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Roadmap for the future of extreme wildfire events

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Abstract

Background Extreme wildfire events (EWEs) represent a growing threat globally, posing substantial risks to ecosystems, human communities, and infrastructure. Despite increased recognition of their ecological, social, and economic significance, current definitions of EWEs vary widely, reflecting disciplinary biases and regional contexts. This article emerges from an interdisciplinary workshop convened to reassess and refine the definition of EWEs, examine their impacts across ecological and social dimensions, and identify critical knowledge gaps impeding our understanding of these infrequent but important events.

Results Our synthesis highlights significant limitations with existing definitions, particularly their reliance on subjective thresholds and their emphasis on extreme fire behavior alone. EWEs encompass a spectrum of complex, multi-dimensional phenomena that extend beyond immediate biophysical characteristics to include cumulative social, economic, and ecological impacts. These impacts often manifest over extended timeframes and include hazardous environmental contamination, severe geomorphic disturbances, ecosystem transformations, and unintended consequences of post-fire management actions. Current wildfire modeling frameworks inadequately capture these compounding factors, particularly the interactions among social systems, ecological conditions, and extreme fire behavior. To overcome these issues, we advocate for an interdisciplinary and context-sensitive approach to defining and studying EWEs. This revised definition emphasizes wildfires exhibiting anomalies in fire behavior, ecological outcomes, or social impacts relative to historically observed baselines, accommodating variability across different geographic regions and ecological settings.

Conclusions Adopting an interdisciplinary framework that integrates biophysical and social sciences will enhance the predictive capability of wildfire models and improve resilience planning and response strategies. Filling identified knowledge gaps—such as limited high-quality empirical fire behavior data and insufficient integration of social dynamics into modeling—will better prepare communities and ecosystems to cope with and adapt to EWEs. This inclusive approach underscores the necessity for collaboration across disciplines and sectors, essential to managing extreme wildfires in an era of increasing climatic and ecological uncertainty.

Keywords Extreme wildfire events, Wildfire modeling, Ecological impacts, Social dynamics, Interdisciplinary research, Wildfire resilience, Community vulnerability, Climate adaptation, Disaster management

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Resumen

Antecedentes Los eventos de fuegos de vegetación de comportamiento extremo (*Extreme Wildfire Events* o EWEs en inglés), representan una amenaza global, exponiendo a riesgos substanciales a ecosistemas, comunidades humanas, e infraestructura. A pesar del reconocimiento sobre su significado ecológico, social y económico, las definiciones actuales de EWEs varían ampliamente, reflejando sesgos disciplinarios y contextos regionales. Este artículo emerge de un taller de trabajo enfocado a re-determinar y refinar la definición de EWEs, examinar sus impactos a través de dimensiones sociales y ecológicas, e identificar vacíos en el conocimiento que impiden nuestra comprensión de estos eventos infrecuentes pero muy importantes.

Resultados Nuestra síntesis resalta las limitaciones significativas de las definiciones actuales, particularmente su dependencia de límites subjetivos y su énfasis solamente en fuegos de comportamiento extremo. Los eventos de fuegos de vegetación de comportamiento extremo abarcan un espectro de fenómenos complejos y multidimensionales, que van más allá de sus características biofísicas inmediatas y que incluyen impactos sociales, económicos y ecológicos. Estos impactos se manifiestan frecuentemente en largos períodos de tiempo e incluyen los peligros de contaminación ambiental, disturbios geomórficos severos, y consecuencias no intencionales de acciones de manejo en el post fuego. Los marcos conceptuales actuales de modelado de los incendios de vegetación capturan de manera inadecuada la composición de esos factores, particularmente las interacciones entre los ecosistemas sociales, las condiciones ecológicas y el comportamiento extremo del fuego. Para superar esta dificultad, abogamos por una aproximación interdisciplinaria y contexto-sensitiva para definir y estudiar los EWEs. Esta definición revisada enfatiza los eventos de fuego como que exhiben anomalías en su comportamiento, en las consecuencias ecológicas o en los impactos sociales relativos a la línea de base histórica observada, acomodando su variabilidad a lo largo de regiones geográficas y a ajustes ecológicos.

Conclusiones El adoptar un marco conceptual interdisciplinario que integre las ciencias biofísicas con las sociales, va a aumentar la capacidad predictiva de los modelos de fuegos y mejorará el planeamiento de la resiliencia y las estrategias de respuesta. El llenar los vacíos en el conocimiento –como el limitado acceso a datos empíricos de calidad sobre comportamiento del fuego, y la insuficiente integración de la dinámica social en los modelos– mejorará la preparación de las comunidades y ecosistemas a ajustarse y adaptarse a estos EWEs. Esta aproximación inclusiva subraya la necesidad de colaboración entre disciplinas y sectores, esenciales para manejar eventos de fuego extremos en una era donde se está incrementando la incertidumbre, tanto climática como ecológica.

