information related to climate and weather as candidates for coproduction work. After identifying a potential set of research areas, we systematically polled both our team and the stakeholders about which were of greatest interest. We then gauged the intersection of stakeholder identified needs and the visualizations that our team had the capacity to generate. Areas of interest were prioritized into two subsets—those for which decision support information could integrate into existing tools readily and those for which future engagement and more complex integration into existing tools would be required.

3 | RESULTS

3.1 | Convergence progress

Progress toward convergence in this research project is evident in the increasing transcendence of disciplinary boundaries by individual researchers, the development of a new research community encompassing our team and stakeholder practitioners, and most critically the productive two-way communication and initiation of research that has emerged between researchers and practitioners in our coproduction work. Improved understanding regarding temporal and spatial aggregation and norms within our disciplines have made this process easier over time, while an appreciation for practitioner needs as we coproduce has led to increased opportunity to engage. We have worked hard to identify potential gaps between existing and future management practices that can be better supported by climate and fire weather projections, resulting in a great set of subprojects moving forward.

We heard a strong and consistent message from stakeholders that climate projections and other decision support tools should be actionable and operationally relevant. One of our stakeholders captured the importance of coproduction approaches in the acceptance of decision support information generated:

> [To get acceptance from decisionmakers on the ground] "in my experience, they have to be part of developing the product and so there's that shared trust and experience."

3.2 | Identification of potential coproduction areas

Within the practitioner community, key measures of our progress on convergence included the successful identification of areas for coproduction work and the continued interest and engagement of these partners despite extremely demanding roles on-the-ground during fire season. Through the approach outlined above, we identified four areas for cocreation around climate and fire information and tools (Table 2). Coproduction is further organized into two phases, with two research areas targeted for each phase. Research area #1 focuses on producing information and visualizations to help confront the challenge posed by dramatic changes in reference periods and thresholds relevant to the most recent 5–10 years of fire seasons in contrast with the past 3–4 decades. Our stakeholders have told us that in some cases decades of experience and local rules-of-thumb based on direct fire management have become less reliable given profound changes in fire season length and intensity. As one of our stakeholders said regarding the unprecedented 2020 Labor Day weekend wind event in the Pacific Northwest:

> From my perspective, what made 2020 difficult was that I had to summon the courage to override what my objective model was telling me with my own intuition and indicate risk for new large fires in areas where traditionally wind is not that big a contributor to fire…I guess what I fear is my 36 years of experience maybe aren't as valuable as I might have thought, over the last couple of years. We may be entering into a new era where the old norms are going to be thrown out the window and the probabilistic model that we based on, going back to 1992, isn't going to be valid in this scenario with climate change. And you know changing fuel density, changing firefighter philosophy, changes in our power grid…

Specifically related to a stakeholder's desire for information about changes in simultaneity:

> [If we project that] "we're going to have periods of time where we're going to have multiple large fires on the landscape competing for resources, that will 100% get people's attention. They'll start trying to get severity, to get people hired, hire them for longer, have them compete for national resources, put them at the top of the list."

Area #1 was closely followed in prioritization by research area #2—the need to improve understanding and communication of uncertainty and variability related to climate and fire simultaneity projections, as well as interpretations of historic

TABLE 2 Coproduction research areas identified for phase i and phase II efforts

Area: Phase	Details	Existing tools for integration
Area #1: Phase I Changing reference periods and fire Index thresholds	Expand information base about changing fire season length and changing temporal and spatial overlap between periods of simultaneous or intense fire activity. Update metrics to reflect the reality that the most recent 5–10 fire seasons have been substantially different than the previous 20–30 years.	Pocket Cards, Fire response and briefings during fire season, 10–20 year Forest Plans, Fire danger level setting.
Area #2: Phase I Uncertainty and variability	Improve visualization and communication of sources and implications of uncertainty and variability related to climate and fire simultaneity projections.	Pocket Cards, Fire response and briefings during fire season, 10–20 year Forest Plans.
Area #3: Phase II Prioritizing fuel treatment	Leverage climate information to identify conditions and landscapes for which to prioritize fuel treatment.	IFTDSS (Interagency Fuel Treatment Decision Support System).
Area #4: Phase II Spatial analysis	Identify "trouble spots" for example, geography and spatial range of newly elevated burn potential.	10–20 Year Forest Plans, PODS (Potential Wildland Fire Operational Delineations), IFTDSS.

observations. Many stakeholders reflected the need for additional decision support information in this area, as well as the importance of ensuring accessibility:

> And that's where, if you throw a lot of information at them, people can get paralyzed and they don't know what to use…I think on the science, products that have more information and uncertainty probabilities are great, and we can kind of wrestle with that and then figure out how we're going to frame that in a simpler way potentially.

> Providing scenarios and translating your confidence into high, medium, low, moderate, whatever—that kind of helps…When you're trying to communicate a level of confidence you need a number of ways to do it.

Two coproduction research areas await attention in Phase II with longer term coproduction given the capacities and user communities for the tools for which integration is targeted.

Regarding the need to prioritize fuel treatment (Area #3 in Table 2) stakeholders reflect:

> Managed wildfires are still framed to some extent as a choice of should we let these fires burn or not, but the reality is [they're going to burn] one way or another.

and,

> Better predictions about synchronous large fires can potentially really help our leadership, the legislature, or decisionmakers come to terms with the fact that, not only do we need to accelerate our treatments, but we've got to get these landscapes in a place where they can burn.

