Fire Safety Journal 162 (2026) 104744

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

The wildfire problem – a path forward

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ARTICLE INFO

Keywords:
Wildfires
Wildland fires
Large outdoor fires
Modeling
Experiments

ABSTRACT

Wildfires continue to grab headlines around the world. To find a path forward, we must first define what is meant by "the wildfire problem." This entails understanding our history with wildland fires and appreciating the needs of our communities as well as our ecosystems. A brief review of our current available tools and how they are used by fire managers will be provided. This will help us gain insight as to how the fire safety engineering community can help to address the weaknesses in our current approach and as well as fill the gaps in our fundamental understanding of wildland fire behavior. The ultimate goal is to realize that wildland fires don't have to be disasters.

1. Introduction

Wildfires continue to attract increasing attention both in the media and within the fire safety community. This is not surprising. This previous year, 2025, started off with a bang – there were the Palisades and Eaton fires in L.A. in January, followed by fires in Japan (such as the Ofunato [1] and Oita fires), the Dragon Bravo fire in the Grand Canyon, and very busy summers in Canada (over 8.9 million ha burned [2]), Portugal (279,000 ha burned, including the Piódão fire [3]), and Spain (393,000 ha burned [3]). Wildfires have also increasingly attracted attention within the International Association of Fire Safety Science (IAFSS). This is the 3rd plenary on wildland fire behavior (5th on wildland fire generally if you count [4] and [5]) at the IAFSS Symposium. Finney [6] was the first, which introduced the fire protection engineering community to fire ecology, the fire paradox, the wildland fire system, and the social/cultural challenges beyond just the scientific, but it largely focused on the U.S. context. The second on wildland fire behavior specifically was Liu [7] which went in depth into surface fire mechanics. The challenge for this author was to build on both previous plenaries. The following paper is my take on the many issues one needs to understand before undertaking research on wildland fire. This is not meant to be a literature review (many good ones already exist) but is meant to introduce the topic to newcomers (also see Ref. [8]), provide land management context, and stimulate thought and research in hopefully productive directions. It is hoped that it builds on the previous plenaries, but also from a paper that Mark Finney and I wrote some years back, based on the plenary he gave to the International Conference on Forest Fire Research which outlines four "known anomalies" in our understanding of wildland fire [9]. In the end, the scope of this paper ended up rather broad, so it comes with a warning that in order to cover such a wide range of topics, simplifications had to be made since each section of this paper could fill textbooks. I chose to risk over-simplification to present the broad context of the topic. Also, I attempt to point out our weaknesses in knowledge and approaches and may inadvertently offend some readers. This is not my intention. Please forgive me.

This paper begins with some background on wildland fire, establishing common terminology and emphasizing the importance of fire ecology. This leads to a discussion of the "wildfire problem." Current tools and approaches are reviewed so that the weaknesses in our approach can be discussed. Finally, a way for the fire protection engineering community to help move the field forward is proposed.

2. Wildfire primer

2.1. Terminology

In an attempt to make this paper useful to those completely new to wildland fire, a brief review of some key terminology is provided. This is in no way meant to be exhaustive, but merely a starting point so that all can understand the rest of the paper. It is helpful as well because several of these terms are misused from time to time. Those discussed below are terms that the author has seen inappropriately used, have somewhat vague definitions, are different from those classically used in fire

This article is part of a special issue entitled: FISJ_IAFSS 2026 published in Fire Safety Journal.

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https://doi.org/10.1016/j.firesaf.2026.104744
Received 29 December 2025; Received in revised form 12 March 2026; Accepted 16 March 2026
Available online 17 March 2026

protection engineering, or are those with definitions still being discussed in the literature. For a comprehensive introduction to wildland fire terminology, see Ref. [8].

Wildland fuels, and the resulting fires, are often classified by strata. Ground fuels are considered the rotted and decomposing material just above the mineral soil. They have lost their defining structure and are usually porous, particulate-like matter. They are frequently called “duff” but can include peat materials as well. The ground fires that burn through these fuels are usually smoldering and burn for long durations. Given the right conditions (low moisture content, high winds), however, these fuels can transition into flaming combustion. Surface fuels can be live or dead fuels consisting of dropped needles, leaves, twigs and branches, shrubs, grasses, and forbs. Surface fires will typically burn through these fine fuels as a flaming fire. Due to their fine nature, surface fuels ignite and burn out quickly so that surface fire spreads as a line of some relatively small thickness (on the order of the height of the flames [10], referred to as the “flame zone depth”). As the fire spreads over the landscape, the local curvature of the fire front becomes minimal, so flame scale processes can be treated by assuming a one-dimensional infinitely long line fire ([11]). This “line fire” concept is how most models treat wildland fire. However, large woody debris (such as a downed log) is also considered a surface fuel. This type of fuel is not usually consumed in the flaming front and may smolder for quite some time after the main fire line has passed. Again, under the right circumstances (low moisture content, high winds), large woody debris may also burn in the flaming mode. Combined with heavy ground fuels, these fuels and conditions can result in area or mass fire behavior, one form of “extreme fire behavior” (see Ref. [12]). First described during the fire-bombing in World War II, area or mass fires are observed when the characteristic diameter of the fire (D) is much larger than the flame height (L) ($L/D \ll 1$). In this regime, continuous flaming over the surface is impossible and the flames break into distributed flamelets (non-dimensional heat release rate $Q^* < 0.1$ or Q^2/D^5 near 10^{-6} [12,13]). Mass fire behavior requires long duration flaming combustion that deep duff and large woody debris can provide under the right conditions. Shrubs less than 2 m tall are often considered surface fuels, while those taller than 2 m are considered canopy fuels [14,15]. Crown or canopy fuels are suspended fuels, typically associated with the live and green needles and leaves of trees. Crown fires are known for their high heat release rates and tendency to generate firebrands that can start spot fires ahead of the main fire front. Ladder fuels provide the bridge between the surface fuels and the canopy fuels. These can be hanging mosses and lichens, or small to moderately tall trees and shrubs.

The wildland fire community also uses unique descriptions of the fire direction. Heading, backing, and flanking fires correspond to concurrent, opposed, and lateral fire spread in the combustion and fire protection engineering literature. In addition to their reference to the wind direction, these terms are also used to indicate direction relative to the topography. For example, a heading fire can refer to both fire spread in the direction of the wind or the uphill direction. When these are in conflict, such as when the wind is blowing downhill, the direction of maximum fire spread rate is considered the heading direction [16].

Another important terminology set worth discussing is the terms wildfire, prescribed fire, and wildland fire. There is some effort in the literature to distinguish prescribed fire science from wildfire science [17]. The intention in Ref. [17] was to emphasize the intensity differences, relative importance of fire spread direction, and general role of the fire itself. Though the actual behavior of a wildfire can be quite variable, wildfires are emergency events often associated with unwanted, high intensity fires covering large areas, mostly in the head fire direction, the effects of which are to be mitigated later. Modeling of these fires is done in a particular way: for safety, to establish suppression priorities based on predicted fire spread and the consequent impacts to critical values at risk, and are run over large space and time scales requiring quick run times. Most of the past effort and models have addressed wildfire management. The terminology “prescribed fire science” is introduced in Ref. [17] to emphasize the nuances of conducting prescribed fires where the intensity is usually much lower (or even marginal), and where ignition patterns are selected that make more frequent use of backing and flanking fire. Fire line interactions are also a frequent phenomenon as multiple strips or points of ignitions are often used to moderate the intensity. Modeling of these planned fires must take into account these different behaviors and the modelers themselves may be asking very different questions of the models (and can wait much longer for the models to run), such as how to achieve the desired fire effect on the landscape to satisfy the prescribed fire objectives. The author here does not necessarily consider these separate entities (and they were never intended to be in Ref. [17]). Wildfires burn in all sorts of conditions and do still indeed burn in the flanking and backing directions and with milder intensities. Wildland fire science is used here as it is the more general term, incorporating both wildfire and prescribed fire science. Note that the title of the paper does still make this distinction in terminology (wildfires are mainly the “problem,” not wildland fires as a whole as we'll see in the next section). It should be acknowledged that “wildland” is a potentially problematic word, especially in the United States, Canada, and Australia, as it implies that the lands were unmanaged prior to our current efforts and neglects any traditional burning and/or the previous management by the indigenous population (most landscapes were never truly “wild”). Wildland fires may also burn through otherwise managed landscapes like plantations and agricultural lands. However, as no replacement has integrated with the common lexicon, here we mean wildland fire simply to be that which burns through vegetation.

2.2. Importance of fire ecology

Appreciating fire ecology is vital to understanding wildland fire, not just as a researcher but because it is also foundational to much of the life on Earth [18]. Unlike fires in the built environment, wildland fires are not necessarily destructive but a natural and required part of most ecosystems. One way to understand the ecological consequences of wildland fire is to consider the historical fire regime. A fire regime is characterized by the dominant type of fire (surface vs. crown), intensity, spatial extent, frequency, and seasonality over space and time [19,20]. Fig. 1 shows a global map of the typical historical fire regimes. These historical fire regimes are what the ecosystems evolved with and which help promote ecosystem health and resilience. As discussed later, these historical fire regimes may not be indicative of current or future fire regimes. Note that the majority of the terrestrial surface is dependent on some kind of fire [21], much of it dependent on surface fires, and in some places, those fires historically occurred at high frequency (every 1-3 years in some cases). Plants can exhibit many adaptations to surface fires: self-pruning (dropping lower branches to prevent spread into tree canopy); thick, fire-resistant bark; resprouting, either from the roots (lignotubers) or stems (dormant or adventitious buds); germination of dormant seed banks (seeds requiring scarification to germinate); and/or rapid growth and development (longleaf pines (*Pinus palustris*) can grow 2 m in a year to quickly rise above future surface fires) [22]. Grasses can both resprout and reseed after fire depending on the species [23]. The common and widespread ponderosa pine (*Pinus ponderosa*) in the western U.S. is an example of a tree that both self-prunes and has thick, corky bark. However, if a sufficiently intense surface fire kills a portion of the underlying cambium under this thick bark, a fire scar, or “cat face, ” can develop on a tree. The surviving cambium on the tree continues to live and grow, but subsequent fires are more easily recorded in the tree's growth rings allowing annual dating of past fires. These fire scars are frequently used to reconstruct the historical fire regime in forested ecosystems [24].