Overview

Most wildfires are small in terms of area burned, but a rare few become very large or extremely fast-moving incidents that exhibit exceptional fire behavior and have severe ecological and socio-economic consequences. Such wildfires tend to overwhelm suppression capabilities, cause substantial impacts to human infrastructure and the environment, and may result in civilian and firefighter fatalities. As they gain attention globally as environmental phenomena that negatively affect society and the environment (Bowman et al. 2009; Khaykin et al. 2020), extraordinary wildfires have been linked to a combination of factors, including climate change, fuel accumulation, and expanding human development into fire-prone landscapes (Halofsky et al. 2020; Pausas and Keeley 2021). These events often defy conventional fire management approaches, and their impacts can cascade across systems—disrupting transportation, degrading air quality across entire regions, and causing long-term ecological transformations. As such, they are now recognized not only as a fire management

challenge but also as a critical issue in climate adaptation, public health, and disaster resilience planning.

In the past five years, several wildfires have exhibited exceptional fire behavior and inflicted extensive damage on human infrastructure and vegetation. The Labor Day Fires of Oregon, USA, which occurred in September 2020, produced the most destructive simultaneous wildfires in the state's history. The Labor Day fires required 40,000 people to evacuate and burned 486,000 ha (1.2 million acres) of land, destroyed over 5000 homes and businesses, and claimed nine lives (Oregon Debris Management Task Force 2022). The fires were caused by an intrusion of dry air and strong east winds that averaged 32–48 kph with gusts up to 160 kph (Oregon Department of Forestry 2022). When these climatic conditions intersected with heavy fuel loads and abnormally low fuel moisture content due to months of below-average precipitation, these conditions produced fire behavior that was challenging for firefighters to contain, especially given the topographic conditions of the Oregon Cascades. More

recently, the wildfires in Los Angeles, California, USA included the Palisades fire and the Eaton fire which are among the top ten deadliest and top three most destructive wildfires in the history of California (CalFire 2025). Similar to the Oregon wildfires, these wildfires were characterized by 45 m s^{-1} gusts, complex terrain, heavy loads of fine fuels and a significant amount of ember casting that ignited a large number of structures, especially within the wildland urban interface (WUI). Many of these common factors can be identified as “syndromes” of other significantly destructive wildfires such as the 2016 Great Smoky Mountains wildfires (TN, USA), 2016 Fort McMurray fire (Alberta, Canada), 2018 Camp fire (CA, USA), 2023 Hawaii wildfires (HI, USA), among others. These fires are not necessarily unprecedented in their location, size, and high rates of spread. However, the intersection of destructive fires with built environments and detrimental impacts to ecosystems have increased in recent years (Daniels et al. 2020), at times resulting from invasion by non-native species and climate change (e.g., 2023 wildfires in Hawaii, 2025 Palisades Fire).

While often used interchangeably to label extraordinary wildfires, “megafire,” “extreme wildfire,” and “disaster” are actually distinct concepts. However, they remain challenging to define and therefore distinguish among them. The term “megafire” initially emerged to describe large fires in the western US, but later its usage became widespread in other regions of the world (Buckland 2019; Linley et al. 2022). Megafire is often defined based on fire size but lacks a universally accepted size threshold, given that what constitutes a large fire is different across ecoregions throughout the world (Stoof et al. 2024). Given the ambiguity associated with the term “megafire,” the term “extreme wildfire event” or EWE is gaining popularity (Tedim et al. 2018). EWE is not defined by size, but rather encompasses the complex nature of these events, and the relevant physical, ecological, and social dimensions of wildfires associated with these rare but extraordinary events. The current definition by Tedim et al. (2018) defines an EWE as a “pyro-convective phenomenon with overwhelming capacity of control (i.e., fireline intensity currently assumed $10,000 \text{ kWm}^{-1}$; rate of spread $> 50 \text{ m/min}$), exhibiting spotting distance $> 1 \text{ km}$, and exhibiting erratic and unpredictable fire behavior and spread. These events represent a heightened threat to firefighters, communities, infrastructure, and ecosystems, and often result in detrimental socio-economic and environmental impacts.” This definition of EWE has gained traction as a way to describe extraordinary wildfires, emphasizing anomalous fire behavior over sheer size.

In this context, Tedim’s description of EWE also distinguishes between anomalies in fire behavior and anomalies in the consequences on human settlements or

ecological systems (Tedim et al. 2018). In their definition, an EWE can lead to a disaster; however, a disaster is not always a result of an EWE (Fig. 1). The authors advocated for the use of the term “disaster” to delineate wildfires with anomalous consequences. Wildfire disasters exceed the resource capacities of people and communities, often due to a lack of preparedness, inadequate event management, extreme weather conditions, and land-use decisions, resulting in significant disruptions to social systems and infrastructure.

The advantage of separating EWEs from disasters is that it provides a conceptual delineation of the biophysical characteristics of a wildfire independent of other factors that may influence the scope of impact a wildfire has on human settlements and ecological systems. As demonstrated in the 2025 Southern California wildfires, the scope of destruction caused by a wildfire can be the result of a complex array of physical, social, and economic factors not directly tied to anomalies in the behavior of the wildfire itself (Brown and Shelton 2025). However, this approach to describing EWEs reinforces disciplinary silos rather than inviting interdisciplinary engagement across scholars with expertise in the biophysical, social, institutional, and economic aspects of wildfire.