Regarding spatial analysis to identify trouble spots of newly elevated potential for impactful and damaging wildfire (Area #4 in Table 2) a stakeholder offered:

> We can't predict exactly where the fires are going to be, but we can identify hotspots, and certainly potentials.

As outlined above, the most consistently expressed input from our stakeholder practitioners was that any innovation must integrate into existing tools (column 3 Table 2). Thus, Phase I of coproduction activity augments basic tools that are in current use, while Phase II coproduction targets more complex tools.

3.3 | Coproduced information

Stakeholder engagement has led to new coproduced visualizations. Some grew out of initial versions presented in our early interactions while others are completely new. Selected visualizations follow for illustration, others are publicly shared on our project web site (University of Washington, 2022). As we continue with coproduction, we have focused on expanding the information base around changes in fire occurrence over time. In particular, we have explored simultaneity of fire with refinements and iteration on earlier visualizations.

For example, we shared a visual comparison of change in peak simultaneity observed over 35 years via a spatial depiction comparing the monthly tally of 1000+ acre fires occurring during periods of peak simultaneity over 2002–2019 to the number in 1984–2001 (Figure 4). This spurred discussion of potential coproduction about the probability of high impact seasons with synchronous wildfires taxing the resources positioned in GACC, and the probability that a GACC is willing or able to share resources with others (Figure 3: nodes A and B).

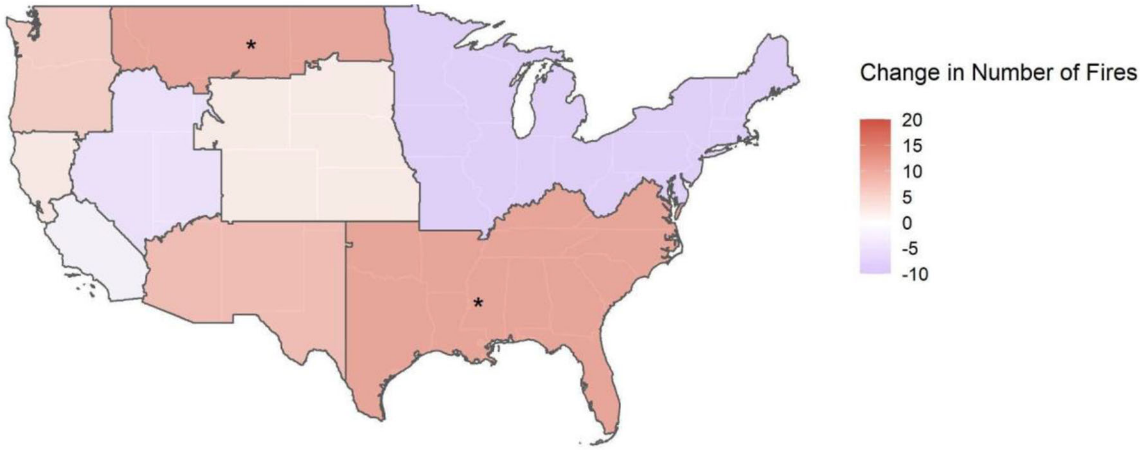

FIGURE 4 Comparison of peak simultaneity in 2002–2019 and 1984–2001. Shading indicates by region how many more (red) or fewer (blue) large fires (1000 acres or greater) occurred during the peak month of simultaneity in the more recent half of the period of observation, that is, in 2002–2019 relative to 1984–2001. Statistical significance of the change in number of fires is indicated by GACC, (* $p < 0.05$). GACC, geographic area coordinating center

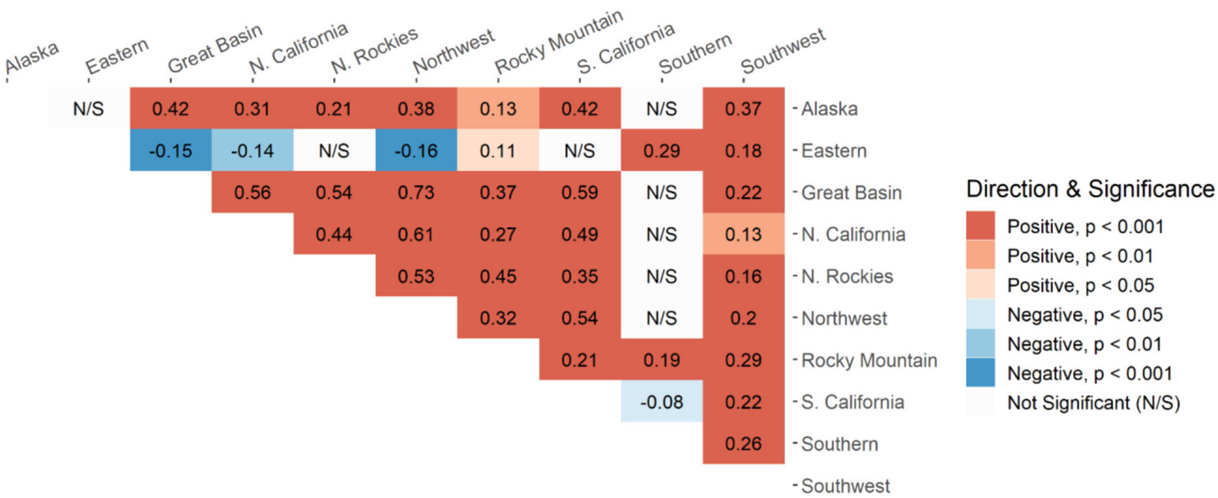

FIGURE 5 Matrix displays correlation between GACCs in the number of simultaneous large fires (1000 acres or greater) during each month. Numbers represent Kendall correlation. Direction of correlation (positive or negative) and statistical significance are indicated by the color bar with intensity of color increasing with level of significance. GACC, geographic area coordinating center

To stimulate discussion about which regions historically experience simultaneous wildfires at the same time, we developed a matrix of pairwise correlations capturing co-occurrence of 1000+ acre fires between GACCs across a 30-year period 1984–2015 (Figure 5). Coproduction building on this information base may help inform the probability of synchronous wildfire in multiple areas at one time taxing positioned resources and ultimately the probability that a GACC may be willing or able to share resources (Figure 3: nodes A and B).