As noted in Fig. 1, other ecosystems, however, are adapted to high intensity crown fires, like along the higher elevations in the Rocky Mountains of the USA; the boreal forests of Canada, Alaska, and Russia; and the east coast of Australia. One way that some tree species have

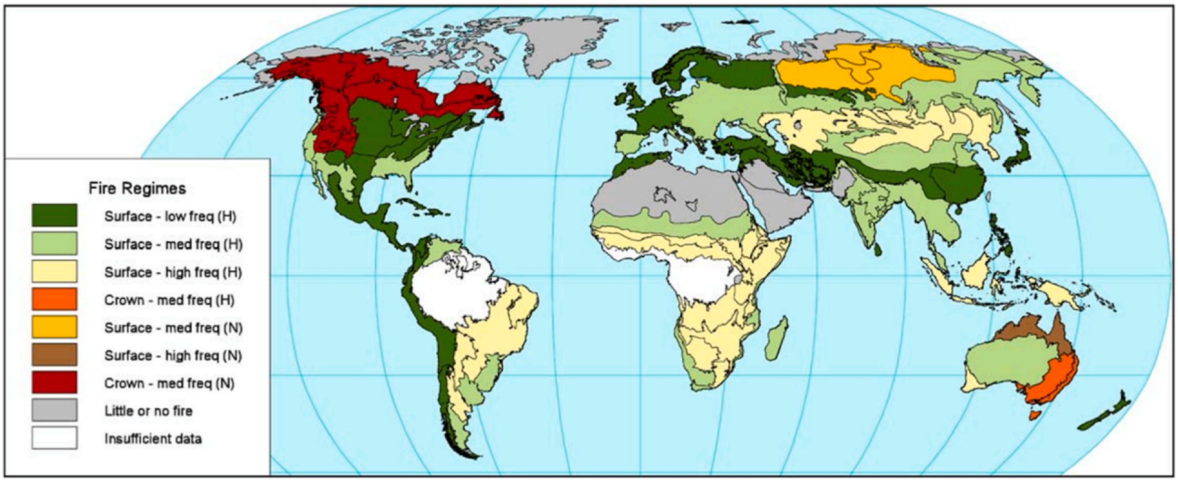

Fig. 1. Global map of estimated historic fire regimes from Ref. [25]. Low frequency is defined here as more than 200 years, medium between 20 and 200 years, and high frequency is less than 20 years. N = natural, H = human caused. Note that future fire regimes may look very different from these due to land management practices and climate change.

adapted to high intensity crown fires is to produce serotinous cones. Serotinous cones are sealed shut and only open and drop seeds after a sufficiently hot fire melts the resin holding them closed. These seeds land on cleared, nutrient rich mineral soil with very little competition and post-fire tree regeneration can be quite dense [26]. Lodgepole pines (*Pinus contorta*) in the Rocky Mountains, jack pines (*Pinus banksiana*) in the boreal forests of Canada, pitch pines (*Pinus rigida*) in New Jersey, and Aleppo pines (*Pinus halepensis*) in the Mediterranean all have serotinous cones. The fire history in these forests is often inferred from cohorts of trees with similar ages or even from charcoal sediments in nearby lakes [27]. Trees and shrubs can also resprout, including pitch pine, eucalyptus (ex: *Eucalyptus globulus* and *Eucalyptus camaldulensis*), and many Mediterranean and Californian chaparral and maquis species (ex: *Adenostoma fasciculatum, Arctostaphylos glandulosa, Ceanothus crassifolius, Quercus ilex*, *Phillyrea latifolia*, *Arbutus unedo*, *Erica arborea*, *Pistacia lentiscus*). The reader is encouraged to seek out the fire ecology literature for their local ecosystems, learn about their fire history and the fire adaptations of their local vegetation. Not only does understanding and appreciating our natural world make us a more well-rounded scientist, but it will help guide research questions. Understanding the historic fire regime and the fire regime required to sustain the local ecosystem's health is an important first step to adapting and safeguarding our communities from the expected type of fires. For example, a low intensity prescribed fire to reduce fuel loads in an ecosystem adapted to low frequency, high intensity fire will not improve the ecological resilience of this ecosystem [28]. Low intensity fires will not help the vegetation in these ecosystems complete their lifecycle, initiate renewal, or promote vigor or growth. Additionally, fires in these ecosystems don't typically occur when conditions are more moderate, when fuel treatments have a higher likelihood of success [29]. Fires in these ecosystems would normally have burned in only the most extreme conditions (they are “weather driven” not “fuel driven”), so the potential reduction in fire behavior seen from such a fuel treatment might be limited [30]. Communities near these ecosystems still likely need to brace themselves for high intensity fires [31].

When we have this fire ecology mindset when we talk about wildland fire and fire disasters, it becomes clear that area burned isn't necessarily the issue [32]. In fact, historically much more area burned, especially in the United States [33,34] (see Fig. 2) and in the boreal forests surrounding communities in Canada [35]. In Australia, there is also convincing evidence of the frequent and consistent use of fire by the Indigenous population prior to British colonial settlement which kept the woody biomass (which is currently driving large fires) at much lower levels than is present today [36,37]). Recent annual area burned in the U.S. has hovered between 1 and 4 million hectares [38]. As shown in Fig. 2, however, it is estimated that over 80 million hectares would burn

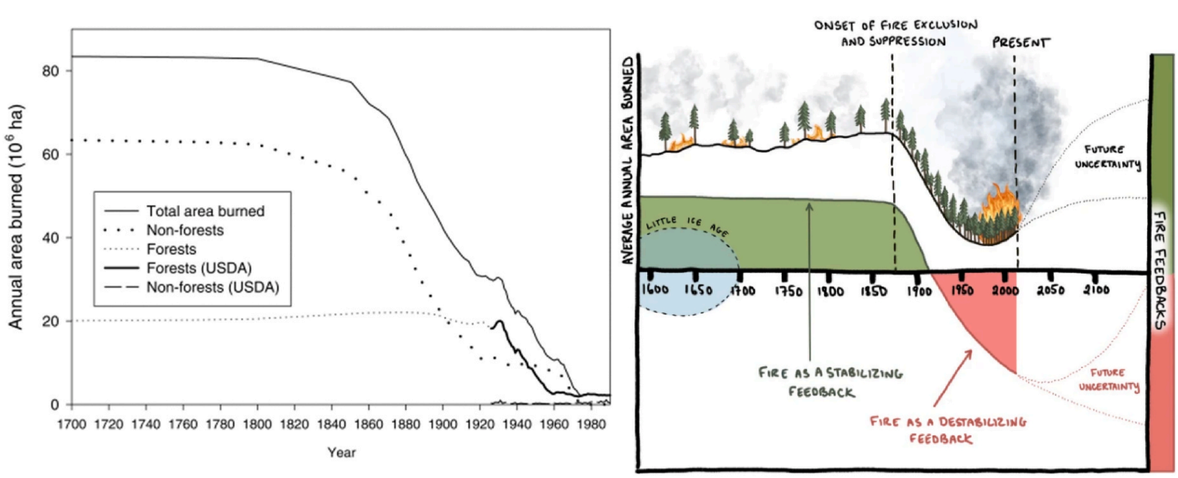

Fig. 2. Left: Estimated annual area burned in the United States between 1700 and 1990 from Ref. [33]. See Ref. [33] for details. Right: Conceptual model illustrating impacts of fire exclusion and suppression on area burned and fire severity in North American forests from [34].

annually prior to European settlement [33]. However, *how* current fires are burning can be a problem. Fire regimes are changing (and the map in Fig. 1 will likely not be accurate into the future), and more fires are burning with higher intensities and fire severities over larger extents (ex: [39]). Note the subtle distinction between fire intensity and fire/burn severity [40]. As engineers, we can understand fire intensity - it is simply the heat release rate of the fire. In wildland fires, it is frequently quantified as fireline intensity, normalized over the length of the fire line, but it can be total energy released or on a per unit area basis. While severity is also used in the engineering field to describe the potential negative consequences in a risk analysis before the fire, in wildland fire it is used after the fire. While somewhat related to fire intensity, fire severity is more of an ecological term and its usage can be inconsistent, even in the fire ecology literature [40–42]. Originally defined to mean how a fire alters the dominant vegetation [19], this meaning can be a bit lost due to efforts to find a way to quantify it, especially over large areas using remote sensing techniques [40,42]. It is now usually quantified by the change in live fuel by comparing the difference in "green" pre-versus post-fire (e.g. differenced Normalized Burn Ratio (dNBR)), but this doesn't always have the same long-term effect on each ecosystem: "there is the possibility that different ecosystems with the same fire behavior may have different fire severity and different ecosystem response" [42]. For example, while complete above-ground consumption of grass would be considered high severity, it will resprout and/or reseed in a matter of weeks, returning to the pre-fire state relatively quickly (for example [22]). Conversely, complete above-ground consumption of fuel in a forest used to low intensity surface fires may result in permanent changes to the ecosystem [43,44]. Another measurement of severity used often is soil burn severity. Soil burn severity is often first assessed using remote sensing techniques (such as the dNBR used for assessing vegetation burn severity) but is then manually verified with field measurements [45]. In some cases, soil severity may be a reasonable indicator or predictor of some of the secondary effects from wildland fires, such as soil sterilization and the tendency for erosion and post-fire debris flows (discussed later). As pointed out in Ref. [40], however, fire intensity is just one factor contributing to soil severity and factors like topography, soil type, and precipitation (and possibly post-fire logging and road traffic [46,47]) are just as important and it may not be a good surrogate for impacts to the vegetation (ex: [41]). It becomes clear then to really understand the ecological consequences of wildland fire, one needs to discuss the ecosystem response [40] and to not equate that with fire intensity or fire severity.