This paper stems from the extreme wildfire events workshop held in Boulder, Colorado in September 2024, hosted by the Environmental Data Science Innovation & Inclusion Lab (ESIIL). The workshop convened a diverse, interdisciplinary group of researchers across the biophysical, social, and data sciences to address the growing complexity of EWEs. Specifically, this collaboration aimed to (1) synthesize our current understanding of extreme fire behavior, (2) identify critical gaps in knowledge about the social and biophysical drivers of EWEs and their risks to communities, and (3) develop a roadmap for improving how these events are represented in models that integrate social and ecological processes. In this paper, we build on the discussions and insights generated during the workshop to assess the challenges of current definitions, evaluate cross-disciplinary perspectives, and highlight priorities for future research and modeling frameworks related to EWEs.

Problems with the current definition of an extreme event

Subjectivity based on disciplinary perspectives

Despite Tedim’s proposed definition (Tedim et al. 2018), there are still not universally agreed-upon thresholds or criteria for what makes a wildfire “extreme.” The term itself is inherently subjective, and perceptions of what constitutes an EWE vary widely across regions, disciplines, and stakeholder groups. Context plays a major role in determining if an EWE has “detrimental

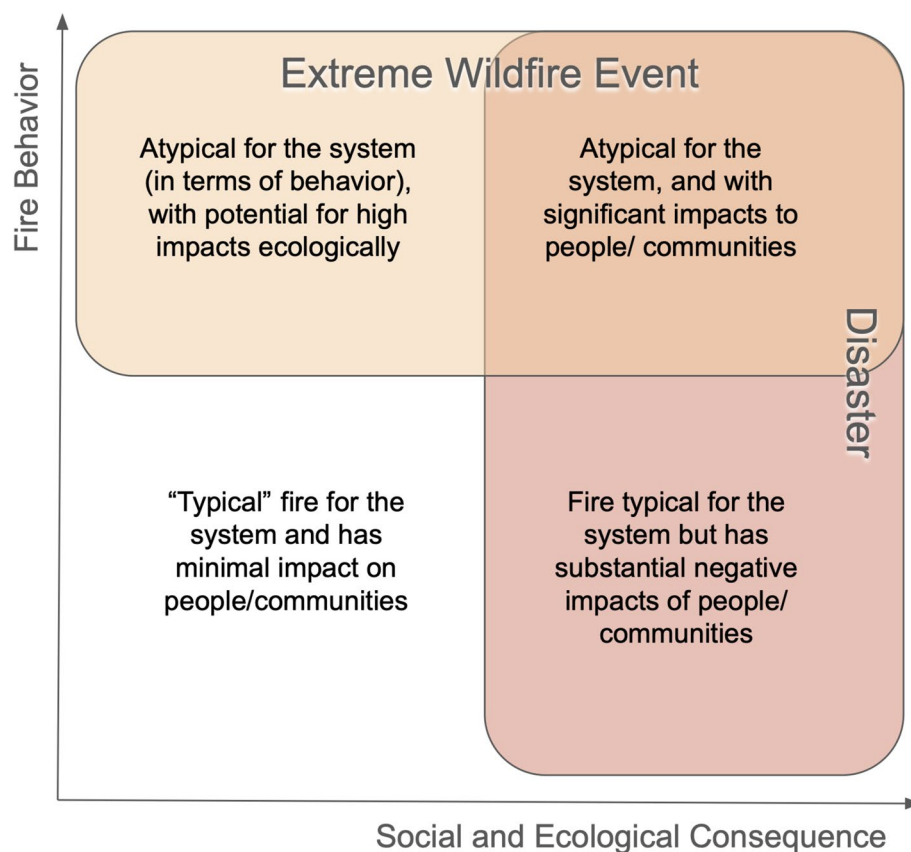


Fig. 1 Conceptual diagram illustrating the distinction and overlap between extreme wildfire events (EWEs) and wildfire disasters as discussed in Tedim et al. (2018). The vertical axis represents the degree to which observed fire behavior deviates from the typical range for a given ecosystem, while the horizontal axis represents the magnitude of human consequences. EWEs are characterized by atypical fire behavior, whereas disasters are defined by substantial negative social impacts. This highlights that an EWE does not always lead to a disaster, and that a disaster may occur without extreme fire behavior

socio-economic and environmental impacts” (Tedim et al. 2018). One community may define an event as extreme based on suppression challenges or loss of life, while another may focus on ecological transformations, economic damages, or cultural loss. For example, the destruction of a single home may be viewed as catastrophic by an individual or family, but the burning of a community gathering place—such as a church—can have wider cultural and social ramifications. Others may define extreme events by fire behavior metrics (Hantson et al. 2022; McFarland et al. 2025), long-term ecological shifts such as type conversion (Coop et al. 2020), or cascading hazards like erosion, landslides, and flooding (Jones et al. 2014; Brogan et al. 2017). This variability in perspective raises the question: who is the intended audience, and what framework is being used to assess extremity? Different disciplines tend to emphasize either the vertical axis (atypical fire behavior) or the horizontal axis (social consequences),

contributing to different interpretations of what constitutes an “extreme” event (Fig. 1).