In a new visualization building on these earlier iterations with the benefit of stakeholder input, simultaneity by GACC is spatially visualized through correlation between the Northwest Interagency Coordination Center (NWCC) and other GACCs, as well as changes over time (Figure 6). These maps show the correlation between the number of fires exceeding the 75th percentile of size occurring in a month in the NWCC and the number of such fires occurring in other GACCs. We acknowledge that correlation is only part of the simultaneity picture because two GACCs may be highly or increasingly correlated due to *either* increasing or decreasing fire occurrence

Figure 6 responded to stakeholder interest in focusing spatially on changes in reference periods and seasons over time. We compare a decade from 30 years ago (left panel, 1984–1993) with a more recent decade (right panel, 2010–2019) examining changes over time in the peak of simultaneity. For this figure convergence and coproduction led to a refinement in the definition of large fires to include fires at upper percentiles of the local fire size distributions,

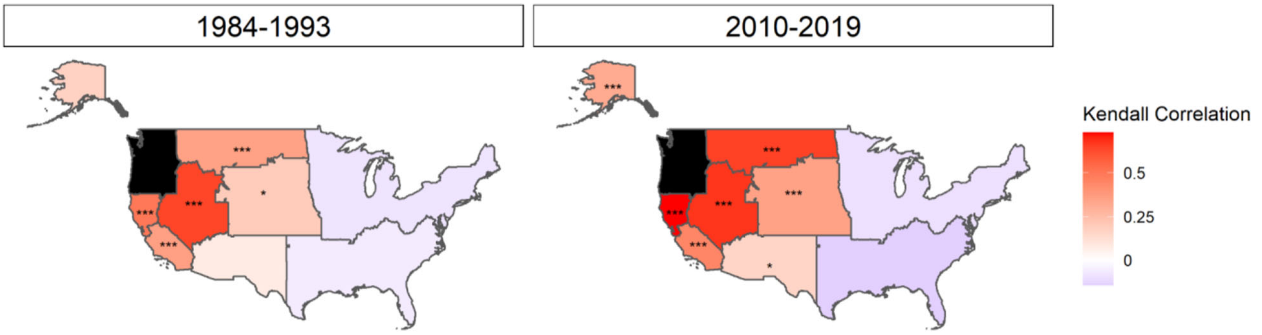

FIGURE 6 Panel displays spatial correlation patterns in cross-GACC simultaneity in terms of the number of very large fires (exceeding the 75th percentile of size for that region) occurring per month in the NWCC and in other GACCs. Color indicates the Kendall correlation between number of simultaneous fires in GACCs, with red shades indicating positive correlation and blue indicating negative correlation. Statistical significance is denoted as (* $p < 0.05$), (** $p < 0.01$), and (*** $p < 0.001$). Note that only positive correlations were statistically significant in this analysis. GACC, geographic area coordinating center; NWCC, Northwest Interagency Coordination Center

rather than by acreage. This innovation allows the visualization to spotlight local impact such as the severity of fire or impacts to communities. We observe that wildfire simultaneity in the northern Rockies and northern California have become increasingly aligned with periods of simultaneity in the Northwest, with implications for an increase in resource competition and a decreased ability to share between these regions. Referring back to our decision tree structure, this information pertains to the probability of a GACC having sufficient response resources, the capacity to share resources, and the probability of effective suppression (Figure 3: nodes B and C).

Turning to the potential impact of future climate, we shared initial example projections of fire weather conditions using ERC as a metric of fire danger representing how intensely a potential fire might be expected to burn based on local fuel moisture conditions. Figure 7 displays projected changes in the number of days with ERC above the reference 97th percentile (with 1980–2010 as the reference period) for 2040–2070 for the western United States. The 97th percentile was chosen as it correlates with the occurrence of large fires (Riley et al., 2013) and is commonly used by stakeholders. Figure 3 shows the projection from one simulation (25-km RegCM4 forced by HadGEM2-ES) from the NA-CORDEX ensemble. The information presented here pertains to extreme fire danger conditions and, when augmented by a full ensemble of model projections, may inform the probability of effective suppression (Figure 3: node C).

Another tool we used to spur coproduction ideas was based on a format known as the "Pocket Card" (Figure 8). Pocket cards are reference tools for firefighters, to put current fire danger conditions for a specific geographic location and fire index into context against historical values (NWCG, 2022). They also contain information about notable past years and fires. A common choice of fire index for Pocket Cards is ERC, thus we have selected ERC for the example shown here.

Our stakeholders are familiar with Pocket Cards and rely on them as a reference. As one expressed:

> We get into the specifics of especially fuels, you know, with Pocket Cards. We tell [operations staff] that the Rodeo-Chediski fire happened at this level of ERC and this fuel moisture. We try to invoke that when we show fire danger plots.

