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Five social and ethical considerations for using wildfire visualizations as a communication tool

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Abstract

Background Increased use of visualizations as wildfire communication tools with public and professional audiences—particularly 3D videos and virtual or augmented reality—invites discussion of their ethical use in varied social and temporal contexts. Existing studies focus on the use of such visualizations prior to fire events and commonly use hypothetical scenarios intended to motivate proactive mitigation or explore decision-making, overlooking the insights that those who have already experienced fire events can provide to improve user engagement and understanding of wildfire visualizations more broadly. We conducted semi-structured interviews with 101 residents and professionals affected by Colorado's 2020 East Troublesome and 2021 Marshall Fires, using 3D model visualizations of fire events on tablets as a discussion tool to understand how fire behavior influenced evacuation experiences and decision-making. We provide empirically gathered insights that can inform the ethical use of wildfire visualizations by scientists, managers, and communicators working at the intersection of fire management and public safety.

Results Study design, interview discussions, and field observations from both case studies reveal the importance of nuanced and responsive approaches for the use of 3D visualizations, with an emphasis on the implementation of protocols that ensure the risk of harm to the intended audience is minimal. We share five considerations for use of visualizations as communication tools with public and professional audiences, expanding existing research into post-fire spaces: (1) determine whether the use of visualizations will truly benefit users; (2) connect users to visualizations by incorporating local values; (3) provide context around model uncertainty; (4) design and share visualizations in ways that meet the needs of the user; (5) be cognizant of the emotional impacts that sharing wildfire visualizations can have.

Conclusions This research demonstrates the importance of study design and planning that considers the emotional and psychological well-being of users. For users that do wish to engage with visualizations, this technical note provides guidance for ensuring meaningful understandings that can generate new discussion and knowledge. We advocate for communication with visualizations that consider local context and provide opportunities for users to engage to a level that suits them, suggesting that visualizations should serve as catalysts for meaningful dialogue rather than conclusive information sources.

Keywords Risk communication, Wildfire visualizations, Modeling, Ethics, Wildfire social science, Marshall Fire, East Troublesome Fire, Public outreach, Research design, Decision-making

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Resumen

Antecedentes El uso incremental de visualizaciones como herramientas de comunicación en el tema de incendios de vegetación, con audiencias tanto públicas como profesionales – particularmente videos 3D y/o realidades virtuales– invitan a la discusión sobre sobre su uso ético en distintos contextos sociales y temporales. Los "Focus studies" existentes enfocan sus estudios en el uso de tales visualizaciones antes de los eventos de fuego, y usan escenarios hipotéticos para motivar mitigaciones proactivas o explorar procesos de decisión, pasando por alto las percepciones de aquellos quienes han experimentado eventos de fuego y que pueden proveer información para mejorar el compromiso y comprensión de la visualización de los incendios de vegetación de manera más amplia. Condujimos entrevistas semiestructuradas entre 101 residentes y profesionales afectados por los incendios de 2020 (Colorado Troublesome del Este) y del 2021 (Marshall Fires), usando modelos de visualizaciones 3D de eventos de fuegos en tablets como una herramienta de discusión para entender como el comportamiento del fuego influencia las experiencias de evacuación y los procesos de decisión. Proveímos de las perspectivas reunidas empíricamente que puedan informar sobre el uso ético de las visualizaciones de eventos de fuegos por investigadores, manejadores de recursos, y comunicadores que trabajan en la intersección entre el manejo del fuego y la seguridad pública.

Resultados El diseño del estudio, las discusiones sobre las entrevistas, y las observaciones de campo de ambos estudios de caso revelan la importancia de los matices y aproximaciones de respuestas en el uso de las visualizaciones 3D, con énfasis en la implementación de protocolos que aseguren que el riesgo de daños a la audiencia objetivo sea mínimo. Compartimos cinco consideraciones para el uso de visualizaciones como herramientas de la comunicación para audiencias públicas y profesionales, expandiendo las investigaciones existentes en el espacio del post-fuego: (1) determinar si el uso de estas visualizaciones va a beneficiar realmente a los usuarios; (2) conectar a los usuarios de las visualizaciones incorporando valores locales; (3) proveer el contexto sobre las incertidumbres del modelo; (4) diseñar y compartir visualizaciones que cumplan con las necesidades de los usuarios; (5) ser conscientes del impacto emocional que pueden tener este tipo de visualizaciones.

Conclusiones Esta investigación demuestra el éxito y la importancia del diseño y planeamiento del estudio que tenga en consideración el bienestar psicológico y emocional de los usuarios. Para los usuarios que no quieran comprometerse con estas visualizaciones, esta nota técnica provee de una guía para asegurar un entendimiento útil que pueda generar nuevas discusiones y conocimiento. Abogamos por comunicaciones y visualizaciones que consideren el contexto local que los contenga, sugiriendo que las visualizaciones deben servir como catalizadores para un diálogo constructivo más que como una fuente de información conclusiva.