Disciplinary perspectives further shape how EWEs are conceptualized and studied. Biophysical scientists often focus on fire behavior characteristics such as intensity, rate of spread, and fire radiative power (FRP), while social scientists prioritize community vulnerability, governance, and recovery. For example, Cunningham et al. (2024) assessed global trends in ‘energetically extreme’ wildfires using FRP as a proxy and found a doubling in their frequency over the past two decades. Yet their work also acknowledged broader impacts, including carbon emissions, smoke exposure, and social and ecological consequences. Relatedly, terms like fire intensity and burn severity are often conflated but refer to distinct phenomena—fire intensity captures energy release and flame characteristics, while burn severity reflects post-fire ecological effects such as biomass loss and vegetation mortality (Keeley 2009; Cunningham et al. 2024). Interestingly, while Cunningham et al. (2024) observed a global decline

in average fire intensity, they also reported increasing trends in burn severity across more regions than those showing declines. Similarly, although global burned area has decreased over recent decades (Cunningham et al. 2024), certain regions—including Canada (Hanes et al. 2019), the western US (Parks et al. 2025), and the Eurasian boreal forest (Li et al. 2024)—have experienced substantial increases in area burned. These findings highlight the importance of considering both the disciplinary lens and scale when defining and interpreting what makes a wild-fire event “extreme.”

Scale of impact

Assessing the scale and scope of wildfire impacts adds complexity to defining extreme wildfire events (EWEs), as the values at risk during wildfires are diverse, encompassing social, ecological, and cultural resources. While extreme fire behavior and rapid spread often dominate public perception, focusing solely on these characteristics can be misleading. For instance, a fire whirl might meet established criteria for extreme fire behavior thresholds, but only cause minimal lasting impacts. Conversely, a slower-moving, lower-intensity fire might significantly damage infrastructure, ecosystems, or culturally important landmarks. This aligns with the lower-right quadrant of Fig. 1, where fires with otherwise typical behavior become disasters due to high exposure, limited suppression capacity, or social vulnerability, rather than extreme fire behavior. Therefore, it is crucial to consider additional factors, including risks to human safety, threats to the built environment, and the effectiveness and availability of firefighting resources. Synthesis methods integrating these multiple dimensions can significantly advance our understanding of EWEs and support more effective, context-appropriate firefighting and mitigation strategies.

Developing a globally relevant and quantifiable definition for EWEs remains challenging given the broad variability in ecosystem characteristics, community vulnerabilities, and historical fire regimes. An event considered extreme in one location might be within the natural variability of another region. For example, a high-severity fire might be ecologically beneficial in fire-adapted grasslands but could lead to irreversible damage in forests that historically experienced frequent low-severity fires. Additionally, fires may exhibit intense conditions only briefly or in localized areas, complicating their classification as extreme. Thus, there is a need for flexible, context-specific frameworks adaptable to different biophysical and social dynamics, while still providing consistency in managing and understanding EWEs across diverse regions.

Compounding/cumulative and second order impacts

EWEs frequently result in impacts extending well beyond the immediate fire damage, producing complex, compounding, and cumulative second-order consequences often over long timeframes (Moody et al. 2013). Post-fire landscapes, especially in areas where built infrastructure is affected, often pose significant environmental health hazards due to the presence of hazardous materials released from burned structures (Brown and Shelton 2025). The destruction of homes and buildings can result in the contamination of soils and waterways by heavy metals, asbestos, polycyclic aromatic hydrocarbons, and other toxins. This contamination may persist long after the wildfire has been extinguished, posing ongoing threats to public health and complicating cleanup and rebuilding efforts.

Additionally, EWEs can trigger severe geomorphic responses such as flooding, erosion, and landslides (Moody and Martin 2001; Robichaud et al. 2008; Higuera 2020), which may not be considered in the initial characterization of “detrimental socio-economic and environmental impacts” (Tedim et al. 2018). These events often result from vegetation loss and soil hydrophobicity, which greatly reduce infiltration and increase surface runoff (Ebel et al. 2012; Gould et al. 2016). For instance, debris flows and flooding after the 2021 Dixie Fire in California significantly exacerbated community recovery challenges. Such geomorphic disturbances can damage critical infrastructure and further degrade watersheds, leading to long-term changes in landscape structure and ecosystem function, such as altered sediment regimes and water quality degradation.

Wildfires can also initiate ecological transformations that perpetuate undesirable feedback loops, particularly in vulnerable ecosystems such as sagebrush steppe or dry conifer forests. For example, in the Klamath ecoregion of northern California, landscape projections suggest that the system is at a ‘fire deficit’ (Parks et al. 2025) and will convert to shrub-chaparral over the coming decades (Serra-Diaz et al. 2018); EWEs will accelerate the transition by creating large areas which increase the distance to seed source (Tepley et al. 2017).

Management responses following EWEs, while necessary, can also introduce secondary impacts. Actions such as emergency salvage logging, reseeding or replanting activities, and restocking fish populations affected by wildfire can disrupt natural recovery processes or unintentionally introduce invasive species.