In our first iteration of a revised Pocket Card, we included projected future conditions to demonstrate the potential value of climate information and spur discussion (Figure 9). The revised Pocket Card included the average, maximum, and upper percentiles of the ERC distribution across the year both for the historical reference period (1970–2000) and the future (2040–2070) from a single simulation. This example card was for the location of the East Troublesome Fire, which burned nearly 200,000 acres in Colorado in 2020. This visualization stimulated discussion about the value of climate projections and also about the interpretation of uncertainty and variability in these projections. Stakeholders expressed frustration in trying to interpret the percentiles on the card, since this graphic presented output from a single simulation, and climate projections can encompass both interannual variability and uncertainty in future climate across different models. Stakeholder feedback spurred coproduction activity and further innovations as described in section 3.3. The information displayed on Pocket Cards pertains to fire weather danger in the context of past and future conditions, and thus can serve as a basis for estimating the probability of synchronous large wildfires and also the probability of effective suppression (Figure 3: nodes A and C).

Building from stakeholder interactions, we generated a further update showing where and at what point during the year simultaneity occurs in multiple regions (Figure 10). This visualization responds to the stakeholders' expressed need for information about recent changes in reference periods and the timing and intensity of fire seasons. Here we use percentiles of the fire size distribution to indicate impact, rather than absolute acreage, to better align with operations staff norms. This figure also addresses the concern that correlation alone does not constitute full information about simultaneity, by

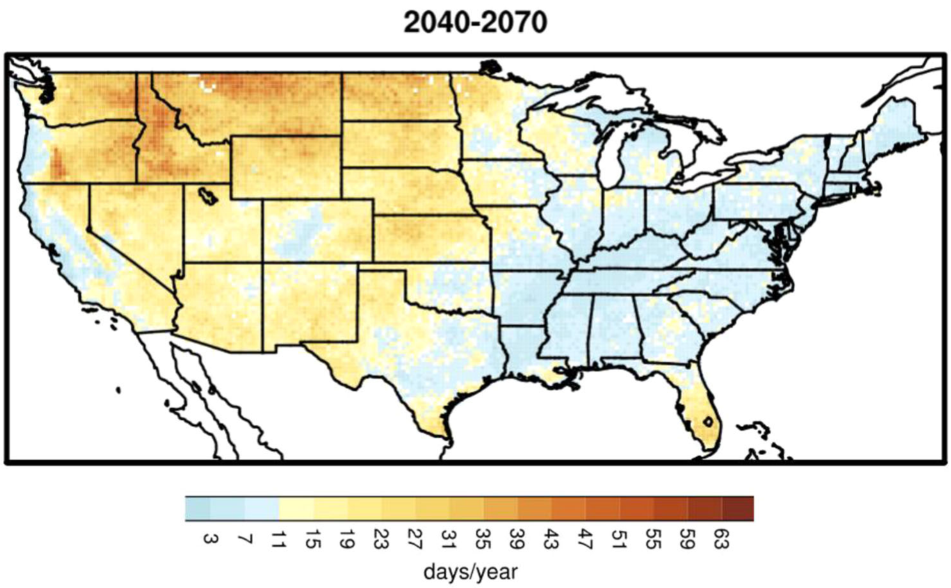

FIGURE 7 Map displays projected change in fire weather extremes between a reference period (1980–2010) and a future period (2040–2070). Fire weather extremes are defined according to the median number of days per year that ERC exceeds the 97th percentile of its distribution. Results are illustrated for one NA-CORDEX ensemble—25-km RegCM4 forced by HadGEM2-ES using RCP8.5. Warm (cool) colors indicate an increase (decrease) in the number of extreme condition days. Note that 3% of 365 is approximately 11, so a value of 11 days corresponds to no change. GACC, geographic area coordinating center; NA-CORDEX, North American branch of the Coordinated Regional climate Downscaling Experiment; NWCC, Northwest Interagency Coordination Center

using counts of fires and clearly showing the amount of fire activity in different regions across time.

We observe changes between the recent decade (2010–2019) and 30 years ago (1984–1993) in the median number of 75th percentile fires occurring by GACC, using a 30-day rolling window. Both the overall season length and the timing and magnitude of peak intensity reveal increases over time. Indeed, for much of the year, more regions now experience multiple fires at one time than in the past and can be anticipated to increasingly compete for resources, which has implications for budgets, hiring, and staffing. The "simultaneity season" at multiple locations also now begins earlier in the spring, and the number of fires at or above the locally referenced 75th percentile has approximately doubled at the peak of the season. This information can support estimation of the probability of GACCs having sufficient resources prepositioned, the likelihood of requesting backup, and the capacity to share resources (Figure 3: nodes A and B).

To move beyond analysis of historical changes in simultaneity, we developed statistical models that relate the number of large wildfires within a GACC to regional statistics of the seven fire indexes mentioned in section 2.2. We then applied the statistical models to output from the NA-CORDEX RCM simulations to project future changes in simultaneity across the Western United States. Coproduction with stakeholders strengthened this work throughout, from motivating the initial analysis, to shaping the spatial and temporal scale of the statistical modeling, to spurring the framing and analysis of the projections in terms of return levels and return periods (i.e., conditions typically seen every *N* years), in order to relate them to the preparedness levels used in fire management decision making (McGinnis et al., 2023).

As an example of this extension to the future, we present a further refinement of an ERC Pocket Card format for the location of the 2020 Creek Fire in California, coproduced with stakeholder input. Relative to the original format and initial refinement (Figures 8 and 9), Figure 11 includes projections from an ensemble of 13 RCMs. As noted above, climate projections encompass both uncertainty about future climate across different models and variability in climate across time. The updated pocket card was structured to help clarify these multiple sources of uncertainty and variability.