Background

Both government entities tasked with wildfire management and scientists conducting related research increasingly use visualizations—particularly those created using model outputs—to enhance wildfire communication with different audiences or end users (Castrillón et al. 2011; Cheong et al. 2016; Preston et al. 2019). Visual materials can serve multiple purposes for hazard communication, including dissemination of warnings and public education, with the intent to communicate complex or nuanced scientific information such as place-based risk, protective actions or measures, and dynamic processes like fire behavior (Lipkus and Hollands 1999; Gill and Malamud 2014; Padilla et al. 2018; Dootson et al. 2023). Visualizations are explored in research related to wildfire training, operations, and public outreach as a vessel for improving risk communication and decision-making related to wildfire (McCaffrey 2006; Cao et al. 2016; Cortes et al. 2023). Many of these emerging efforts explore a shift from the use of 2D materials such as maps and still images to 3D formats that include virtual or augmented reality, interactive models, and videos (Clifford et al. 2018, Dootson et al. 2023). As the popularity of 3D visualization use grows, this technical note provides five empirically identified best practices for using wildfire visualizations as a communication tool with a focus on social and ethical considerations.

Integration of 3D visualizations into wildfire communication is relatively novel, meaning that there are numerous gaps in research and practice around their effective and appropriate use. Exploration of user interactions with visualizations *after* wildfire events is particularly needed; existing research tends to explore user perspectives prior to a wildfire, typically with the intent to motivate protective actions or mitigation activities, or during a wildfire in an effort to improve operational or evacuation decision-making (Cao et al. 2016; Clifford et al. 2018; Dootson et al. 2023; Molan et al. 2023). Such studies typically seek input from participants who have yet to experience a wildfire or who are training to respond to wildfire incidents, highlighting the need for exploration of ethical use of visualizations for communication with populations

who may have experienced loss or trauma from a wildfire (Molan and Weber 2021; To et al. 2021; Richards and Jacobson 2022). Lastly, few studies invite user critiques of visualizations, often assuming study participants will find value in this communication format. Social scientists are well-positioned to explore this assumption and examine the extent to which current visualization capabilities meet the needs of users, encouraging greater interdisciplinarity in this space (Molina León and Breiter 2020; Peek and Guikema 2021; Shah et al. 2023). We provide input that can inform these research needs and incorporate social and ethical considerations, drawing from lessons learned during case studies of two recent wildfires that included the use of visualizations to promote discussion with residents and professionals.

Approach

The considerations presented below emerged from two qualitative case studies of fire-affected communities that leveraged wildfire visualizations as discussion tools to examine how residents made evacuation decisions during these events. These case studies were part of a larger project focused on understanding the role of fire behavior in household evacuation decision-making. The first and second authors conducted 83 semi-structured interviews during the summer of 2022 and spring of 2023 with 101 residents and professionals affected by two wildfires respectively: 47 following the 2020 East Troublesome Fire and 50 following the 2021 Marshall Fire, in addition to four atmospheric scientists with expertise related to fire behavior and modeling for these events. Both fires occurred in the US state of Colorado, causing rapid, widespread evacuations in their respective areas before becoming the third and most destructive wildfires in state history respectively. Residents contacted to participate in this study had diverse identities within their respective areas that allowed a representative data set to emerge, including both full and part-time residents, renters and owners, and multi-generational families as well as newcomers. Professionals included in this study included federal and state land and fire management agencies, local government representatives, emergency management professionals, and local fire department staff among other roles. In order to participate, each interviewee must have been present at the time of the study fire in order to ensure they had first-hand experience to draw from when viewing visualizations. In some instances, participants were interviewed in pairs or small groups if they had a shared evacuation experience—for example, if they lived in the same household and evacuated together. Interview participants were recruited through a combination of theoretical sampling, whereby researchers identified individuals with specific expertise related to each fire through media coverage and staff directories, and snowball sampling, where participants were asked to suggest others who might be well suited for study participation at the end of each interview (Bryman 2012; Charmaz 2000). Recruitment only stopped once theoretical saturation was reached—that is, no new themes or findings emerged (Thornberg and Charmaz 2014). Interviews were audio-recorded with the permission of each participant. In one instance where an interviewee declined to be recorded, researchers took hand-written notes.

Interview protocol questions focused on the following topics: (1) perceived local wildfire risk and experience with previous fires and evacuation; (2) experience with the study fire, including when they first learned of it and how they decided whether to evacuate; (3) observations of the fire itself, including fire behavior and weather; and (4) opportunities to improve future evacuation experiences, including related communication and information sharing. Probing questions were frequently used to seek specific details about fire behavior, communication, and other observations or exchanges that influenced the interviewee's thinking; for instance, when discussing fire behavior, interviewees might be asked to describe the color or location of smoke, direction of the wind, etc.