Revising the current definition of an extreme event

These problems with the current definition emphasize the need for a transdisciplinary approach to defining extreme wildfire. Such an approach should integrate

knowledge from both biophysical and social domains and acknowledge the contextual nature of “extreme.” This will allow researchers and practitioners to work towards a more comprehensive and nuanced understanding of extreme wildfires. Extreme wildfires can be better understood through contextualizing their behavior and embracing a transdisciplinary definition that incorporates both contextual fire behavior benchmarks and community coping capacity (Fig. 2).

Contextual nature

Existing definitions use absolute thresholds of metrics of fire behavior to define EWEs (Tedim et al. 2018), yet generalized definitions should recognize that what constitutes extreme conditions in one context may be normal in another. Extreme fire behavior based on absolute criteria (e.g., fireline intensity or flame lengths) might represent conditions that are quite typical for fires burning in crown-fire-adapted forests, such as North American boreal forests (de Groot et al. 2013)—yet surely not all fires in those ecosystems should be considered extreme. An alternative to setting absolute criteria is to characterize extreme wildfire events as “outside of distribution” or “outlier wildfires,” defined based on fire frequency, behavior, or effects outside the historical range of variability for a given location and ecosystem type. Outlier wildfires exhibit characteristics at the extreme tail of the historical distribution, e.g., more than two standard deviations from the mean of historical data (e.g., Balik et al. 2024). Outlier wildfires could be defined based on many distinct axes (e.g., intensity, severity, or size; Turner and Seidl 2023), and importantly, individual wildfire events might meet the criteria for some axes while not for others. Identifying outliers in wildfire data using traditional quartile analysis (Tukey 1977) is challenging because wildfire metrics often span enormous ranges and exhibit highly skewed distributions. For instance, fire size can vary over several orders of magnitude, and ignition counts frequently follow zero-inflated distributions with many zero-valued observations. Due to this wide variability, wildfire sizes are sometimes modeled as following a power-law distribution (for exception see Newman (2005), though landscape fragmentation can truncate the distribution and prevent fires from reaching larger sizes (Ricotta et al. 2001). A commonly applied technique for detecting outliers in skewed data is the Extreme Studentized Deviate (ESD) test, which is designed to detect multiple outliers by iteratively removing the most extreme value from the dataset and recalculating the test statistic until no outliers remain (Rosner 1983). More recent approaches, such as the “relative range” method, which relies on interquartile ranges rather than standard deviation to identify outliers (Dallah et al. 2024), offer

potential advantages for wildfire applications but remain largely untested. An event may be defined as extreme when it threatens containment operations through unexpected fire behavior. For example, wildfires are typically expected to burn fast upslope and slower downslope (except for Foehn wind-driven fires), due to the pre-heating efficiency of downstream fuel because of flame contact angle differences (Werth et al. 2011). This typical fire behavior is used as a rule of thumb for firefighting operations, as crews set up defensible space and use downslope areas as buffer zones. However, perhaps due to extreme fuel accumulations and fire weather, these terrain effects can be countered, and many recent fires have been characterized by a similarly fast downhill rate of spread (e.g., 2020 East Troublesome Fire, Colorado). Another example that can lead to unexpected fire behavior is highly rugged terrain, which can cause small-scale patterns in the turbulent fire-wind, such as recirculations and extreme gusts, which can exacerbate fire behavior (Werth et al. 2011). This unexpected fire behavior pattern can catch personnel off guard, therefore creating dangerous situations for both firefighters and local communities.

Outlier wildfires are often—though not always—linked to detrimental ecological impacts. When novel wildfire characteristics do not resemble the historical fire regimes that have shaped species composition and ecosystem function, resident species may not have the adaptations needed to persist or recover after fire (Welch et al. 2016; Davis et al. 2023; Turner and Seidl 2023). In recent years, for example, there are more stand-replacing fire as a proportion of total area burned, fires with larger patches of high-severity fire effects, and short-interval high-severity fires (Singleton et al. 2019; Whitman et al. 2019; Coop 2023; Francis et al. 2023). Many of these observations are considered uncharacteristic of historical fire regimes and are increasingly resulting in fire-catalyzed changes in forest type, including conversion from forest to non-forest (Coop et al. 2020). However, outlier wildfires are not necessarily related to detrimental social impacts. Conversely, an ecologically “typical” wildfire event could have devastating social impacts if it encounters human infrastructure. Defining an EWE in this manner poses challenges to defining an EWE because they would require establishing reliable baselines of historical fire regimes and operationalizing the relevant spatial extent to which a wildfire event would be compared. Current understanding of historical fire regimes varies greatly by ecosystem type, largely based on differences in fire history data quality and availability (McLauchlan et al. 2020). Similarly, there are tradeoffs in determining the spatial scale used for determining the baseline, which might be based on coarsely defined ecosystem types