Climate change is frequently pointed to as the apparent cause of the increasing intensity of wildfires (for example [48]). While it is certainly true that climate change is increasing the number of "red flag days" [49,50] and extreme weather events [51] making it nearly impossible to fight unwanted wildfires (and urban conflagrations - see below) (for example [52]), this narrow focus on climate overlooks the importance of past land management and fire suppression decisions [53,54]. Land use changes, such as the abandonment of agricultural lands and the regrowth of natural/fire-prone vegetation [55,56] or the large-scale use of plantations of flammable trees [57–59], are certainly a factor. In the U.S., Canada, and Australia especially, and even acknowledged in Greece and other Mediterranean places now too [57,60], this takes the form of aggressive fire suppression. Our natural response to fire is to "put it out as quickly as possible" or to do our best to prevent it in the first place. In some cases, this is the right answer, like when an ignition occurs in close proximity to a community in extreme weather conditions (e.g. the 2018 Camp Fire, see Ref. [61]). But, for example, the United States already has a 98% initial attack success rate [62] - we put out 98% of all wildland fires before they grow past 100 ha. The Palisades and Lahaina fires were declared contained/extinguished before they rekindled under extreme weather ([63,64]). The 2% of fires that do escape initial attack do so because of the confluence of extreme conditions of weather, difficult terrain, long-term drought, fuels, and the presence of other fires resulting in limited suppression resource availability [65,66]. By all accounts, being 98% successful at something is reasonably good, and yet it seems many are still striving to improve this number. Complete success at fire suppression is nearly impossible, especially in the worst possible scenarios (ex: [6,52]), and this is not a call to double down on suppression technologies. As argued here, this is detrimental to most ecosystems, further exacerbating the increasing fire intensity and severity problem [67,68]. This emphasis on fire suppression has resulted in the fire paradox: the harder we try to fight wildfires, the worse they get [69–72]. Fuel keeps accumulating (see Fig. 3), only to burn in the worst possible conditions. This fuel accumulation has other feedbacks as well, reducing ecosystem resilience: overstocked forests have decreased drought resistance and increased susceptibility to insects and disease, both increasing the inherent pre-fire mortality [69,73–75]. As a result, many ecosystems around the world are considered to be in a degraded state, largely due to the lack of the right kind of fire [21]. Instead of trying (and failing) to suppress all fires, we should be focused on mitigating their undesirable impacts.

One final point related to fire ecology, but also very much fire behavior, is that it is important to realize that each fire isn't a monolith. Any given fire can experience a wide variety of fire intensity, severity, and fire behavior, especially if they have a chance to spread for long durations (days, weeks, even months). One perfect example is highlighted by Ref. [32]. The August Complex fire in 2020 still stands as California's largest since modern record keeping began, burning nearly 418,000 ha [77]. There was one fatality, and 935 structures were lost. The fire was so big that maps of the fire had to be split into a north and south zone so that any detail could be seen. As discussed by Ref. [32] and illustrated in Fig. 4 showing the soil burn severity in the north zone, only a small portion of the area burned with high severity. For the north zone, 8% was characterized as high soil burn severity, 31% moderate, 29% low, and 32% was very low or unburned [78]. For the south zone, only 4% of the area was categorized as high soil severity, while 44% was moderate, 43% was low, and 9% of the final fire area was categorized as unburned or very low soil severity [32,79]. So, for most of the days it burned, it did not look like the scary pictures in the media. Clearly, lives and structures lost are undesirable consequences of a wildfire, but ecologically, wildfires can otherwise be beneficial and act as "fuel treatments," providing ecosystem benefits while reducing the potential harm of the next fire (for example [80,81]).

As discussed in this section, wildland fires are different than those in the built environment. They are an ecological necessity, so we must fight our instinct to entirely prevent and suppress them. We need to accept that we have to live with wildland fire, and as researchers, target our research towards this end.

3. Wildfire problem

This background of fire ecology helps clarify what is meant by "wildfire problem." As argued above, it's not that the vegetation is consumed by fire per se. A fire burning through remote forest far from people should not be considered a disaster, and in many cases is an ecological necessity. Extensive media attention to these events certainly leads to an impression that these "disasters" are increasing in frequency (even if the data don't support this [83]). However, when a "wildfire disaster" occurs, we usually mean that a fire burned through a community. Along with informal settlement fires, they are all "outdoor fires" [84], but it is important to make the distinction between wildland fires, wildland-urban interface (WUI) fires, and urban fires here. Most "wildfire disasters" that come to mind are more precisely classified as WUI fire disasters or just urban fire disasters [85]. The more "classic" WUI fires could include Pedrógão Grande (Portugal 2017), Mati (Greece 2018), Black Summer fires in Australia (2019-2020), Ofunato fire (Japan 2025), and the Dixie Fire (California 2021), some of which still may have experienced the structure-to-structure spread that typifies an urban fire disaster (it was noted in Ref. [86] specifically however that structure-to-structure spread in the Pedrógão Grande fire was limited).

Fig. 3. Photo point series of changes due to fire exclusion in a pine forest with historically frequent low intensity fires [76]. Photos show same marked location (photopoint 13) for the following years: Left: 1909, Middle: 1958, Right: 1989.

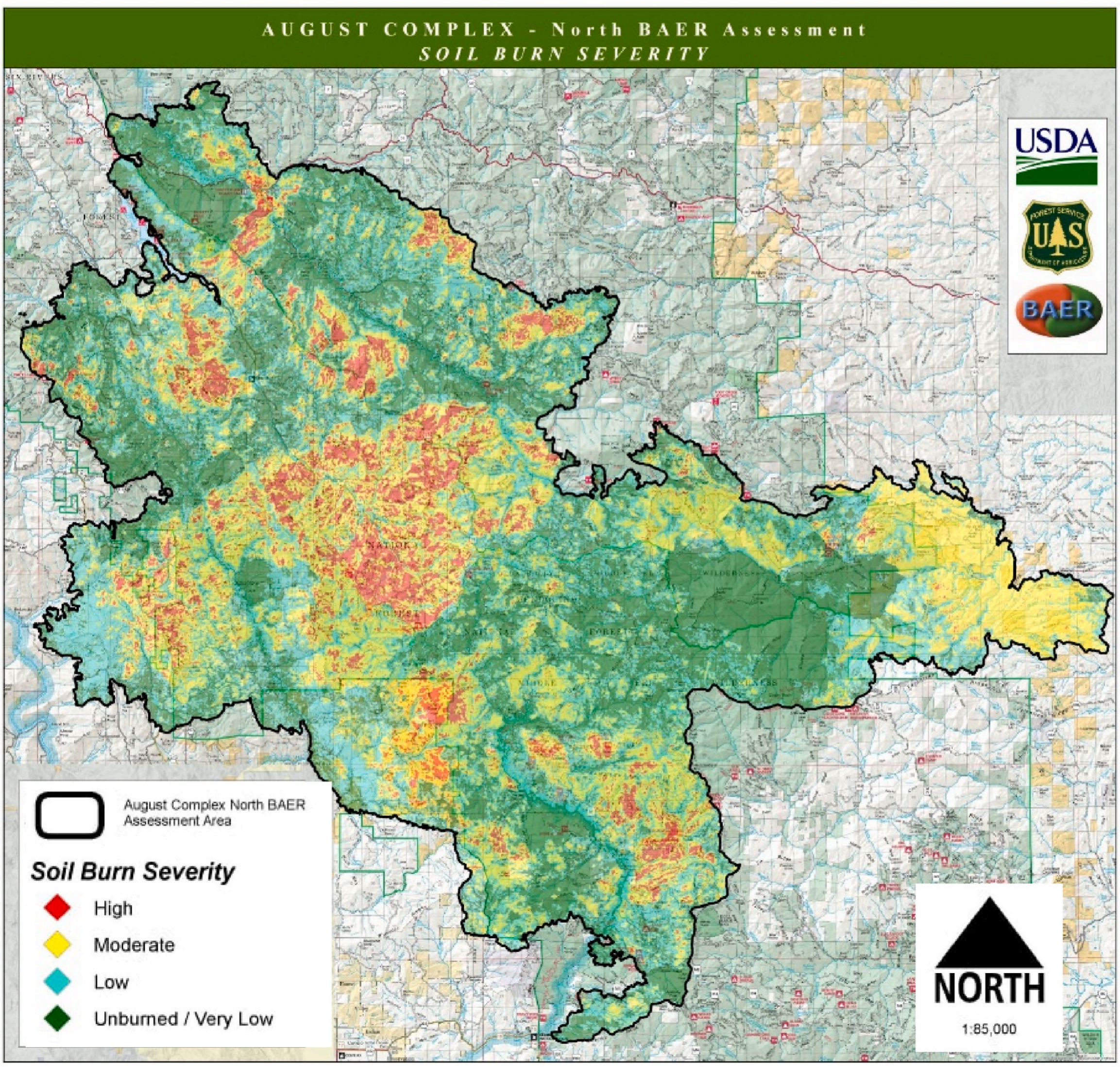

Fig. 4. Soil burn severity map for the north zone of the 2020 August Complex fire (comprising 551,493 acres or 223,181 ha), generated as part of the Burned Area Emergency Response (BAER) assessment [82]. Red are areas of high soil burn severity (8%), yellow moderate (31%), blue low (29%), and dark green are unburned or very low (32%) soil burn severity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Disasters more correctly categorized as urban fire disasters include Lahaina (Hawaii 2023), Palisades and Eaton fires (California 2025), Camp (California 2018), Marshall (Colorado 2021-2022), etc., because these were largely urban fires that happened to have ignited via natural fuels. Calling these urban fires “wildfire disasters” not only detracts from the importance of the ignition of the structure (and the application of more classic fire protection engineering approaches), but it creates the expectation that these fires always start far away from communities. In the U.S. (but also Canada and Russia), large swaths of land are publicly owned and managed by the government, so this assumption that the ignitions occur far away from the community often implies that the ignition occurred on public land and that the governments are solely responsible for community protection [87]. However, this assumption that ignitions on public lands are responsible for fires tearing through communities just isn't true - most start on private land, even in the U.S. [88]. This would be especially true in Australia and Europe where there is much less public land to begin with. Calling these WUI and urban fires all a "wildfire problem" also implies that the solution should be to just fight wildland fires harder. This not only doesn't address the fact that structure ignition and structure-to-structure spread is the driving factor of the "wildfire disaster sequence" (when a significant number of structures ignite simultaneously, overwhelming suppression forces [70, 89]), but denies the natural role of fire in our ecosystems and brings us back to the fire paradox: the harder we fight fires, the worse they get [69–71]. This "wildfire disaster sequence" defined in Refs. [70,89] should really be called the "urban fire disaster sequence."