Towards the end of each interview, researchers requested participant consent to introduce wildfire visualizations of the relevant fire event on a tablet where appropriate (see the last consideration below for more detail). A total of 75 interviewees agreed to participate in this portion of the study. In these instances, researchers encouraged interviewees to explore several visualizations depicting environmental conditions and fire behavior and discuss the extent to which they reflected their own understandings of the fire event, with the goal of identifying household decision-making processes related to fire progression and behavior over time in greater detail (Fig. 1). Visualizations can be shared across a broad range of platforms and technologies, including immersive experiences using virtual reality headsets, controlled rooms with surround technologies, and use of tablets, computers, or television screens (Hoang et al. 2010; Wetterberg et al. 2021; Clifford et al. 2018). We used tablets to share visualizations for multiple reasons, including their portability, intuitive touch screen interactions that a majority of interviewees would instinctively understand how to navigate, and lower cost relative to more immersive technologies (Akpan and Brooks 2012). Together, the intent of guiding and probing questions combined with the use of visualizations was to gather the most comprehensive account of the interviewee's experience with the study fire and detailed thought process behind their evacuation decision-making. Recommendations presented below represent an exploration of both

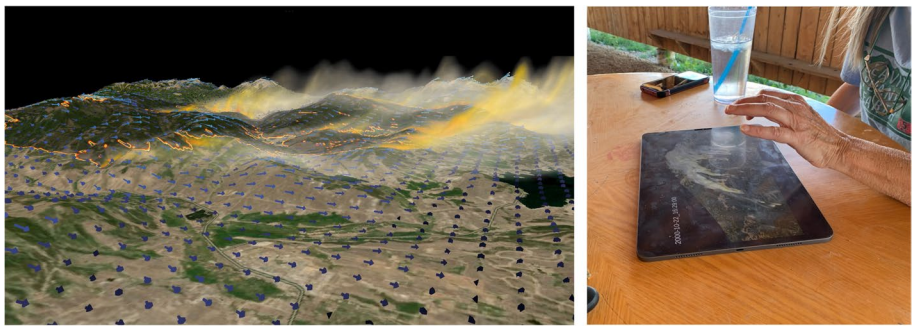

Fig. 1 Left, still image of a video visualization shown to interviewees during the East Troublesome Fire (picture credit: Scott Pearse), and right, a photograph of an interviewee interacting with that visualization on a tablet during an interview (picture credit: Catrin Edgeley). Arrows in each image indicate wind direction. Color gradients of the arrows depict wind speed, where lighter arrows show high wind speed and dark blue arrows show low wind speed. Fire perimeter is represented by a paired yellow and red line

researchers' ability to use wildfire visualizations as a qualitative data collection tool and residents' and professionals' ability to interact with visualizations and use them to interpret their own decision-making.

Several existing studies explore decision-making during wildfires or bushfires using visualizations (e.g., Molan et al. 2023); however, these efforts predominantly focus on understanding *intent* to evacuate, rather than lived evacuation decision-making experiences during a fire event (Molan and Weber 2021; Molan et al. 2022; Cao et al. 2016). Here, we focus on interactions with and perceptions of visualizations as communication tools in this context. Notably, most studies that use wildfire visualizations place imagery at the forefront of their methodologies (e.g., Molan et al. 2021); in this effort, they were secondary tools that supplemented discussion, allowing more organic interactions later in the interview as well as greater interviewee comfort offering critiques.

Visualizations were created using atmospheric models generated using WRF-Fire, a module within the Weather Research and Forecasting (WRF) modeling environment that can produce wildfire behavior simulations and capture its interactions with localized atmospheric and environmental changes. Model data were then visualized in VAPOR (Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers) (Li et al. 2019), a computer application that allowed generation of numerous visualizations recreating fire progression, flame fronts, wind direction and speed, terrain, and smoke generation from different angles to showcase specific fire behavior dynamics. Visualizations were presented as a sequence of 3D videos that interviewees could pause, rewind, or fast forward.

At the end of each interview, interviewees were invited to provide input on the visualizations, including which elements they did and did not find helpful, how they might foresee themselves interacting with such visualizations at different points in time, and whether they personally saw value in visualizations as a communication tool. The first and second authors documented feedback during each interview and discussed emergent themes across interviews during field work (Glaser and Strauss 2009). This entailed taking notes during the interview that were then reviewed together; in these discussions, the first and second authors identified any new information that had not emerged in previous interviews, and where appropriate, they crafted a line of questioning for subsequent interviews to determine whether this new information was anomalous or more widespread, meriting further investigation. At the end of each day in the field, the first and second authors wrote analytic memos together, which entailed note-writing about both the content of the interviews and the emergence of possible themes to draw from and expand upon during analysis (Saldaña 2021). We used NVivo, a social science analysis program, to qualitatively code the interview data; this process involves documenting commonalities and patterns across interview discussions through iterative rounds of categorization. Coding began with a round of descriptive codes that identified commonly discussed interview topics. The first and second authors began by identifying descriptive codes noted during the fieldwork memoing process, then sought to identify any additional descriptive codes that emerged during their reads of each transcript. The second round focused on thematic coding that identified common connections between topics to highlight integrated ideas across study fires (Saldaña 2021). One set of codes across both rounds focused on interviewee interactions with the visualizations; first, coded descriptively (e.g., "alignment with observed fire behavior" and "ideas to improve visualizations"), then thematically (e.g., "place-based connections improve risk communication"). At the outset of the coding process, the first and second authors separately coded a subset of