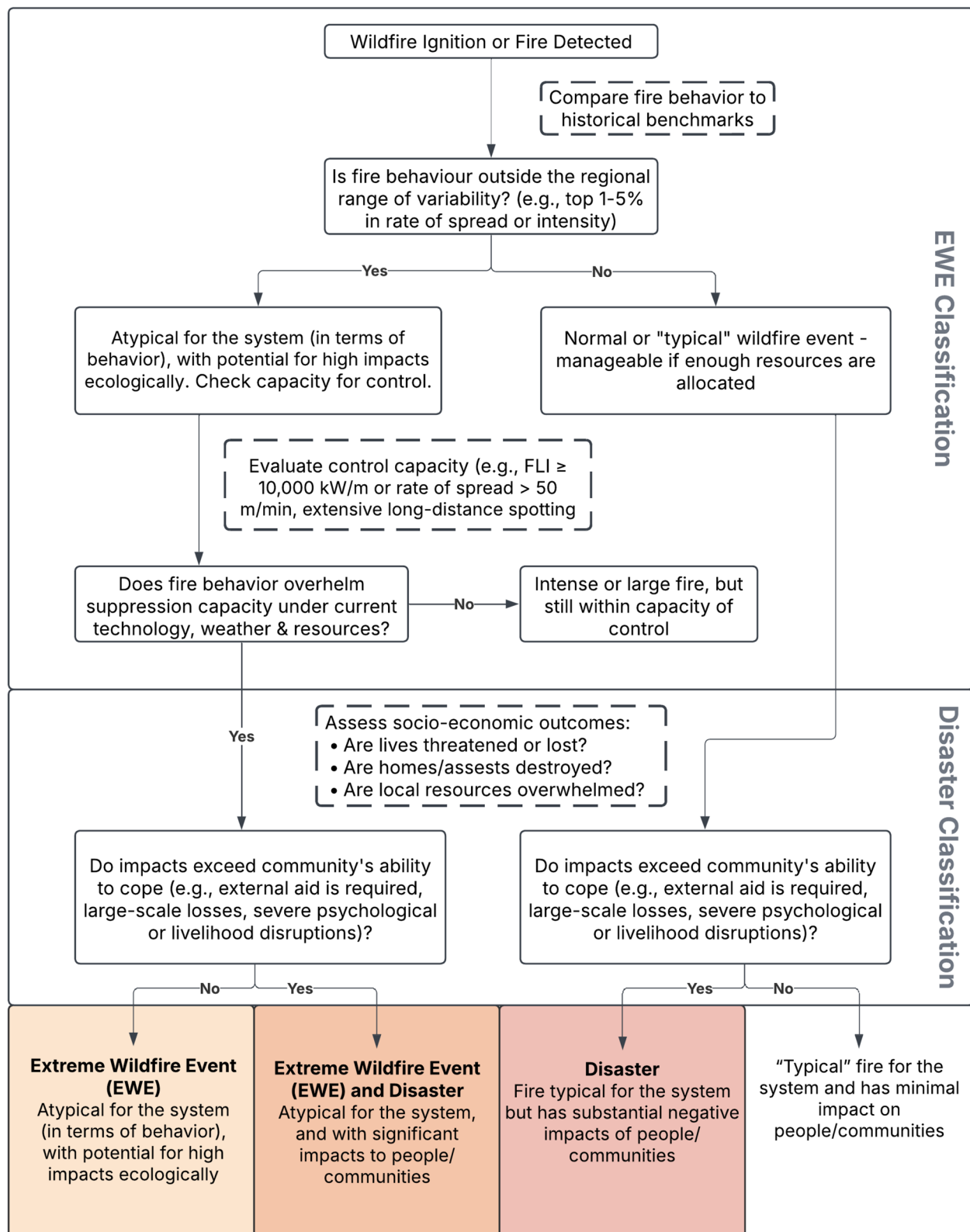


Fig. 2 Operational decision pathway for applying the conceptual framework in Fig. 1 to classify wildfire events along two dimensions of fire behavior and human consequences. Events are classified as EWE based on the fire behavior classification, while events become disasters based on human impacts. This also illustrates how an ignition can evolve into an EWE, a disaster, or both

(for which there is more evidence), mid-scale ecoregions, or modeled expectations for a given location based on bioclimatic information.

Embracing a more interdisciplinary understanding of EWEs

To foster an interdisciplinary community of scholars engaged in studying EWEs, it is important to treat EWEs as “boundary objects,” concepts that enable engagement and collaboration, but do not require consensus (Star 2010). Concepts and definitions that serve as boundary objects can either encourage or discourage engagement across a broader or narrower range of disciplines (Star and Griesemer 1989; Star 2010), but when definitions resonate more broadly, they encourage a more diverse group of scholars to interact. For instance, wildfire severity maps function as boundary objects, often facilitating collaboration among ecologists, community planners, emergency responders, and policymakers. While each group uses the maps differently, their common use fosters interdisciplinary dialogue and coordinated action. Clear definitions prevent inadvertent comparison of apples and oranges, while enabling integration across the social and ecological sciences.

Following, Simon (2018), we caution against completely relying on categorical a-contextual heuristics based on potentially subjective thresholds (e.g., a wildfire is extreme if fire spread exceeds a rate of spread > 50 m/minute) when dealing with complex phenomena. We suggest there is scientific value in a contextualized description (Fig. 2). Wildfires can be anomalous in causes, behavior, or consequences, often in multiple, often interacting ways. For example, the conditions that give rise to a wildfire in a given locality can be anomalous, such as in conditions of drought. Fire behavior can be anomalous in both its characteristics or its duration. Finally, the consequences of a wildfire can be extreme in multiple ways and at multiple scales. We assert that understanding the causes, consequences, and interactions of these anomalies is an overriding and shared concern for most scholars of EWE, regardless of whether they are modelers, ecologists, or sociologists.