It has been well-established [70,89–91] that if structures are the only concern, the focus needs to solely be on the home ignition zone (HIZ). However, "WUI communities consist of more than homes. The wildland component defines the environmental context and values for communities, including views, recreation, watershed, and lifestyle benefits to the inhabitants … Thus, the goal of creating a fire-adapted WUI community is not achievable by focusing solely within the HIZ, but must encompass the land management options afforded by the ecological requirements of the wildland ecosystems" [90]. Along those lines [92], calls for a paradigm shift to re-separate the wildland fire from the urban fire which would allow for more properly making landscapes fire resilient, but also reinforcing the fact that the homeowner, private land owners, and communities themselves need to be responsible for preventing urban conflagrations: "Society largely defines the wildfire problem in terms of the destruction of communities. Yet emphasizing community protection as the prime objective of wildfire management overlooks the unavoidable and beneficial need for more fire on the landscape, inadvertently impeding our ability to create both resilient landscapes and fire-adapted communities." Despite decades of trying to do this in the United States [6,87], this may be much more "easily" accomplished in certain regions of the U.S., Canada, and Australia where there may be clearer delineations between dense, urban communities and large areas of natural vegetation where fire can freely burn and play an ecological role. Reintroducing fire into areas characterized by more of an "intermix" between the vegetation and structures will likely be even more challenging due to social and political barriers [6]. Increasing development in the WUI certainly means that more communities are at risk and will be facing these decisions [93]. Many may not realize that they're in the WUI, especially when these fires turn to urban conflagrations and burn well away from the actual interface with the vegetation (e.g. Santa Rosa during the Tubbs fire [94] or see nearly any of the other urban fires listed above). There is clearly no one-size-fits-all approach to how communities can live with fire, but there is an ever-expanding body of non-engineering literature dedicated to addressing these issues which the curious reader is encouraged to seek out. Good starting places include: [31,57,95–100]. A common theme to this body of literature is acknowledging that wildland fires will happen, should happen, and maybe should even happen more often.

When we do speak of undesirable impacts of wildland fires themselves, we should be thinking about "second-order, indirect" human impacts of large vegetation fires [96], such as smoke production and the effect on soil and water. Wildfire smoke is increasingly linked to health issues, both for firefighters [101,102] and the public well downwind of fire (ex: [103,104]). The 2019-2020 Australian fire season was estimated to result in smoke-related health costs of AU$1.95 billion and an estimated 429 smoke-related premature deaths [103]. Another prime example of the potential widespread impacts of smoke from distant wildland fires is provided by the 2023 Canadian fire season. Smoke blanketed much of North America, including at times the eastern seaboard of the U.S. with its large population centers, and was noted as far away as Europe. Zhang et al. [105] found that over 350 million people were exposed to elevated PM2.5 emissions daily throughout North America and even into Europe. They also estimated that about 5400 direct deaths occurred and over 64,000 deaths from chronic conditions were hastened because of the smoke from the 2023 Canadian fire season.

While smoke was a major issue throughout Canada, other impacts of the 2023 fires within Canada were from the displacement of remote communities, often of Indigenous or First Nations peoples [106,107]. These evacuations occur not just for an impending fire front, but also because of smoke impacts and the remote nature of these communities [5]. "First Nation reserves and communities with a primarily Indigenous population represent 5% of the population in the country, but experience 42% of wildland fire evacuation events. In the last 20 years, some Indigenous communities have been evacuated as many as five times because of wildland fires alone. In 2021, 75 of 217 or 35% of evacuation events affected Indigenous communities. This is four times the 20-year average of 49 evacuations per year (2001-2021). Overall, Indigenous peoples are 30% more likely to be impacted by wildland fires" [108]. This can understandably lead to declines in the social and mental health of these communities, along with other "cascading, interconnected, and long-term consequences" [106].

Other fire impacts to consider include those on soils and water supplies. Low intensity fires can have beneficial effects on the soil by creating a pulse of beneficial nutrients [22]. However, high intensity fires can generate hydrophobic soils, increased erosion and potential debris flows, and the loss of soil microorganisms. The loss of soil microorganisms can include both the beneficial and detrimental ones, either removing those required for plant growth or clearing away disease. In terms of effects on water, fire influences the rate of rainfall interception and infiltration, as well as snowfall amount and melting rate [22]. Erosion and debris flows after high severity fires can clog up streams and rivers, reducing water quality for humans and habitat quality for aquatic life. Low severity fires generally have little effect, but suppression activities themselves can be even more harmful than high intensity fires [22,109]. In the United States, 46% of the nation's drinking water originates on public and private forested lands [110], clearly resulting in impacts far away from the fire itself.

While "wildfire disasters" are largely defined by their impact on highly visible and populated communities, wildland fires are a key part of functioning ecosystems and often have positive benefits. It is clear that wildland fires should be thought of as distinct from WUI and urban disasters, and the wildland fire itself is still very much worthy of study.

4. Current primary tools and approaches

As wildland fires are not going away, managers and communities need tools to help plan for and live with fire. Some of these required tools will need to be designed for the built environment (for WUI and urban fires) and therefore are out of the scope of this paper, but we still need to understand and better predict the wildland fire [6]. In particular, we need better training tools for firefighters [6], as well as tools for land managers to plan fuel treatments that significantly alter wildfire behavior in severe conditions [90]. As we will discuss, however, existing models and tools don't work well under those conditions.

Perhaps it is useful to make a distinction between theory, models, and tools here. Theory is the physical understanding of phenomena at the most basic level. Models are simplifications of theory, developed to gain traction on a problem [9]. Tools can be conglomerations or systems of models, developed to answer specific needs and questions for specific user groups. It is important to acknowledge that models and tools don't have to perfectly express the actual physics to be useful in certain circumstances [9], but the more basic theory is incorporated, the more scalable and more widely useful it might be. As addressed in Ref. [9] and discussed further later, there is a general lack of theory in wildland fire. There are plenty of models and tools, however. The discussion here is not meant to be an exhaustive review. Sullivan [111–113] provides a comprehensive review of all models up to 2007, divided into those that are physical, semi-physical, semi-empirical, empirical, and mathematical. Here we will approach the discussion more in terms of models and tools that are used operationally (by managers) or those used for research (however vague this distinction may be in some cases). While the categorization used by Sullivan is accurate, thinking about how models are actually used and by whom helps to identify their strengths and weaknesses and roads for future research.

4.1. Operational models

There are three main operational systems in use globally: the U.S. system, Canadian system (CFFDRS), and the Australian system. The Canadian (see Ref. [114]) and Australian systems (see Ref. [115]) are largely empirical using extensive field experiments and wildfire datasets (Canadian system uses over 300 fires) - developed for specific fuel types and conditions - but the methodology has been applied elsewhere. For example, the Canadian CFFDRS system has been fully adapted to work in parts of the United States and New Zealand, while the Fire Weather Index (FWI) component of the system is used in Spain, Portugal, Sweden, Switzerland, Costa Rica, Argentina, Fiji, Indonesia, and Malaysia [116]. Because of the nature of empirical models, they are still limited to the conditions and fuels used to develop the predictions. These limitations are why there is a call for updating the CFFDRS [117], which hasn't had a meaningful update since 1992.

The U.S. system is based on the Rothermel spread equation [15] for surface fire spread, van Wagner's for the transition to crown fires [118], and the Rothermel crown fire spread model [119] for the behavior of crown fires. The Rothermel surface spread equation is a semi-empirical model, meaning it has an energy balance as the backbone, but with empirically derived coefficients. The energy balance was fit to laboratory spread experiments using homogeneous fuels of excelsior (shredded wood), wood cribs built of 0.64 cm (¼") sticks, and wood cribs built of 1.27 cm (½") sticks. It assumes one-dimensional steady state spread in the head fire direction and was originally developed for homogeneous dead fuels of one size. A weighting scheme was added by Albini [120] to make the model work with fuel models representative of real vegetation (though this was not based on experimental data). The van Wagner transition model is based on 8 experimental and wildland fires in limited fuel types [118]. It predicts that torching of an individual tree will occur if the surface fire intensity attains a critical value. This value is based on the crown base height and foliage ignition energy (dependent on the moisture content). Rothermel's crown fire spread model [119] is an empirical correlation based on 8 observations from 7 wildfires. It was only meant to be applied to "wind driven" crown fires (and not "plume driven" crown fires) where the strength of the wind outweighs the vertical plume momentum (much like a Froude number, see Ref. [121]). The average Rothermel wind-driven crown fire spread rate is predicted as 3.34 times the surface fire spread rate of Fuel Model 10 (timber - litter and understory, see Ref. [120] or [122]). The maximum crown fire spread rate is simply 1.7 times the average rate. The U.S. system includes dozens of tools developed to help land and fire managers answer specific questions (ex: NFDRS, BEHAVE, BEHAVEPlus, FEMS, FireFamily Plus, WFAS, FARSITE, FlamMap, FSPro, FSim, WFIPS, WFDSS, IFTDSS, FOFEM, FIREMON, FFI, FuelCalc, etc.). All of these tools rely at some point on spread predictions using Rothermel's surface spread equation, van Wagner's transition model, and Rothermel's crown fire spread model. These tools help managers in a wide variety of ways including planning, risk analysis, operations, training, danger rating, fire effects, and fuels. For example, the BEHAVEPlus model is estimated to be used 50% of the time for training, 30% for prescribed fire planning, 20% for suppression (Dr. F.A. Heinsch,[1] personal communication, November 12, 2025). Overall, the Rothermel spread model is estimated to be used in U. S. systems 20% of the time in training, 50% in prescribed fire planning (especially via BEHAVEPlus and IFTDSS), and 30% in suppression (ex: WFDSS) (Dr. F.A. Heinsch personal communication, November 12, 2025; Confirmed by L. Hollingsworth,[1] December 19, 2025). The Rothermel spread equation is also the basis of fire prediction in Portugal, Greece, France, New Zealand, and Italy [123].