interviews and compared the outcomes to ensure consistent interpretation of the data—a process called intercoder reliability. During the initial stages of thematic coding, the first and second authors met several times with the other authors who provided model outputs and related visualizations to support interview work, sharing emergent themes related to visualizations. Discussions focused on translating these findings into recommendations that were actionable for scientists and practitioners; for instance, building on the example above about place-based connections to risk communication, we generated the second recommendation below that encourages the inclusion of local values within visualizations. The considerations below emerged through the iterative coding process associated with this subset of codes and associated author discussions.

Considerations for using wildfire visualizations

Determine whether the use of visualizations will truly benefit users

Many emerging studies that use wildfire visualizations for communication operate on the implicit assumption that end users want to interact with 3D or virtual environments and will inherently find value in visualizations as a communication tool. Our research suggests that the perceived value and necessity of visualizations are highly variable and that interviewees between case studies and within a given group (e.g., residents of the same community, local fire professionals) are not necessarily in agreement about the relevance of such visualizations for their own use based on personal context and experience with wildfire. For example, some opted not to see visualizations due to trauma caused by experiences associated with the study fire, while others felt a need to engage deeply with visualizations to more comprehensively understand the event they had experienced in order to promote their own healing. Those who had completed higher levels of education or worked in wildfire management and related fields more readily identified personal benefits to visualizations, while those with lower familiarity with technology were more hesitant to engage or felt that reviewing a visualization would not provide them with new information. Additionally, we found it helpful to have secondary forms of communication such as 2D maps and narrative information available to ensure that those who were not comfortable engaging with visualizations could still access information (Cao et al. 2016). Together, these observations indicate that the value of visualizations will vary significantly within and between populations, and therefore, their use should be intentionally tailored to reflect that diversity and employ protocols that can be adapted to the preferences of each potential user.

The appropriateness of introducing visualizations likely depends on numerous local and individual considerations. Existing studies indicate that there is little to no hesitancy to engage with visualizations prior to a wildfire or with populations that have not recently experienced a fire, suggesting that willingness to engage with visualizations varies significantly depending on an individual's temporal relationship with wildfire (Molan and Weber 2021; Dootson et al. 2023). The use of visualizations therefore may not be suitable for mass public communication such as large public meetings during or after wildfires, particularly if losses have or are likely to occur. Our research indicates that when individuals do want to engage with 3D wildfire visualizations, more nuanced communication and discussion related to fire dynamics emerge. Compared to those who declined to interact with visualizations, interviewees who did interact with visualizations demonstrated more detailed understandings of (1) the scale of the wildfire relative to their knowledge of the local landscape; (2) fire behavior, including the timing of fire progression across places they were familiar with, localized variations in fire behaviors, and how social and ecological impacts occurred temporally during fire events; and (3) experiences of friends and family in other areas of the wildfire by comparing how the fire progressed and behaved in different neighborhoods. Future research should explore the development of protocols for determining whether to share a visualization in broader public settings where individuals may have extremely varied histories with wildfire, and the extent to which use of 3D visualizations truly improves communication over 2D materials during and after wildfires.

Connect users to visualizations by incorporating local values

When visualizations are intended to recreate a wildfire that has already occurred or present hypothetical events within a specific landscape, rapidly orienting users to the geography of visualization is critical for accelerating accessibility and communication. In our first case study of the East Troublesome Fire, no local landmarks were labeled in visualizations and many interviewees relied on lake placement or input from the researchers to orient themselves. As a result, we engaged interviewees in discussions about what should be labeled to improve the visualizations. Common suggestions included roads, lakes, peaks, and city or town names. However, many also identified points of interest specific to fire events; for example, many Marshall Fire interviewees identified the Costco store in Superior as a key location that grounded their fire experience because many were in that area when they first learned of the fire or had to drive past the store to evacuate. Additionally, many residents used

colloquial, locally known place names rather than formal mapped place names to describe areas (e.g., Colorado Highway 119 north of Boulder is locally referred to as "the Diagonal"); identification and incorporation of these names may also help prevent confusion.