We propose defining EWEs in a more interdisciplinarily inclusive approach as wildfires that represent a special class because they are anomalous in one or more key ways (Fig. 2). Adopting Simon’s recommendation, it then becomes essential to provide a rich description and justification for how a given wildfire event or set of events is “extreme” on one or more theoretically, empirically, or practically meaningful dimensions. This description should include not just a description of the known distribution and theoretically important thresholds for key characteristics, but also the geospatial and temporal scale upon which the judgment of “extreme” is based. Because

we often are most interested in how an exceedance in one threshold contributes to, or has consequences for other incident characteristics, this approach has the advantage of allowing for a broader and more transdisciplinary discussions of EWEs that support coupled natural and human systems, similar to the framework proposed for resilience (McWethy et al. 2019).

Gaps and roadmap for extreme wildfire events research

While we suggest that extreme wildfires can be better understood through contextualizing their behavior and embracing a transdisciplinary definition, we find significant gaps in the empirical data collected during and after extreme wildfire events, in both biophysical and social data. Also, current wildfire models often fail to capture the complex, nonlinear interactions of extreme wildfires. Finally, addressing extreme wildfire events requires interdisciplinary collaboration across biophysical and social scientists, diverse stakeholders, and the public to improve preparedness, promote effective communication during and after EWE, and strengthen resilience in increasingly fire-prone landscapes.

Empirical data

A significant gap in our understanding of EWEs arises from limitations in historical fire data and the biases introduced by focusing primarily on the satellite record. The majority of our current understanding of fire size is based on data collected since 1984, a period during which substantial increases in fire size have been observed in regions such as western North America, Australia, and southern Europe (Westerling 2016; Boer et al. 2020; Linley et al. 2022; Vallet et al. 2023). In California, for instance, a relatively small number of large wildfires—those greater than 200 hectares—have accounted for a disproportionately high share of the area burned in the past two decades, significantly more than during the previous eight decades (Li and Banerjee 2021). However, relying solely on recent satellite-era data can be misleading. Historical reconstructions using methods such as fire-scarred trees in the Pinaleno Mountains of Arizona have revealed that large fires were relatively common between 1640 and 1880, yet were virtually absent from 1881 to 2008 (O’Connor et al. 2014). In such contexts, recent fires appear “out-of-distribution” due to severity, not necessarily size.

These limitations in data extend to other critical biophysical variables. Fuel data—such as live and dead fuel loads, fuel moisture, and species composition—are often incomplete or lack the necessary spatial and temporal resolution to be meaningful at the scale of active fire spread (Hantson et al. 2016; Bakhshaii and Johnson

2019). Furthermore, meteorological data used to model fire behavior is often sparse in both coverage and historical depth, particularly in remote or topographically complex areas (Krivtsov et al. 2009; van Leeuwen et al. 2014; Andela et al. 2019). These limitations hamper efforts to model and predict fireline intensity, rate of spread, and other behavioral metrics. Compounding this, physiological factors such as drought-induced stress or pest infestation can alter live fuels in species- and location-specific ways, making modeling even more complex (Dickman et al. 2023). Future research should focus on developing high-quality, real-time, and retrospective datasets that integrate both ground observations and remotely sensed data. Doing so would improve model calibration and enhance situational awareness during fire events.

Integration of social dynamics

Another substantial gap lies in our limited understanding of how EWEs impact communities and how social dynamics shape vulnerability and response. Comprehensive, fine-grained social data is needed to assess whether an event exceeds a community's ability to cope. This includes information on built environment density, land tenure and ownership patterns, jurisdictional responsibilities, local firefighting resources, and demographic vulnerabilities. Additionally, there is limited understanding of how suppression actions were carried out—both spatially and in terms of effectiveness—during past extreme events. Research into how anomalous fire behavior translates into social and economic consequences remains sparse.

Emerging technologies such as anonymized cell phone records, GPS data, and traffic surveillance footage can help reconstruct evacuation dynamics, providing insight into what went right and what failed during emergency responses. These data can reveal evacuation timing, route choices, congestion patterns, and social behaviors. However, integrating this information into predictive models requires accounting for complex human dynamics: trust in authorities, prior preparedness, community cohesion, and institutional capacity. Evacuation modeling efforts must better reflect the real-world conditions faced by residents and responders. Understanding the socio-behavioral factors that influence evacuation decisions—such as previous experience with fire, access to transportation, and communication reliability—is essential (McCaffrey et al. 2018; Lovreglio et al. 2019; Kuligowski et al. 2022).

Wildfire modeling

Current models used in wildfire science often fall short in representing the complex, nonlinear, and interdisciplinary nature of extreme wildfire events. While progress has been made in physics-based models that simulate fire

spread, many models still do not adequately represent the influence of long-range ember transport. Recent research shows that embers can be lofted and carried far beyond the fire front through bursts created during the thermal degradation of fuels and turbulent wind interactions, leading to spot fires in seemingly safe areas (Petersen and Banerjee 2024). This dynamic is often underestimated in conventional fire behavior models, posing serious challenges for predicting fire spread into urban areas.