Figure 11 incorporates model uncertainty across the ensemble of models in contrast with variability as represented by percentiles in the future distribution of ERC, allowing communication of the relative magnitude of these sources of uncertainty and variability. This figure projects earlier spring and later autumn in future fire seasons as shown by model averages. For model maxima, future fire danger in the spring is projected to exceed historic levels and to do so at earlier times in the year. This information supports estimation of the probability of synchronous large wildfires and the probability of effective response (Figure 3: nodes A and C). This visualization responds to the stakeholder suggestion that decision support be integrated into familiar tools for better uptake and usage. Our innovations are directly incorporated into the basic Pocket Card tool but given the Card's role in a complex decision system, we posit that even modest advances in the underlying information represent substantial progress. We are also generating Pocket Cards for additional contemporary and future periods (e.g., 2030–2060) in response to

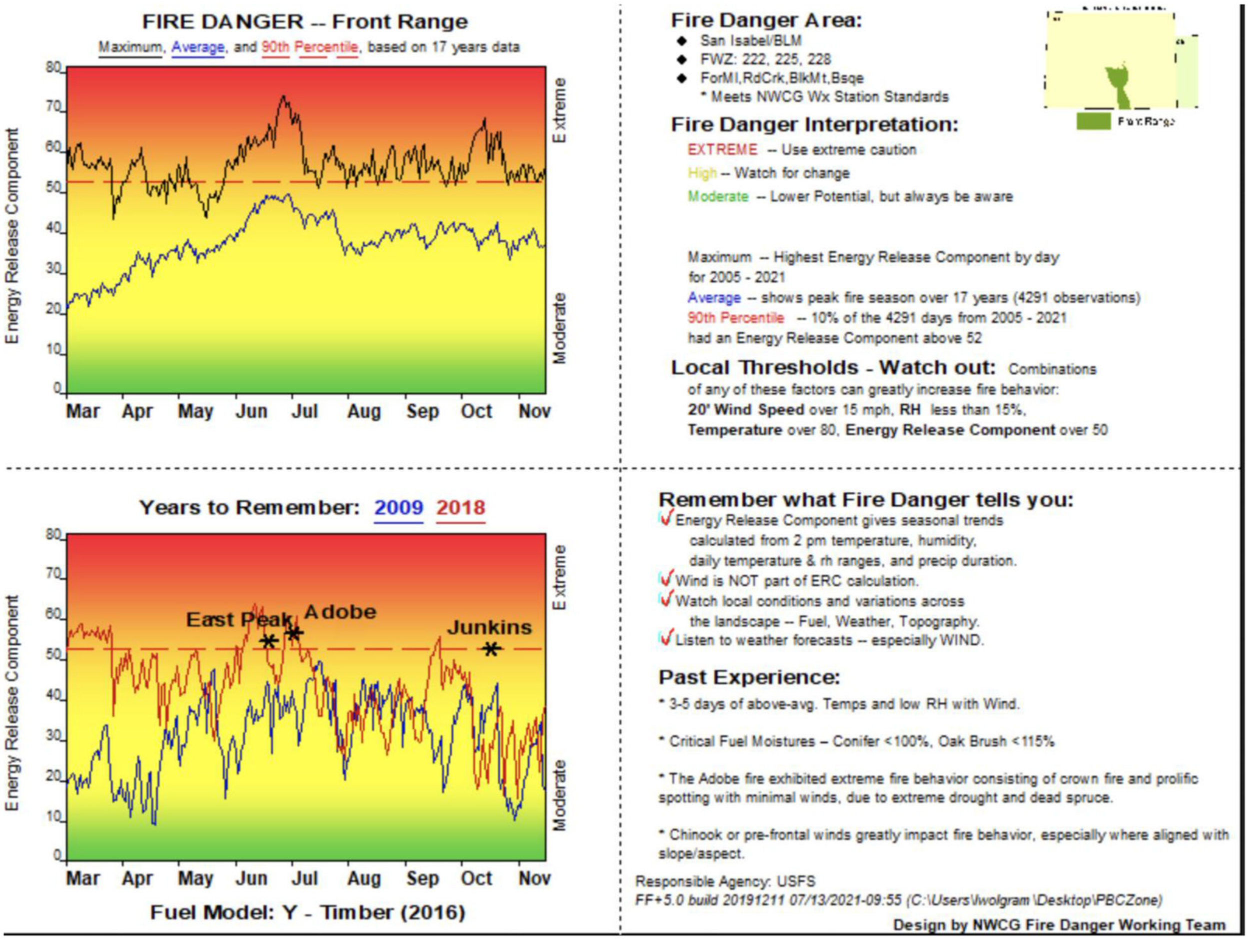

FIGURE 8 The figure shows a sample NWCG Pocket Card. The pocket card displays ERC with a timber fuel model and demonstrates how to interpret ERC through the maximum, average, and 90th percentile values during the fire season (March through November) for the Front Range in the Rocky Mountain GACC. ERC values and statistics are generated based on 17 years of observations. ERC, energy release component; GACC, geographic area coordinating center; NWCC, Northwest Interagency Coordination Center; NWCG National Wildfire Coordinating Group

stakeholder needs for information relevant to decisions in the nearer term, such as for supporting burn planning for the coming 10–20 years.