We suggest that for visualizations to connect users to specific fire events, researchers should first identify potential points of interest that go beyond basic map features to acknowledge user experiences with the modeled landscape (e.g., Fig. 2, where modification of a bird's-eye view visualization to a side angle was better received by users because it more clearly depicted the Flatirons, a familiar rock formation against a mountain range) (Parush and Berman 2004). This could be achieved using key informant interviews, systematic review of photographs taken by residents and professionals during the fire event on social media, or visual methodologies such as photovoice, which entails the collection of meaningful photographs from study participants that could identify common viewsheds. Efforts to incorporate these local waypoints into visualizations can result in a greater understanding of local ecological knowledge (place-based knowledge about a landscape, typically gathered through observations and shared experiences by those living there over time) among scientists and professionals. The use of local landmarks also leverages this knowledge through more intentional communication about the role of local ecological processes like wildfire in discussions about evacuation and land management, among other topics, which can help connect long-standing local ecological knowledge to new experiences or risks.

Provide context around model uncertainty

The use of model outputs in visualizations can help examine human decision-making under uncertainty, but the models themselves can also generate cascading epistemic uncertainties associated with the quality of data fed into visualizations (Cheong et al. 2016, Maslin 2013; Preston et al. 2019). Many professionals in our studies were hesitant to support the use of visualizations to communicate with the public because they were concerned that viewers would not understand the uncertainty produced by model inputs and might overestimate visualization accuracy when making decisions about safety as a result. Resident interviewees often did assume that visualizations were accurate representations of fire behavior and spread, but when engaged in discussion about model uncertainty, began focusing on broader takeaways instead of trying to understand highly localized processes (e.g., understanding broader patterns of fire spread rather than focusing on timing of modeled fire front arrival on their street that did not align with their lived experience). In both case studies, discussions emerged about whether visualizations should look realistic, with those who took a more analytical approach showing greater interest in high visual accuracy while those who were less comfortable sought the "animated" appearance of more basic visualizations. Concern regarding the possible emotional impacts of realistic visualizations aligns with existing discussions about the depiction of other visualized hazards like sea level rise (Richards and Jacobson 2022). Acknowledgment of uncertainty and discussion about the effect it has on user interpretation of communication goals—for example, the impact that transparency regarding uncertainty has on trust in evacuation messaging or other risk communication—should be central to future social science research that uses visualizations based on both real and hypothetical events (Howe et al. 2019, Speigelhalter and Riesch 2011).

We suggest that uncertainty related to the data used to generate visualizations should be communicated prior to the introduction of visualizations, or immediately upon viewing them to minimize epistemic risk or assumptions of model accuracy. We implemented this by pointing interviewees to an example of an area within a visualization that exemplified model uncertainty early on in the discussion to help ground their interpretation; for example, both the East Troublesome Fire and Marshall

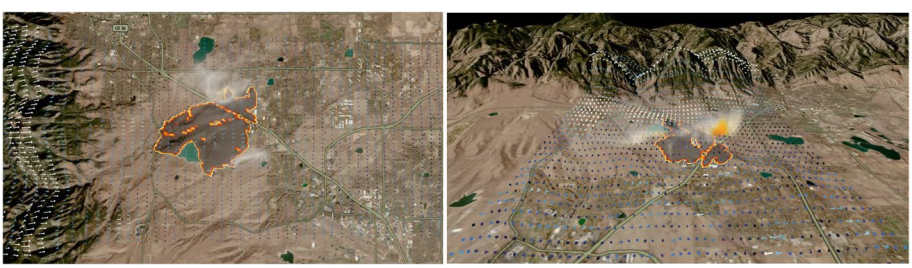

Fig. 2 Comparison of a generic visualization of the Marshall Fire shown from above (*left*) with a modified visualization that shows a perspective sought after by interviewees that provided spatial context and scale related to the Flatirons, a rock formation above the affected communities (*right*). Arrows in each image indicate wind direction. Color gradients of the arrows depict wind speed, where lighter arrows show high wind speed and dark blue arrows show low wind speed. Fire perimeter is represented by a paired yellow and red line

Fire exhibited behavior that was not captured in initial visualizations (e.g., jumping the Continental Divide and Highway 36, respectively), requiring modelers to manually enter this fuel break "jump." While this model intervention helped better simulate fire dynamics, it was not necessarily accurate in terms of the location of the jump or timing of that ignition. We were then able to engage interviewees in discussions about their interest in interacting with model visualizations that have uncertainty, and their capacity to make decisions with this new knowledge. Ensuring conversations about model uncertainty take place prior to visualization use is critical to contextualization; sharing visualizations on platforms where this discussion cannot occur or can be overlooked (e.g., posts on social media, web pages, or other places where users can selectively review information) may risk presenting assumptions of high accuracy that can lead to unsafe decision making during future events. Future studies could explore the influence of incorporating inaccuracies into the visualizations themselves, for example, by overlaying the actual fire perimeter with the modeled perimeter to demonstrate discrepancies.