In addition, climate models—particularly those used in long-term fire risk projections—typically operate at coarse spatial and temporal resolutions, which limits their ability to capture localized and short-lived meteorological phenomena that can drive extreme fire behavior. For instance, dry east wind events, such as those that occurred during the 2020 Labor Day fires in the Pacific Northwest, are significant drivers of fire severity but are not well represented in global or even regional climate models (Abatzoglou et al. 2021). These events are often considered statistical outliers and are smoothed out or underrepresented in ensemble climate outputs, limiting the models' predictive power for fire-prone regions (Chen and Knutson 2008). Additionally, the typical daily aggregated data in climate models poses a significant challenge for accurate Fire Weather Index (FWI) calculations, necessitating the inclusion of sub-daily meteorological data in future climate modeling projects to enhance accuracy (Jain et al. 2020). Fire weather modeling needs to be improved with enhanced resolution and a focus on event-based climatology to better represent extreme, short-term weather events that are critical to fire spread.

Human activity plays a significant role in shaping both ignition and suppression dynamics. While anthropogenic influences on ignition probability and suppression have been integrated into some landscape-scale models (Kloster et al. 2010; Scheller et al. 2019), further work is needed to bridge the divide between models that simulate fire spread in vegetated areas and those used in the urban fire protection field (e.g., Himoto and Tanaka 2008; Shaham and Benenson 2018). One critical gap is the lack of fine-scale integration of the built environment—especially the materials used in homes, fencing, decks, and landscaping. Studies have shown that enclosed eaves, fire-resistant vents, multi-pane windows, and defensible space significantly reduce structural ignition risk (Quarles et al. 2010; Miller 2017; Syphard and Keeley 2019).

Models that couple fire behavior with the social fabric of communities and their physical layout—buildings, roads, vegetation buffers—are key for accurate

risk assessments (Koo et al. 2012; Ghodrati et al. 2021). These models must also integrate perspectives from sociology, geography, public health, and emergency management to ensure that they are usable by local governments and aligned with community needs. Future research could examine strategies to better document and map building design, building materials, and landscaping, perhaps through the use of AI and high-resolution remote sensing data and/or LiDAR. Models also need to extend beyond the active fire phase to incorporate long-term impacts such as post-fire erosion, hydrological changes, vegetation succession, and community recovery. Once a fire occurs, Burned Area Emergency Response (BAER) assessments currently focus on immediate post-fire threats and are largely confined to federal lands, omitting many areas of concern for local communities (Buettner and Schultz 2025; Carney et al. 2025).

Interdisciplinary collaboration and community engagement

The interdisciplinary nature of EWEs demands a collaborative, integrative approach in the future that spans biophysical science, data analytics, social science, and community-based practice. Engaging a wide range of stakeholders—including emergency responders, local governments, Indigenous communities, researchers, and residents—will improve both the relevance and effectiveness of research. Human encroachment into wildland-urban interface areas, land-use changes post-fire, and climate variability are shifting the baseline conditions for fire regimes (Li et al. 2022; Solander et al. 2023).

Research must also prioritize public engagement and co-production of knowledge. Understanding how communities interpret and respond to EWEs, and how they distinguish extreme events from more routine fire seasons, is essential for designing effective preparedness strategies. Public perceptions influence not only personal preparedness but also political and institutional responses. Exploring what levels of fire behavior, intensity or impacts trigger public concern and response can help to design more effective communication strategies during EWEs. This communication must be clear, culturally appropriate, and tailored to different levels of risk literacy.

Establishing metrics to evaluate the effectiveness of public engagement initiatives—including shifts in knowledge, behavior, and community resilience—will ensure that outreach efforts are impactful. Translating scientific findings into accessible formats and involving citizens in data collection and planning (e.g., through citizen science

and participatory mapping) can enhance buy-in and strengthen local capacity. Ultimately, addressing these data, modeling, and social gaps through collaborative and interdisciplinary research will improve our collective ability to predict, respond to, and recover from extreme wildfire events in an increasingly complex and fire-prone world.

Implications

Given current climate trajectories, extreme wildfires will become increasingly common and will increasingly influence the future of ecosystems and human communities. While clarifying the definition of EWEs is an essential starting point, substantial knowledge still limits the ability of science to anticipate such events and the capacity of institutions and communities to prepare for, respond to, and mitigate them. Addressing the research needs outlined above is paramount to improving the understanding, prediction, and management of EWEs. Improving research is necessary but not, however, sufficient. Given the growing uncertainty about system feedbacks, non-linear thresholds, and climate futures, we need to simultaneously engage with communities to help them prepare for these high-risk, low-probability events, recognizing that the only alternative to managing under deep uncertainty is acute risk to human lives, livelihoods, and infrastructure.

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Authors' contributions

ML, JEL—developed main idea for paper, wrote first draft, wrote subsequent drafts, editing; BN, RS – developed main idea for paper, wrote subsequent drafts, editing; TB, CB, JF, MH, SP, WR, ZR, LSD, AS, AU, SW- wrote subsequent drafts, editing. All the authors read and approved the final manuscript.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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