One common thread between the Canadian, Australian, and U.S. systems is that they predict only the head fire rate of spread. For predicting fire over a landscape, they all assume an elliptical shape and solve for the flanking and backing spread using purely mathematical relationships (e.g. Refs. [11,124]). It is also important to recognize that these fire behavior predictions are strictly for *steady*, head fire spread and will not predict other spread behavior, such as fire front interactions. Fires in these models are typically assumed to spread as a line of fire across the landscape, burning primarily in the fine fuels (in the U. S. system, this is mostly the so-called 1-hr fuels, defined based on their time to reach an equilibrium moisture content and classified by their diameter).

4.2. Research models

There are a number of research models for wildland fire and are often referred to as "full physics" or "multi-physics" models. For a full summary, see Ref. [111], but the more frequently used include: FDS/WFDS[2] [125,126], FIRETEC (with HIGRAD) [127], QUIC-Fire [128], Balbi [129], Grishin [130], FireStar3D [131], FireFoam [132,133], ForeFire-MesoNH [134,135], and WRF-Fire/WRF-SFire [136]. WRF-Fire, however, is incorporated into the Colorado Fire Prediction System (CO-FPS) so it is a bit of a hybrid research/operational model [137]. ForeFire-MesoNH was also developed with both operational and research usage in mind [138]. Similarly, QUIC-Fire is under development with the aim of being utilized by managers for prescribed fire planning due to the fast running times achieved [128]. All involve some level of conservation equations but make different assumptions because of the wide range of spatial scales involved (from sub-mm to km+). FDS/WFDS, FireFoam, and FireStar3D probably have the most ability to solve the smallest scales of the combustion processes. The models of Balbi [129] and Grishin [130] also are focused on more flame-scale processes, though they are still quite different. For example, the most recent iteration of the Balbi model is a simplified steady-state physical model where the rate of spread is calculated as the sum of contributions from radiation of the burning fuel bed, flame radiation, and convection, requiring many assumptions to render each of these components calculable faster than real time [129]. The Grishin model [130], however, was indeed a more "general mathematical model," starting from conservation equations and is much more like a computational fluid dynamics model, similar to FDS/WFDS, FireFoam, and FireStar3D. These "flame scale" models are likely the most appropriate for capturing the behavior of small-scale prescribed fires and phenomena such as the

[1] Dr. Faith Ann Heinsch (Research Physical Scientist) and LaWen Hollingsworth (Fire Behavior Specialist) are the co-development leads for BehavePlus. They are responsible for the maintenance and development of new versions of the software, as well as for the development and delivery of several required training courses for Fire Behavior Analysts (FBANs) and Long-Term Analysts (LTANs) in the United States (S390, S490, and S495 courses). Actual usage data is not recorded. These figures are best estimates from their experience.

[2] Note that WFDS was originally developed as an extension to FDS starting sometime around 2007. WFDS was developed separately before it was merged back into FDS sometime in the early 2020s.

transition from surface to crown fire.

FIRETEC, QUIC-FIRE, ForeFire-MesoNH, and WRF-FIRE, on the other hand, use simplified fire spread models and focus on larger-scale atmospheric flows. For example, WRF-FIRE is an atmospheric model that is paired with the Rothermel surface fire spread equation, so it has the ability to predict fire-atmospheric interactions. Similarly, ForeFire-MesoNH uses the Balbi model to calculate the rate of spread for a Lagrangian front tracking method (similar to FARSITE) [134,139] and is paired with the MesoNH atmospheric model [140], though it is designed to be modular and could run other fire spread models, including the Rothermel spread equation [135]. ForeFire-MesoNH is often run with nested grids to allow for much faster run times necessary for operational use, with the smallest grid used near the surface of 30-80 m with the fire front in large fires resolved at 2 m [134,140,141]. As such, it is developed to primarily simulate large and intense wildfires [140], and like most of the other coupled fire-atmospheric models, not necessarily for use in low intensity prescribed fires or the initial stages of a wildfire [138]. Both WRF-Fire and ForeFire-MesoNH can do two-way coupling: heat and water vapor released from the fire is accounted for in the atmospheric model while the atmospheric model calculates local winds (which include both ambient and fire-induced winds) as an input to the fire spread model. Though it is not an atmospheric model (a.k.a. numerical weather prediction model), FDS/WFDS also has a mode where the Rothermel spread equation is used in a level-set approach so that some of the larger-scale atmospherics can be incorporated with varying levels of fire-atmosphere coupling (FDS-LS1 through FDS-LS4) [126,142]. QUIC-Fire is a combination of a modified version of QUIC-URB (fast running urban wind model that uses empirical correlations and mass conservation [143]) and a cellular automata spread model (FIRE-CA). FIRETEC uses HIGRAD, a hydrodynamics model, to solve for 3D terrain-following flow and ensemble averages for the conservation equations to capture the “essence of the combination of many small-scale processes without describing each process in detail” [127]. Because research models capture more of the physics, behaviors such as fire line interactions ([141]), fire induced winds ([144]), and the transition from surface to crown fires ([145]) can be more successfully modeled than with the operational models. However, no single model can really solve for the tiniest combustion scales (sub-mm) while still solving atmospheric feedbacks for the largest, landscape-scale fires (km+).

5. Weaknesses in current approach and gaps in understanding

As outlined in the previous section, there are clearly many tools and resources available to decision makers and researchers. This section is not meant to denigrate these efforts, as many of them have been very useful (back to the adage “all models are wrong, but some are useful”). This section is meant to highlight just how open the field is for contributions to making these tools even more useful.

5.1. Operational modeling gaps

After understanding how the operational models were developed and the assumptions made (in particular, steady heading fire spread), it becomes clear that there are many fire behaviors that are not captured (nor were they intended to) that are relevant for both prescribed and wildfire scenarios. Non-steady behaviors that are important for prescribed fire include fireline interactions (how do multiple ignition spots or lines influence overall fire behavior?), spread thresholds (will a fire even spread under marginal conditions?), tree torching and the transition to crown fire (sometimes this is desired, other times it is to be avoided), and spread through discontinuous fuels (most natural fuels are clumpy). Of additional concern for prescribed fire would be the behavior of backing and flanking fires (many prescribed fires avoid heading fires to reduce intensity and increase fuel consumption), live fuels (many prescribed fires occur during the early growing season when live fuels can moderate fire intensity), the transition between smoldering and flaming under marginal burning conditions, and full understanding of the effectiveness of a fuel treatment at reducing fire behavior (will this help under wildfire conditions?).

Many of these same behaviors are relevant under wildfire scenarios as well, just with a slightly different context. Fireline interactions are still relevant, just at a larger scale when multiple fires merge (ex: Pedrógão Grande fire). Non-steady spread is important because the model outputs are often “worse-case” - fires don't spread at that rate all day and night. Users of the U.S. system, for example, must enter a “burn period” for the day so that the models don't dramatically overpredict the daily spread. This “burn period” is a best guess made by the modeler based on previous days, the stability of the atmosphere, weather forecasts, and expert intuition, requiring a lot of art on the modelers' part (i.e. they must skillfully and creatively apply their experience and a solid scientific foundation). Smoldering and the transition to flaming contribute to this as the fire will transition back and forth over the course of the day and night, determining whether the fire is “active” or not. Backing and flanking fire spread are still relevant as they contribute to the total burn area of the fire. Crown fires are common in wildfire scenarios, requiring understanding of the transition of the fire from the surface to the canopy fuels and the burning behavior of the live foliage. As the scale of the fire grows, fire-atmospheric interactions and the transition to area/mass fires become more relevant. As noted in the previous section, “plume-dominated” fires are not modeled at all by the U.S. system, which would include being able to predict phenomena such as “plume collapse” (such as the Dude fire, see Ref. [146]) and firebrand deposition in all directions. With the increasing fuel loads and drought conditions in recent times, the transition between smoldering and flaming of heavy ground fuels and coarse woody debris are responsible for fire behavior deviating from “line fire” behavior to behave more like area or mass fires as these fuels burn with very long durations. Fire induced winds now become important to capture because this can not only change the wind that the fire front experiences, but this may also impose a positive feedback on the transition to flaming of fuels that would normally smolder [147]. Large-scale topographical interactions and fire whirls may also be dangerous phenomena and warrant prediction (ex: 2018 Carr Fire in California, see Ref. [148]).

There are other factors that go into running these operational models that require a fair amount of art and skill from the modeler. How to define the wind? (This goes for research models too). Weather stations frequently report the wind at 10 m or 20 ft above the ground, but all the operational models require some sort of “wind adjustment factor” that translates this to something like the “mid-flame windspeed.” Where to take the weather from? What fuel model and what fuel loading to use? While these things may be auto-filled or default, on-the-ground and previous experience with the actual fire behavior often requires tweaking or tuning of these inputs to better match with recent observations so that future behavior can be better predicted, especially when the modeler is deployed to an active wildfire. Fuel maps may be out of date and don't reflect recent fires or fuels treatments. In prescribed fires that have a research component, detailed information about the local conditions at the burn unit may be available from temporary weather stations that would be helpful to model particulars of the fire behavior after it occurs. However, in most operational applications this is not available. There may be several permanent weather stations within some radius of the fire, but the nearest weather stations by distance may not be the best representation of the weather (temperature, humidity, wind speed and direction) experienced by the active fireline. These issues with fuels and weather often require the modeler to be onsite to visually assess these inputs or at least have local knowledge. When modeling future fire behavior, the modeler also must deal with the usual issues of inaccurate weather forecasts, especially when trying to predict fire perimeter over three days out, which is important for initiating evacuations. How these parameters and variables are selected will also depend on what the model runs are being used for (ex: evacuation warnings vs suppression strategy or even just prescribed vs wildfire).