Specific strategies for communicating model uncertainty may include (1) transparent discussion about limitations in the data used to create models that visualizations leverage and the compounding affect that may have on the quality and accuracy of the processes or events that visualizations present; (2) the generation of a suite of visualizations of the same event using different model data or parameters to demonstrate variation in accuracy and reliability while also simultaneously preventing overreliance on a singular output; (3) engaging audiences in simplified, low resolution modeling activities using beginner-friendly interfaces to allow them to experience decision-making about model inputs that could affect model uncertainty; (4) discussing biases that the end user may have both before and during review of visualizations; and (5) communication or outreach partnerships that include both scientists who create models, communication specialists, and local fire professionals to ensure that there is triangulation between trusted sources to consistently highlight uncertainty (Fischhoff and Davis 2014).

Design and share visualizations in ways that meet the needs of the user

Different visualization users may connect with the same content in diverse ways based on their understanding of the local landscape, meaning that one single visualization may not meet the needs of varied populations and professions. Our findings indicate that an emphasis on user takeaways may be a helpful starting point for visualization design and content due to the assortment of different information needs they may have. To achieve this, we suggest determining the suite of potential user types and how their needs vary for a given place or study. Our case studies revealed several different visualization end-user groups (Table 1) with varied needs; for instance, when reviewing wind-focused visualizations with barbs to show direction and speed, we found that fire professionals sought as much detail as possible in an effort to understand both large-scale fire behavior and the extent that local dynamics played into broader fire activity. Conversely, residents found high levels of detail overwhelming and instead prefer mid- or high-level information generalized for specific locations that illustrated overarching patterns in fire behavior. Consideration for the needs of residents as end users, in this instance, would mean diminishing the spatial resolution of wind data sought by fire professionals in favor of greater geographic understanding of the visualization as a whole. User groups were identified and refined via the interview recruitment process, memoing between the first and second authors during field work, and triangulation with interviewees by asking for both their own perceived uses for visualizations and how they thought others might use them. We note that wildfire management professionals and emergency management and law enforcement interviewees shared similarities in the ways they interacted with visualizations, while mental health professionals and residents also bore similarities.

Determining how users initially approach a visualization and then seek to interact with it may also be critical. First, the level of user familiarity with a landscape dictated their process for orienting themselves to the visualizations; users who were personally impacted by the fire being visualized sought familiarity within the landscape being visualized first to orient themselves prior to investigating additional layers of fire information, whereas those with operational wildland fire or emergency management experience prioritized fire layers and then integrated their interactions with the landscape underneath. Second, the level of control and interactivity a user had over a 3D visualization had a significant impact on the ways they saw themselves interpreting and using visualization content. We shared visualizations on tablets that allowed users to control the speed of visualization videos in order to consume information at their own pace and discuss their experiences at differing points in time. However, many interviewees across user groups wanted to be able to zoom in without pixelation or adjust their viewpoint within the same visualization rather than having to seek out another video produced from a different angle. Future research may benefit from the comparison of static visualizations with interactive immersive visualizations on portable devices like tablets, or examination

Table 1 An overview of potential applications for wildfire visualizations across different user groups that emerged during case studies, illustrated with representative quotes from interviewees

User group	Potential visualization application(s)	Examples of interviewee discussion about visualization use
Wildfire management professionals (e.g., incident command, fire chiefs, volunteer, seasonal, or career firefighters)	• (Re)building trust with communities • Tabletop/training exercises • Incident Management Team briefings and handovers	"We have cooperators come in from Texas, Wyoming, Oregon, Washington, California, they show up, they don't know the area. They look at a topographical map and they're like, "Okay, I know how to read a topo map, but what type of fire behavior would you expect to see in this topographical map?" So this type of information, sit down those teams out and show them this [visualization]. I know for me, if I went to somebody else's area, this would be huge."
Mental health professionals (e.g., counselors, therapists, recovery specialists)	• Discussing and processing traumatic events	"[Visualizations] would be useful with addressing trauma. PTSD [Post-Traumatic Stress Disorder]. Because what happens is, the disassociation and bracketing of the event is closed out and one of the problems is reprogramming to accept and be able to deal with the event that you went through."
Diverse publics (e.g., residents of place-based communities, landowners)	• Gathering event information • Understanding the fire's behavior as a whole, rather than at one location	"Honestly, if this [visualization] was something that had been happening as we were watching it [the fire] progress, I think that would've saved a lot of what made heartache for people. But also, given a lot of insight into the power of this particular fire. We all knew it was big, but we couldn't get any information about how big and where."
Emergency management and law enforcement (e.g., Sheriff's Office, emergency managers)	• Justifying evacuation decisions • Communicating public safety challenges • Planning future evacuations	"Let's say it [the fire] doesn't do what we thought it would do. You packed up your stuff, you were ready, you left, you went somewhere and annoyed somebody at their house or whatever for a few days. Now, you're back at home. Your house is still here. Worst case scenario, we can show you what [fire] can do and it makes it real to people."

of the transferability of model visualizations into existing interactive platforms such as Google Earth.