Another marker of the success of our approach is that coproduction activity has begun to flow directly from stakeholders and practitioners, who are now initiating subprojects and citing specific scientific needs. For example, we have partnered with NWCC to coproduce projections around the role of the ENSO cycle as a driver of fire weather over time. From its inception this work has been directly integrated into developing the knowledge base on which daily briefings during the fire season depend. Also, the team was invited to hold a virtual workshop at the AFE 2021 Fire Congress. A mix of fire managers, forecasters, and graduate students attended plenary and breakout sessions to generate new ideas for incorporating climate change projections for proactive management. More recently, the team has been invited to offer a briefing to FEMA analysts and decisionmakers to inform risk management for fire as one among multiple hazards they balance.

3.4 | Policy recommendations

We identified key policy messages through review and coding of interview transcripts and workshop records. As part of our work, we have transmitted these messages directly from stakeholders to decisionmakers and budget planners in the US Department of Interior, FEMA, the USFS, and the White House. Recommendations pertain to policies around budgeting, fire response, fuel treatment, hiring of crews and managers, timing of deployments and assignments, as well as positioning and trading of resources.

Stakeholders expressed an overarching need for climate projections to inform policy:

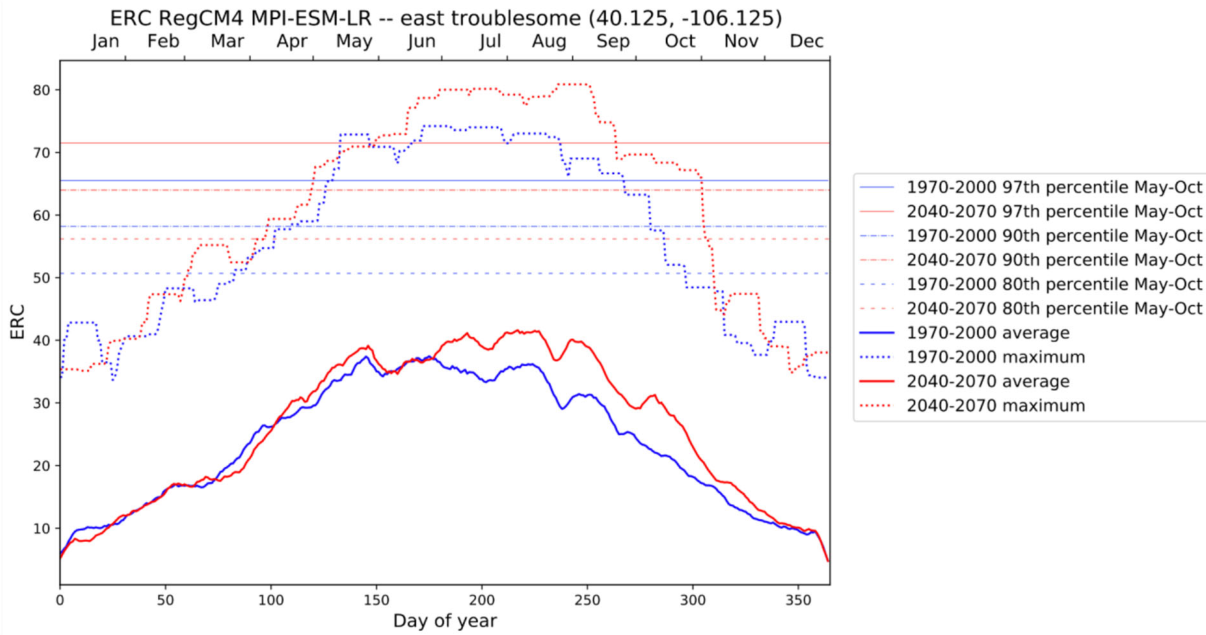

FIGURE 9 This figure displays the ERC statistics presented in the observation-based Pocket Card in Figure 8, but rather projected with the RegCM4 RCM driven by the MPI-ESM-LR GCM using RCP8.5. These values are for a single RCM grid cell that encompasses the 200,000-acre area burned in the East Troublesome Fire west of Fort Collins and Boulder, CO. The reference period is meant to represent historic conditions displayed on Pocket Cards, and the future period communicates the changes expected by midcentury. ERC, energy release component; RCM, regional climate model