5.2. Research modeling gaps

Most things that require skill by the modeler to reliably run operational models still apply for research models, perhaps even more magnified. For example, it's not just choosing the weather station to use, but how that weather station's wind speed measurement is converted into the wind field boundary conditions required for a “flame scale” computational fluid dynamics (CFD) simulation (e.g. FDS, FireStar3D, etc.) is up to the modeler's judgment [149]. Even though the coupled fire-atmosphere models partially side-step this issue by “simulating the weather,” the atmospheric models themselves still make assumptions about atmospheric processes that can affect fire behavior [150] and are likely not resolving the ground winds finely enough to capture the details that may be important on a small-scale prescribed fire [150]. Especially when modeling a fire before it occurs in an operational context, a wildland fire modeler must cope with the fact that the details of the fuels and weather will never really be known. For a relatively small-scale prescribed fire, more of the details of the fuels may be known *a priori* (especially with recent developments in fuel mapping techniques), but the weather conditions on the day of the burn will have to be estimated, sometimes months in advance. When modeling wildfires, even less will be known about the fuels. For example, the U.S. system has fuel models mapped to 30 m resolution with general information about dominant tree species [151,152], but where those trees are located, how clumped together they are, what's underneath them, etc. will all have to be assumed without drastic changes in the way we've measured and mapped our fuels. FIRETEC acknowledges these unknowns and tries to mitigate them with the ensemble average approach [127]. The other flame-scale models do not, and the atmospheric-scale models essentially use operational models for the flame spread itself, so these details are not even available to consider. The author here is reminded of the round robin exercise to model the Dalmarnock Fires [153]. In this eye-opening study, seven teams of fire modeling experts were given the same information about an apartment that was heavily instrumented before being ignited and allowed to burn. The results of this round robin clearly indicated that the difference in how the users input the same data can drastically alter the model outputs. No such round robin study has been conducted with wildland fire to understand how such things will play out in this context. This may be one advantage of operational models over research models - their fast run times means that it is easy to run thousands of simulations in a Monte Carlo fashion with slight tweaks in the input conditions to understand how their uncertainty impacts the modeling outputs (ex: FSim - see Ref. [154]). This is impractical with the more computationally expensive research models. QUIC-Fire has the run speed to allow for this, but since the model is under development for prescribed fire applications, it is unclear whether it will be reliable for wildfire applications.

As mentioned when introducing the research models, assumptions must be made to handle the 6+ orders of magnitude involved in wildland fires. This is true even for the more flame-scale models like FDS/WFDS and FireFoam. Depending on the domain size considered, even FDS/WFDS is run on a 1 m grid cell when modeling “larger” outdoor fires (e.g. see Refs. [155–159] for domains of around a few hundred meters. Smaller domains or variable sized meshes can accommodate 0.5 m or even 0.25 m grid cells for the solid fuel layer [160–162]). Even with the more resolved simulations, sub-grid processes are approximated with sub-models. Some of these embedded sub-models may not be the most suitable for wildland fire, but no better option existed and a placeholder was needed. FDS/WFDS is still continually updated with improvements to these sub-models [163]. The issue of sub-models may be even more prominent with the more atmospheric-level models, like QUIC-Fire and WRF-Fire. The developers have made it clear that they are using empirical spread models for the fire itself which are subject to the same limitations as discussed for the operational models above. For example, even if the coupled fire-atmosphere models do incorporate fire induced winds, the underlying spread model doesn't have the ability to predict the transition from smoldering to flaming of the duff and large woody debris to fully capture the mass fire nature of extreme fires. QUIC-Fire additionally uses a simplified model for the atmospheric flows to enable faster than real time runs. All these sub-models and assumptions come with drawbacks that the user needs to be aware of so that questions of the models beyond their capabilities aren't asked. And if those questions need to be asked, the user must understand the consequences of those assumptions on the results.

In contemplating the future of research models, one must understand the users of these models and what these models are intended to do. Is the intent of these models to be used by land managers? Prescribed fire planners may have more time and desire to run a more complete physical model, but barriers still exist in terms of training and gaps in relevant sub-models. Will these users be up to the task of learning the nuances of these complex models? Will the models be fast enough to run them for the full range of conditions that might be expected for a particular prescribed fire or wildfire? Or are these models intended to help other researchers better understand the controlling phenomena behind some experiment or previous wildland fire? Full physics research models can certainly still be quite useful in this sense because they are able to probe and measure things that are otherwise unavailable during the actual experiment or fire, but again, the limitations of the sub-models are still present.

5.3. Machine learning (ML) and artificial intelligence (AI)

Machine learning (ML) and artificial intelligence (AI) are attracting considerable attention these days. Naturally, there is interest in applying these techniques to wildland fire. ML and AI have already been actively applied for detection applications [164,165] and a number of other wildland fire applications [166], but the natural pinnacle application would be to develop spread prediction tools using these techniques. As with all applications of these tools, there are huge data requirements to feed the models. While this data can be generated by running other fire spread models, as was done by Refs. [167–169], the limitations of the models used to generate the dataset are still present. To feed ML/AI models with real wildland fire data, due to the large number of embedded potential variables, one would need tens or hundreds of thousands, if not millions, of fire perimeters with corresponding fuels and weather data. Perhaps surprisingly, these datasets simply do not exist right now, and it may be some time before they are obtainable. Fuels and weather data at an appropriately fine resolution are simply not available or would require a whole other modeling effort to fill in the information between weather stations or fuels measurement grids to account for localized variability in air temperature, humidity, wind speed and direction, fuel loadings, fuel moisture content, etc. Historically, fire perimeters were mapped by flying the perimeter daily (or maybe twice a day) and drawing the fire perimeter manually on a map. Satellite technology has made this a more automated process, but even this is surprisingly limited. High resolution fire areas (30 m) are possible using LANDSAT satellites (Landsat-8 launched in 2013, Landsat-9 in 2021) but the fly-by time is every 8 days [170,171]. The Sentinel-3 series has a 1 km resolution available twice a day [172], and the Sentinel-2 series (launched in 2015 and 2017) has 10-30 m resolutions but is limited to every 5 days [171,173]. Other polar orbiting satellites like those with MODIS and VIIRS make observations 1-2 times per day near the equator, or more as the latitude increases [174]. MODIS can provide observations with 1 km resolution 1-2 times per day for each of the two available satellites (Terra and Aqua) [175]. ASTER data is 30 m resolution and is onboard the NASA Terra satellite with one of the MODIS sensors, producing 2 scans a day near the equator [176]. VIIRS has resolution down to 375 m also with twice daily maps for each satellite [177]. Newer geosynchronous satellites (such as GOES-R, Meteosat series, and Himawari) can do observations every 1-10 min, but their resolution is even more coarse, 2-3 km [171,178,179]. Due to the lower resolutions, the GOES and other geosynchronous satellites are unreliable at capturing smaller scale or low intensity fires [171,180]. The first GOES satellite (GOES-16) wasn't launched until 2016. The rest of the GOES-R series were launched in subsequent years (GOES-17 in 2018, GOES 18 in 2022, and GOES-19 in 2024). Himawari-8 and -9 launched in 2014 and 2016 respectively and are the first of that series to provide fire detection at 2 km resolutions [181,182]. Meteosat 8 was the first “second generation” (MSG) Meteosat series satellite with fire detection capability. It was launched in 2002 with 3 km resolution every 15 min [178,183]. Meteosat-12 is the first Meteosat Third Generation (MTG), launched 2022 and will soon be able to provide scans at 1.5 km resolution for Europe every 2.5 min (European regional Rapid-Scan Service) [184]. All satellite detections, however, require the sky to be relatively cloud free [180]. It is clear then that the availability of more than two fire perimeters per day (on good days) for even large fires is still a relatively recent development. Additionally, the perimeter data available so far will be heavily skewed towards very large and intense fires because of the coarseness of the resolutions (∼1-2 km). Though there is a somewhat larger daily fire area dataset, the lack of temporal data leaves huge gaps in identifying *how* the fire spread to its current location. Did it continuously spread in a single direction, veer with windshifts, or did it jump ahead by spotting? This information can be very important for safety, planning, and suppression strategies. While ML/AI may be able to provide essentially the ultimate empirical spread model (at least for large fire conditions), this still only goes as far as the data that fed it and doesn't provide any physical insight. This begs the question: do we actually learn anything?

5.4. Known unknowns and anomalies

As outlined above, our current tools and really our basic understanding of the phenomena leave many unanswered questions. Others have begun to list these “known unknowns.” Limitations in our knowledge of surface fire spread were outlined in Ref. [7]. In that work, four challenges were identified: lack of consensus on fuel preheating mechanisms, fireline behaviors (flame length and temperature of deflected line fires in wind), issues in scaling fire behavior, and unsteady behaviors (fireline interaction/merging, crown fires, fire whirls, and spot fires). Similarly, Finney et al. [9] also outlined four known “anomalies:” fuel particle heat exchange leading to ignition, convection, ignition, and live fuels and their distinction from dead fuels (moisture content, leaf chemistry). In the sections below, these and many other gaps in our understanding are addressed. While we may never be able to perfectly model all of these, some deeper understanding is required to get a better handle on what we can and what we can't ignore in our models.