Our research examined visualization use across two fires that occurred in different social and ecological contexts, and variation in critiques and discussions about the use of such outputs among interviewees highlighted both the versatility of visualization applications and nuances in design considerations for different users and contexts. The most common perceived uses of wildfire visualizations shared by interviewees are presented in Table 1. Ideas presented in Table 1 highlight both the transferability of visualizations across diverse social environments and an assortment of research avenues for further exploration of visualization design and use.

Be cognizant of the impact that sharing wildfire visualizations can have

Wildfire visualizations—particularly those that recreate real fire events—contain information and imagery that may have significant impacts on the mental health or well-being of those affected, or those who have experienced similar experiences. Researchers have an ethical duty to minimize or remove the potential for adverse emotional impacts on study participants and therefore should think carefully about the unintended consequences that sharing such information may have and plan accordingly (Haggerty 2004; Goldstein and Kennedy 2022). We spent time determining how we would address this risk beyond what was required by our institution's Institutional Review Board process for screening human subjects research, and identified two key components: developing a protocol that protects the interviewee, and ensuring that the interviewee was in control of what they chose to view.

Our interview protocol had several key "checkpoints" that helped determine whether to proceed with sharing visualizations. First, during the earlier portions of our interview protocol, we sought to indirectly determine interviewees' comfort level with discussion of fire events, with particular attention to indicators of common mental health conditions related to wildfire such as PTSD, anxiety, depression, grief, or stress (To et al. 2021). Both first and second authors completed training related to the identification of indicators related to mental health conditions prior to field work and paid attention to interviewee responses, language and speech patterns, body language, and willingness to engage in different kinds of questions. If the lead interviewer determined that the interviewee appeared comfortable, we then sought their permission to explain what the visualizations would show to help inform their decision to continue. At this point, we asked for explicit permission to open the visualizations and share them with interviewees. If they agreed, we introduced the tablet with a folder of labeled visualizations for them to interact with. Interviewees were then able to select visualizations and start, pause, stop, or rewatch content at their own pace in line with their level of comfort. Our protocol evolved over the course of these studies as we met with more interviewees and gained a greater understanding of social contexts surrounding fire experiences. The protocol also varied slightly between fires as interviewees affected by the East Troublesome Fire tended to show greater disinterest in visualizations and declined to view them because they didn't see value in such materials, whereas Marshall Fire interviewees had greater interest but were often less comfortable with viewing their content. Researchers and professionals who share wildfire visualizations must be attentive to user reactions and responses; the proactive establishment of research protocols like the process described above for determining whether to proceed with certain questions or materials can provide a framework for mindfully navigating potentially distressing topics with specific audiences.

Researchers and professionals planning to use visualizations with populations affected by fires should first seek to understand where end users currently stand emotionally; this can be explored through key informant discussions with community leaders or local fire professionals who have greater insights into how community members are collectively emotionally processing a wildfire. If it is still deemed appropriate, discussion about how the visualizations should be shared within that context is critical. For example, it will be important to know whether it is better to share this with small groups or individuals instead of projecting it onto a screen for a large crowd. Importantly, while the majority of a community or population may be making positive progress towards emotionally processing a wildfire event, that does not necessarily reflect an individual's state given the potential for significant variability within a group. The use of trigger warnings or similar statements at the beginning of such events that briefly describe forthcoming content and invite attendees to leave the room if needed can also prevent unintended trauma. Similarly, the level of control users need over the visualization (e.g., the ability to start or stop it, bring it up or put it away, duration it is shown for) is also important. There may be no need to provide the viewer control of a visualization if the fire was a distance away and caused little social impact to users and a researcher or practitioner can decide what is shown; however, if the fire was destructive and caused a significant loss, the absence of control or no opportunities to "opt out" of viewing visualizations could cause significant distress or harm. We note that interest and comfort with viewing visualizations related to fire events likely will

change over time and that it may be easier for individuals to interact with visualizations once more time has passed.

Conclusion

This technical note presents best practices for using wildfire visualizations with end users after wildfire events, seeking to provide social and ethical guidance for research and application at this nexus. The considerations reviewed here are summarized in Table 2 and collectively underscore the importance of social contextualization surrounding wildfire visualization use. The data used to develop these considerations emphasize how wildfire visualizations can have significant benefits for risk communication, relationship building, and knowledge sharing around wildfire, but only when they are introduced appropriately with consideration of the social contexts they are being shared in and the impact they may have on the user(s). Visualizations may not always be necessary or appropriate as a communication tool, and where misused or introduced without appropriate contextualization, could have the potential to cause significant harm or generate misinformation. As the use of visualizations become more prevalent, researchers and practitioners using these tools must take the time to develop a deeper understanding of local conditions and experiences in order to ensure their approach is considerate and appropriate. Additionally, visualizations were often a productive tool for generating depth of discussion about a fire event, leading to reflective discussions about evacuation management and public safety. As a result, we suggest that visualizations should be operationalized as a starting point for engaging users in meaningful discussions about wildfire and its management, rather than an end point or conclusion to social processing of an event.