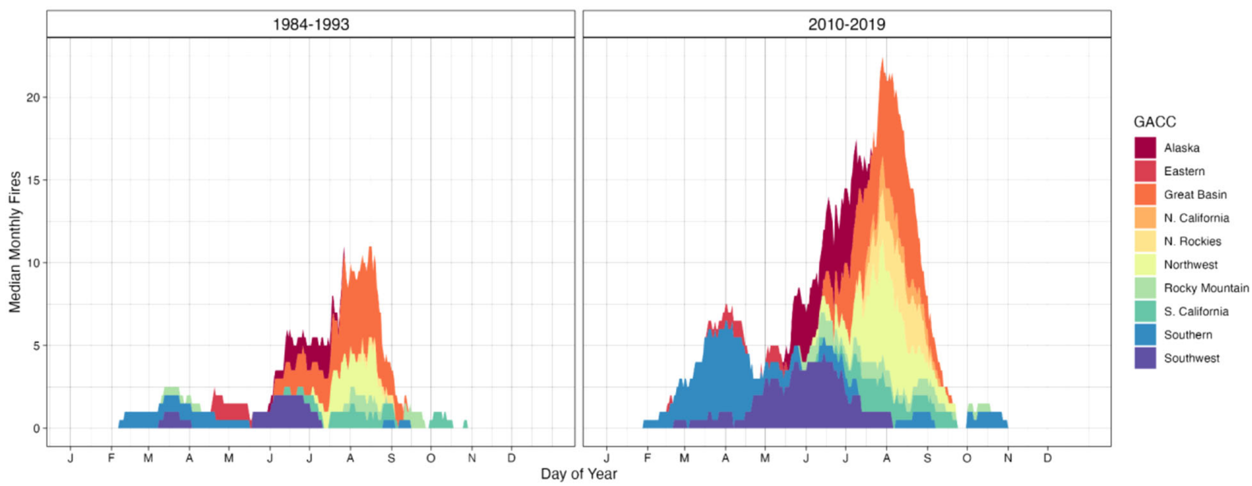

FIGURE 10 This figure presents fire occurrence and simultaneity within and between GACCs. Simultaneity is considered within and between GACCs for fires at or above the 75th percentile of the local fire size distribution for the reference period 1984–1993. Median number of fires is determined in a 30-day rolling window. GACC, geographic area coordinating centers

> If managers had a tool to more mindfully project where they're going to be in 50 years I think we would see a dramatic shift in policy.

> Most practitioners are more inclined to embrace that we need to plan for climate change if there's a tool to help [them] or there's a framework to work with, so that [they] can factor in all of [their] local stuff and come up with a plan.

> It's going to be warmer and drier in the future with in general, larger and more fires… that information can be tiered down to be able to apply it in the fire management organization…for demonstrating the viability of the tool.

They also called out a need to pivot to proactive future planning such as for fuel treatment, and for changes to hiring and the workforce.

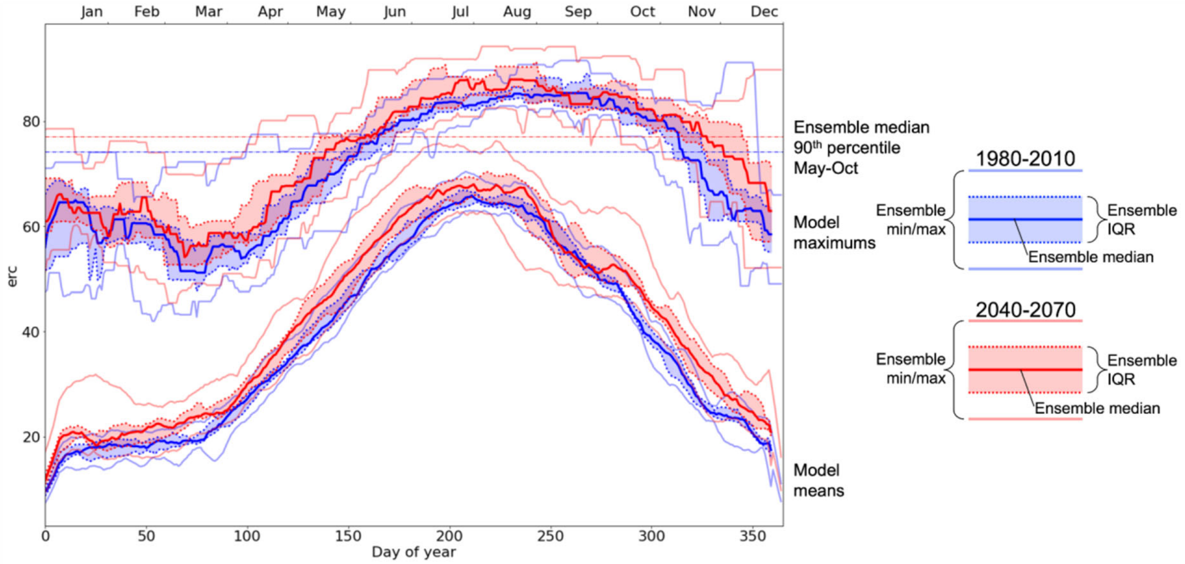

FIGURE 11 This figure presents future projections of ERC in a pocket card format. ERC is projected with an ensemble of climate models and calculated using NFDRS fuel model G for each of the 13 regional climate models, at the grid cell encompassing the burn area of the 2020 Creek Fire in Northern California. The model data for average and maximum ERC values have each been distilled down into 5 daily values: the model minimum, 25th percentile, median, 75th percentile, and maximum, which communicate the uncertainty associated with the model ensemble. The reference period (1980–2010) is shown with blue lines and blue-shaded IQR (interquartile range), while the midcentury future period (2040–2070) is shown with red lines and red-shaded Interquartile range (IQR). ERC, energy release component

> The last few years have put us in a reactive mindset. We need to be proactive in creating plans for the future.

> We need to seriously accept where we are and start applying what we know, we have to accept opportunistic fire. And we need much more fuel treatment around communities.

> The current workforce does not match need on the ground at present. We need different skill sets, need year-round crews, need more experience with fire behavior.

Climate change, which contributes to increasing fire weather and simultaneous fires, is a reality for these stakeholders. To proactively address risk, policy and management decisions must incorporate climate and fire projection to inform strategy. For example, US suppression policy is allowing wildfires that escape to have the greatest impact, since escape happens under extreme fire weather, while prescribed and managed fire generally burns under moderate conditions. Meanwhile, fuel reduction treatments, which are viewed as effective for mitigating long-term wildfire risk, cannot be effective at the current pace and scale of treatment. Because of this gap, fire management tends to be reactive, looking to the past to guide decisions, although the present context is already different than it was 30 years ago, and change continues.