5.4.1. Heat transfer and unsteady behaviors

The obvious overlap between Liu [7] and Finney et al. [9] is in the concern for fuel preheating mechanisms. While Liu emphasized understanding heat transfer mechanisms in different fire spread scenarios, it is crucially important to do this for different fuel contexts as well [9]. Too frequently, convection is measured using total heat flux gauges and subtracting the radiant contribution. While this may be adequate in some scenarios, such as large flat surfaces of continuous fuel, this wholly misrepresents and dramatically underestimates convective heat transfer for the small, discontinuous particles that make up wildland fuels [185]. As a result, the role of convection in fine fuels during wildland fire spread is still misunderstood and not well studied outside of a few efforts. Cohen and Finney [186] conducted careful experiments paired with numerical modeling to examine the heat balance for different sized particles. They clearly revealed that ambient natural convection alone is enough to cool a 1-mm particle and prevent it from igniting even under radiant heat fluxes of up to 36 kW/m^2, but not 3 mm or larger particles. They also demonstrated that the classic approach of considering the surface area to volume ratio of the particle isn't what is actually driving this behavior. In a follow-on paper, Cohen and Finney [187] also clearly demonstrate the importance of convective heating and cooling for small particles during flame spread. In Ref. [187], as in Ref. [188], instrumented 1-mm and 12-mm particles were placed inside a fuel bed with a spreading fire. For both sized particles, flame contact was required for ignition. The 1-mm particle cooled considerably between flame pulsations, but the 12-mm particle did not. However, the duration of the radiant heat flux from the approaching flame in these experiments was too short to cause ignition for the 12-mm particles by radiation alone. What is clear from these papers is not only the important role of convection that is dependent on the size of the fuel particle, but that this convection acts in a non-steady fashion, even for situations of “steady” flame spread. The unsteady nature of this convection has subsequently been examined by Refs. [189–196]. So really, one can add “steady” head fire spread to the list of challenges of unsteady fire behaviors [197,198]. Crucially, this effort to understand heat transfer mechanisms has still largely focused on the head fire direction. Very little work has been done to understand heat transfer in flanking and backing spread in beds of fuel particles [199]. Without a physical explanation for flanking and backing, we cannot do anything better than simple geometrical guesses at a fire's shape as it spreads over the landscape or improve our modeling ability for prescribed fire.

Spread thresholds are a further challenge of unsteady fire behaviors that are critical to improving our ability to predict all forms of wildland fire, from prescribed fires to wildfires. As emphasized in the discussion about operational modeling weaknesses, we still don't have the ability to answer the question “will a fire even spread?” Because of the great importance of this question to conducting prescribed fires in particular, statistical models do exist (such as [200]) but are empirical in nature and are thus very limited in their application. In the realm of wildfires, this can be an important aspect to whether the width of a control line or fuel break is adequate, for example, or to understand whether the fire will be active overnight. When thought of vertically, there are spread thresholds for whether a surface fire will transition to a crown fire that are also poorly understood. Spread thresholds happen at the smallest scales and thus require detailed understanding and accurate representation of the fuels and processes down at this level.

5.4.2. Live fuels

Live fuel anomalies are still an issue and of great importance in both small-scale prescribed fires and the biggest blowup crown fires. It is still painfully unclear why live fuels can ignite and burn at moisture contents above 100%, and why some species don't support crown fires (ex: many broadleaf/deciduous trees). Since [9], there have been some recent efforts to understand the fire behavior of live fuels. Because of its importance to both fire behavior and fire effects, studies are conducted via both engineering and ecological approaches. While ecological approaches tend to try to find statistical linkages in physiological traits and some aspect of “flammability,” engineering approaches tend to look for more mechanistic causes. For example [201–203], used a more engineering approach to understand leaf-scale ignition behavior. In Refs. [201,202], it was demonstrated that water vapor is still being released at the moment of ignition, indicating that even though these fuels are physically thin, temperature and moisture gradients exist at ignition (this is contrary to the way most research models treat wildland fuels). By conducting ignition experiments over the course of the growing season to allow for natural variation in moisture content, it is clearly demonstrated by Ref. [203] that for many species, the ignition time is not well correlated to the moisture content. In fact, for some species, the higher the apparent moisture content, the faster they ignited. This makes it clear that we need to think about live fuels differently (such as [204,205]) and that the driving mechanisms between live and dead fuels are different and unknown. Are these differences chemical or physical? Chemical differences include the fact that live fuels are living and photosynthesizing. This makes it difficult to really define moisture content since the dry mass of the fuel can change due to plant processes without changing the amount of water contained within it [205]. Because they are making sugars and starches, transporting materials, growing and hardening new needles and leaves, the chemical composition of the needles and leaves changes during the growing season and may even change over the course of the day. Deciduous and evergreen species may also invest in varying levels of lignin or other chemical components that alter their fire behavior. Insect damaged trees may also have changes in their chemical composition as they try to ward off or succumb to the attack [206]. In other words, the chemical composition of the fuel itself, i.e. the gaseous species that are combusting, is unknown. Some of these chemical differences have been studied by Fletcher and coworkers [207–211].

There are also physical differences between live and dead fuels, and between different species. For example, dead fuels can store water both as free water in the extracellular/intercellular spaces and bound water that is chemically bound to the cell walls [212]. Live fuels have a third water storage mechanism that is unavailable to dead fuels. Live fuels can store large amounts of intracellular water (sometimes referred to as loosely bound water or physically trapped water) [212,213] – water stored in the vacuole and cytoplasm inside the cells. As a live fuel heats, this intracellular water builds pressure within the leaf which is suddenly and violently released, potentially along with flammable materials from inside the leaf [201,202,214,215].Fig. 5 below shows this phenomenon in grand fir (*Abies grandis*). Different plant species also have different strategies and adaptations for handling drought conditions, such as protective waxy coatings, which can add to this pressure build up and sudden explosion of water vapor. These physical mechanisms have been examined by Blunck and coworkers [216–218] and [219], confirming that the explosive release of water can indeed include droplets of flammable materials, but whether this is the driving mechanism of live fuel flammability is still unknown.

Adding to the challenge is understanding how leaf flammability translates to plant flammability and how that translates to fuel bed level flammability. For example, needles or leaves are not evenly distributed over the volume of the shrub or tree. So how does leaf or needle spacing and arrangement along the branches and the arrangement of the branches themselves contribute to how the entire plant burns? Does an average bulk density of the entire plant capture this? On the whole plant and fuel bed level, the mix of live and dead also becomes important, especially in shrubs where the dead needle or leaf drape is known to dramatically change fire behavior [220,221]. Understanding whole plant and fuel bed flammability is also important for making recommendations for landscaping and ornamental vegetation and better understanding “green fuel breaks.”

Fig. 5. Grand fir branch heated in 800 °C air. Image is a frame captured using a high-speed camera at 1000 fps showing flammable gases jetting from the needles, several seconds before the entire branch ignites.

There are several major challenges to answering these questions about the fire behavior of live fuels. One is that it is virtually impossible to control all the needed variables. One cannot dissociate the chemical from the physical differences, nor can one alter these in a controlled fashion to test which is the driving mechanism. Another major hurdle is that there is no standardized method of testing “flammability” for wildland fuels. Bench-scale tests include the muffle furnace, epiradiator, dropping burning matches, flat flame burner, cone calorimeter, or Fire Propagation Apparatus (FPA). Some are favored by the ecology field, and others by the engineering field. While the experimental approach used by the ecological community may be considered less “rigorous” by the engineering community, the ecological field brings a better understanding of the physiology of these plants which might be driving these differences in flammability [222]. With such a wide range of approaches, it is impossible to compare studies, let alone develop a cohesive understanding of controlling mechanisms.

5.4.3. Smoldering

Smoldering and the transition to flaming are also known unknowns that are important for the whole range of wildland fire behaviors [123]. This includes firebrands and spot fires; duff and surface fuel consumption, soil heating, and fire effects; large woody debris consumption and contribution to the flaming front, especially in extreme wildfire conditions; re-kindling of fires thought suppressed; and a basic on/off switch during long duration fires. Smoldering itself is a poorly understood, underappreciated, and understudied form of combustion [223,224]. As reviewed in Ref. [225], while we have a general framework for the transition from smoldering to flaming, there is much still to be learned, particularly for wildland fuels as much of the previous work in this area was using synthetic polymers. Our ability to predict smoldering initiation and spread and the transition to flaming is severely limited even with the most complete physical wildland fire behavior model available currently.

5.4.4. Large-scale behaviors

Large-scale fire behaviors are another major challenge [11]. As fires grow in size, they likely do not behave as line fires and therefore are not captured by operational models at all or fully captured in all of our research models. Large fire behaviors include plume-dominated crown fires and other fire-atmospheric feedbacks (which could still occur on the small scale). Peterson et al. [226] have a conceptual framework for the formation of pyrocumulonimbus, a characteristic of plume-dominated crown fires, and there are the Byram and convection numbers [121,227] as a rough criteria, but because of their scale and relative rarity, our ability to predict when they will occur and how they will behave is still limited [11]. The classic conceptualization of plume-driven crown fire still assumes a line fire configuration (due to the way the Byram or convection number is typically calculated using the fireline intensity), so it does not hold for area fires or fires where the plume entrainment could be restricted due to large-scale vorticity. Additionally, there is much still to learn about how large-scale interactions with topography can influence fire behavior, such as the fire tornado formation during the Carr Fire in California in 2018 [228].

Other atmospheric feedbacks can occur with large fires in extreme conditions as large woody debris and deep duff layers become involved in the flaming front. While predicting this is related to our understanding of the transition from smoldering to flaming, we know that this can contribute to mass or area fire behavior (when the fire deviates from line fire behavior). Firebrand showers over large areas are also likely a contributing factor. Mass or area fires are typically characterized by tall plumes with strong fire-generated surface winds. There are several possible mechanisms for the generation of this wind [12], but no consensus has been reached. However this wind is generated in a wildfire, experiments in Ref. [147] using a chimney as a simple method to reduce plume entrainment demonstrated that strong induced winds have a positive feedback on the burning of the solid fuels involved, potentially doubling burning rates and increasing the participation of the larger woody material. It is possible that mass or area fires can form plumes with counter-rotating vortex pairs that interact with the wind in different ways than standard plumes or develop plumes with a single coherent rotation ("fire storm") [11]. There are no precisely defined conditions when this fire behavior will develop and what changes in the fire behavior will be seen. Large woody fuels and deep duff layers are not considered in any fire behavior model, so we have no ability to predict this behavior [11], but this can clearly be of great importance to firefighter safety.