The considerations presented above highlight several challenges and opportunities for future research and risk communication using wildfire visualizations. While this study focused largely on evacuation, future studies may seek to explore other components of human experiences with fire such as air quality. We also believe that these cases may provide a template for ethically considerate studies of other hazards such as hurricanes or flooding using visualizations. Other avenues for exploration are tied to software capacity; the creation of 3D visualizations is complex, resource-intensive, and time-consuming, meaning that utilization of visualizations during

Table 2 Best practices for using wildfire visualizations with varied end users, including suggested considerations for the development and use of visualizations in future research and communication efforts

Best practice	Considerations for the development and use of visualizations
Determine whether the use of visualizations will truly benefit users	• Will providing visualizations improve communication compared to simpler visuals such as maps or photographs? • Does the visualization and its content truly benefit the user? • Is this the right time to share this kind of information?
Connect users to visualizations by incorporating local values	• What local values or places of importance can help improve visualization accessibility and navigation? • Are there some perspectives, areas, or processes that are more important to visualize in order to achieve the visualization's intent? • Is it possible to collect preliminary data or partner with a key informant(s) who can share insights regarding which spatial framings of the model or visual data might be most useful to users?
Provide context around model uncertainty	• How will the location or platform of the visualization be shared through support or prevent communication about uncertainty? • What examples can be provided to demonstrate uncertainty at a level that the user will understand? • Will more realistic visualizations be interpreted as more accurate by the user?
Design and share visualizations in ways that meet the needs of the user	• What level of detail do users need to understand visualizations? • How familiar are users with the processes being modeled and visualized? • How can visualizations be presented in ways that allow users to connect with the most important information?
Be cognizant of the impact that sharing wildfire visualizations can have	• Has there been a wildfire in the user's area recently? • Is there local conflict or concern around the wildfire or area being presented in the visualization? • Is the visualization being shared by an organization that the user trusts? • To what extent can users have control over the timing and duration of the visualization so that they can step away if needed? • How will researchers or practitioners sharing the visualizations assess if users have the capacity to interact with such content? • How will those sharing visualizations communicate the content of the visualization so that potential users can make an informed decision on whether they are comfortable viewing it?

wildfire events may not always be feasible. VAPOR, the software used to generate our visualizations, can be integrated with servers that have graphics cards to allow real-time generation of visuals, indicating that opportunities to explore social responses to real-time use of wildfire visualizations are forthcoming. Another common interest among interviewees was the ability to engage with more interactive versions of the visualizations we prepared; the use of Python to code model data into HTML formats can allow this, and we also encourage the exploration of opportunities to import visualization data into existing platforms like Google Earth to support more personalized experiences. Both opportunities necessitate renewed examination of ethical approaches to visualization use, in addition to introducing the need for additional contextualization around uncertainty, particularly in the case of real-time visualization generation.

As technocratic solutions to risk communication around wildfire are increasingly sought after, this technical note invites caution and care around their use with the public, particularly in communities that have recently experienced impactful fire events. Existing wildfire social science research also extensively documents variances in social contexts across communities that lead to divergent approaches, understandings, and attitudes towards wildfire, underscoring the importance of avoiding a one-visualization-suits-all approach. The considerations outlined here were developed after two case studies, each within a different social context; we invite future efforts that conduct similar research to expand on these considerations by working in different contexts, states, and fire conditions to support the advancement of the most appropriate and ethical use of visualizations across different end users.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
PTSD	Post-traumatic stress disorder
VAPOR	Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers
WFDSS	Wildland Fire Decision Support System
WRF	Weather Research and Forecasting

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Authors' contributions
CE: study conception and design, data collection, analysis and interpretation of results, manuscript drafting and revision; WC: data collection, analysis and interpretation of results, manuscript drafting and revision; SP: visualization creation, manuscript revision; BK: model creation, manuscript revision; GP: model creation, manuscript revision; RK: model creation, manuscript revision.

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Availability of data and materials
Data for this manuscript are IRB-protected; therefore, we are unable to share interview materials with others.

Declarations

Ethics approval and consent to participate
This study was approved by the Northern Arizona University Institutional Review Board as exempt, project #1806004. Participants provided informed oral consent to participate in this study and to be audio recorded.

Consent for publication
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The authors declare that they have no competing interests.

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