4 | DISCUSSION AND CONCLUSIONS

Although we are still at the beginning of the coproduction effort, substantial changes to our individual and collective research approach to analysis and visualization have already occurred. We learned early to seek ways for innovative information to integrate into existing tools that are accepted by the fire operations and planning communities to better ensure acceptance and uptake—and this will continue. Our augmentation of the Pocket Card format ties comparisons of past experience and future projections to specific locations of major historic fire events which were intense and memorable, while also building on a trusted and valued tool. Our focus on simultaneous fire, and the shifting and expansion of fire season overlaps across regions, responds directly to the operational needs of fire danger briefing and response. Additionally, we are in the process of producing information pertaining to international resource sharing globally as competition and scarcity intensify (Bloem et al., 2022). Importantly, we have continued a deliberate pivot to sources of information that can support proactive decision making, while also taking care to generate visualizations that allow future projections to be interpreted in relation to both the observed and simulated past.

Convergence is an ongoing process that requires introspection while bringing research and science across boundaries, ultimately for application to real world needs for which it is not always a ready fit. With each new research activity our team must continue to strive anew to deepen convergence, as this process is never truly complete. One measure of success in this context is the continual return of team members to the conversation, centered on stakeholder needs. Important breakthroughs have come from stretching our scientific approach and objectives to bridge the gap between the format of information usually available and what is desired on the ground. As discussed, temporal and spatial scales commonly used in climate modeling and landscape ecology are not necessarily aligned, but centering stakeholder needs pushes researchers to converge.

In a similar vein, we are learning to highlight uncertainty that is salient for decisionmakers while being transparent about the assumptions that lie behind analysis. We devote attention to distinguishing model uncertainty from variability related to different future states of the world. We continue to shift the temporal scope of analysis to the near-term future for climate based projections where possible, while focusing on comparisons to the past to lend context to the most recent decade which has been unusual relative to the historic record. We also have developed an increased awareness of the geographic scales relevant to fire and landscape ecologists and the challenges associated with much coarser scales of inference for climate projections. Specifically, we have targeted analysis and visualizations on regional scales (GACCs) that are relevant for operations. Further, we have altered our approach to relative comparisons of fire and simultaneity, shifting from using absolute measures to using relative measures that reflect regional fire size distributions and local impact.

Although the COVID-19 pandemic presented many challenges for our convergence team, it also prompted us to hold substantive weekly meetings on video platforms, which brought many benefits. We all shifted to remote work in March 2020 and thus never met in person as a team, which might have accelerated convergence. Still, our reliance on Zoom meetings, shared documents and drives, and virtual whiteboard tools did not pose an actual barrier to convergence. For example, we did not save information exchange for what would have been infrequent face-to-face meetings.

While the COVID pandemic was changing the lives and interactions of the research team, our stakeholder partners (as fire operations and practitioner managers) were facing some of the worst fire seasons in modern US history. It is a testament to their interest in our shared work, and their need for climate information, that they have remained engaged, even sending occasional updates during the fire season. One measure of success in coproduction is realized when word of new and valuable information sources spreads organically, and new organizations become entrained. Through such channels our work has now influenced national budget priorities at DOI, and we have been invited to participate in local deliberations about prescribed fire tradeoffs through briefings for FEMA and the National Association of Counties.

As we continue into the next phase of coproduction, we carry the lessons learned in this initial work. If new tools and information are to be used in decision making, the relevant decisionmakers must be engaged deeply. Early career scientists are natural leaders in convergence because in many cases they are not yet deeply entrenched in a field or its self-perceived boundaries. All parties must be willing to participate in new ways of engagement beyond their field of expertise, including new ways of communicating about, and valuing, science and its applications. Satisfied practitioner partners are the best and fastest connection to new opportunities that build on past progress. If innovations are directly integrated with existing tools and framework, even modest changes in the information that is incorporated in very complex decision systems can represent huge progress. As fire and land managers look for guidance under a changing climate, convergence on innovative ways to incorporate new information and translate it into actionable decision support is both timely and imperative.

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APPENDIX A
WELCOME AND INTRODUCTION

- Thank you for making this time for our conversation.
- Introductions.
- Background on the project.
- What we hope to accomplish in this meeting
- We will be asking you a set of interview questions that we've prepared
- Our questions are organized around decision making, the 2020 fire season, and information sources.
- We'd also like to know who else we should be talking to.

QUESTIONS RELATED TO DECISION MAKING

1. What types of fire and forest management decisions are central to your work/role?
2. What is the time frame and spatial scale of the decisions central to your work?
3. What information do you use to support these decisions? For example, do you use historical climate records and/or future projections of climate? *If so, what type (ERC, live/dead fuel moistures, drought indices, snowpack, etc)*
4. If you knew from climate projections that large co-occurring fires would happen simultaneously much more often in your management area, how would that change your approach to the decisions that you make? At what spatial scale and what level of certainty would you need this information?

LESSONS LEARNED FROM 2020 FIRE SEASON

1. In your work, what was the most important characteristic of the 2020 season? What made 2020 most intense? What distinguished it most?
2. What information sources did you use in decision making before or during the 2020 fire season?
3. Did the 2020 fire season reveal any gaps in information? What could or would you do differently with better, more, or different information?
4. Based on climate projections or other factors over the past decade or so, were you anticipating that a season like 2020 would occur? If yes, what made you expect it?
5. If seasons like 2020 become more frequent, and simultaneous high-impact fire events become more common, what information would you use to inform longer term proactive decisions?
6. If new support tools or climate information become available, what is the process by which they could be incorporated into decision making? What does it take for something new to be accepted? What are the barriers and how might these be overcome?
7. If you received projections about the changing frequency of simultaneous large wildfires in your management area/region, could you act on that information? What barriers might prevent you from taking action?