Another unsteady fire behavior usually associated with large fires is spotting. Spotting is not discussed in detail here, but this is an aspect of wildland fire that has received a fair amount of attention from the engineering community due to the importance of this phenomenon in structure ignition. But there is still plenty to learn about the formation, transportation, and ignition processes, particularly for large-scale fires [229].

As mentioned by Liu [7], scaling in wildland fire research is a major challenge. Can small-scale laboratory or even field experiments capture the important behaviors of large-scale fires? Rigorously scaling all parameters may be very difficult or even impossible [112,230,231] as complete scaling laws often result in conflicting scaling requirements. Saito and Williams [232] point out that "successful scale modeling really represents partial scaling (i.e., it is based on various approximations), so that scale modeling is more of an art than a strict science." Once again emphasizing the "art" involved in wildland fire science. Little et al. [123] drive home the importance of getting scaling right: "we are still largely unable to translate high-resolution, accurate small-scale measurements to larger-scale behaviour, especially due to the differences in fuel heterogeneity at different scales. This becomes significant in translating combustion physics and chemistry phenomena (i.e. processes) into real predictive tools that enable landscape-scale predictions in different fuel types."

5.4.5. *Additional thoughts*

Important applications of fire behavior models and tools that land managers care about include assessing fuel treatment effectiveness and predicting fire effects (such as tree mortality). As mentioned above, it is estimated that the Rothermel surface fire spread equation is used 50% of the time for prescribed fire planning. Key to prescribed fire planning is understanding potential tree mortality. Predicting fire effects and tree mortality is dependent on accurate models of soil heating, tree bole and stem heating, and crown scorch. As Liu [7] pointed out, one of our challenges in wildland fire is predicting flame lengths and temperatures, which are driving parameters for bole and stem heating and crown scorch. Soil heating is largely dependent on post-frontal combustion (i.e. smoldering) which can be responsible for tree mortality due to root damage. While prescribed fires are conducted to promote ecosystem health and resilience, they are also frequently conducted to reduce fuel loads and potential future wildfire behavior. Part of prescribed fire planning is thus understanding under what conditions will that fuel treatment be effective. Will it successfully alter wildfire behavior under severe conditions? Being able to answer that requires understanding all the above "known unknowns."

Though not a question of physics per se, an additional challenge in wildland fire moving forward is the need to connect fuels measurement with fire behavior models: are the right things being measured? As we move to more physically-based models and tools, we also must ensure that the required inputs for these new models are measured. In particular, this means the way we measure fuels needs to match our model inputs. Historically in the U.S., the fire behavior models were developed first, then fuels were measured to feed the fuel models required for the fire behavior models (for example [120,122,151,152]). Right now, development of new fuels measurements is occurring rather separately from fire behavior model development. Some of this is due to land management needing to quantify the vegetation in terms of not just fuel for fire, but also assessing the health and resilience of the ecosystem or timber production. Some coordination between those that measure fuels and those that develop wildland fire behavior models must be made, which will likely involve cooperation between research engineers and land managers.

This section focused largely on wildland fire behavior, but some other equally important topics include emissions and smoke modeling as well as evacuation modeling. This includes understanding and quantifying the differences in emissions and health impacts between prescribed fires and wildfires (is a little smoke now acceptable to prevent much more and prolonged smoke later?). Continued work on the WUI and urban fire side of the issue includes improving structure and community resistance [54,70,91,233,234]; modeling fire spread through a community [235–237]; community planning for fire (separation distance, ingress/egress, landscaping) [238]; again, also socio-ecological system and socio-political system research to help adoption of research findings (most people know they live in a high risk area but don't do anything about it. Why?) [96,239].

6. How to move forward

Our modeling and tool development efforts are clearly hampered by our lack of understanding of the underlying governing mechanisms of wildland fire behavior, as evidenced by the long list of "known anomalies." It is imperative that research focuses on these "known anomalies," as well as the anomalies yet to be identified. Experiments have to play a critical role in this [9,240]. In this author's view, this will require two kinds of experiments. The first may be the most obvious and the one most accepted, and that is the focused/rigorous experiments. However, these need to be done not just to generate data for data's sake but must be conducted within the proper context. Are you asking the right questions? Are you probing the mechanisms in the correct scenario? Maybe the proper context is achieved through scale modeling of the experiments, but maybe this is something very simple. As Hirano and Saito [240] point out: "The preliminary experiment must be simple or a minimum complexity; it is also called a backyard experiment by H.W. Emmons … a simple experimental apparatus may serve the better role to help us understand the phenomena. It is not an easy task, however, to design a simple apparatus which allows us to capture the essence (only the essence) of mechanism (sic) by isolating it from other mechanisms." In conducting these rigorous experiments, it is clear that we need to move towards generating a standardized experimental approach, much like we have for testing materials in the built environment. Even though it may be argued that these standardized tests for building materials are imperfect or unrealistic, at least a consistent testing methodology exists to compare materials, which is completely lacking in the wildland fuel context (see section 5.4.2 especially).

We need not just focused/rigorous experiments, but researchers should feel free, or even obligated, to do some experimental "play." We should be doing the "what happens when I do this?"-type of experiments. We should be doing experiments to "break stuff," to challenge the current theory or understanding and to push the limits, to question things that we thought we knew. For example, it was long assumed that radiation dominated heat transfer in wildland fires, but recent experimental observations revealed the critical importance of convective heat transfer to the ignition of fine fuels as discussed above [188]. It should be clarified that it was recently re-revealed since these observations were also made in early wildfire and fire protection engineering papers but were largely forgotten or ignored (ex: [241–243]). We have also long assumed that only the fine fuels carry the flaming front of a wildland fire. In the U.S. system, this means the so-called 1-hr fuels. But is this always true? When does a fuel actually transition from being thermally thin and serving as kindling, and when does a fuel become thermally thick and burn like a log? These types of "play" experiments are where the real breakthroughs in our understanding can happen, but must still subsequently be followed up by experiments of the first type to fully elucidate the discovery.

Regardless of the type of experiment though, they must be done with emphasis on unbiased and keen observation. Hirano and Saito [240] emphasize this: "… we think pure and unbiased observation is the source of imagination and the foundation to guide us to correct interpretation … We think verbal models applied to described observation should be appreciated as equally as the mathematical models." Saito and Williams [232] introduce the importance of a sort of inductive approach or "Kufu"[3] [244] to research: "An inductive approach to the development of assumptions is Kufu which, in a sense, amounts to a highly developed professional intuition … One good experiment can hold a rich deposit of information, which can be extracted by Kufu eyes, while Kufu can help develop new perspectives, and imagination by carefully observing the experiment and successfully speculating about what is controlling the phenomena that the experiment is showing." They stress that this intuition about what's happening isn't just important for experimentalists, but for modelers as well: "Contrary to experimenters, many recent computational experts are often remote from the experimental site and do not experience enough interactions with experimenters to develop Kufu eyes. Such limited interaction does not help computational experts to attain Kufu eyes, and this is becoming even more problematic for students and future engineers and researchers who want to fully develop their capacity to solve engineering problems using the computational method."

It is important to keep in mind that these known anomalies are still unexplained for a reason. They are not easy problems. If they were easy, they'd be solved by now. In fact, they should be considered Very Hard Problems, but we shouldn't be afraid of them. As a community we need to recognize that anomalous behavior is something worth embracing. If anomalous behavior is identified, it should be daylighted, presented and discussed, because without the full weight of the community, a researcher may never gain traction on the problem. We should never be afraid to say, "I don't know what's going on here." As Hirano and Saito [240] state, keen observational data should be valued as much as numerical modeling results, even if we can't fully explain the physics behind the observations just yet. If we had all the answers, is it really research? How can we ever learn something new if we don't acknowledge what we don't know? Science and research are a series of hypotheses, testing, results, and re-assessment. Engagement and discussions with the broader community should be part of this cycle and we need to accept this role and be ready to help propose new explanations when none are immediately obvious.

While the author feels that experiments are critical at identifying and exploring the known (and unknown) anomalies holding us back, modeling is ultimately how knowledge gets translated into practical tools for our land managers. There is still plenty that modelers can focus on. For one, it is important to do the decidedly unglamorous and tedious work to revisit the assumptions in many of the research models that were meant as placeholders until better versions became available. This includes ongoing work to measure the drag and convective heat transfer through pine needle beds [245,246] or measuring convective heat transfer coefficients for single and piles of firebrands [247,248]. Numerical models will never be "exactly right" (all models are wrong, some are useful). As pointed out by Williams [249]: "Theory needn't be right to be good …" and "the theory that is exactly right not only will contain too much to comprehend but also ultimately may become tautological - devoid of content - testing only the practitioner's ability to run the computer. If you want to make progress in theory, you've got to make at least a little error (preferably knowingly)." Even though the models may never be perfect, and don't necessarily need to be to answer many practical questions, we should still strive to improve these models, especially if they're being used to probe the governing mechanisms of fire behavior. It is therefore still important that all the modelers out there dig through their models and understand where they come from and revisit the assumptions that are made, especially if you are new to the field or a new modeler. This is the author's worry about transitioning research models to operational use - we must make sure that the underlying assumptions are good because land managers and community planners that will use them don't have the technical background to do this themselves. CFD is great for making visualizations which are easy to take as "truth." Do we trust all users of models to have enough gut feelings (Kufu eyes) about the outputs to notice when the model is giving wrong answers? And to know why? Again, I am reminded of the results of the Dalmarnock round robin modeling exercise [153] and the importance of defining initial and boundary conditions in just the right way to have confidence in the results and have the Kufu eyes to identify the assumptions that lead to useful results [232]. Can we have confidence in all model users to do this?

It is clear that there is ample room for the fire safety engineering community to help in the improvement in our fundamental understanding of wildland fire behavior and the ability of our tools to predict it. There needs to be a two-way partnership, however, between the engineering community and with the ultimate users of this knowledge and the tools derived from it. In our study of wildland fire, we must appreciate what the decision makers actually need, be they land managers, or community planners, fire-fighters, or the general public. We must understand how these tools are used in training, planning, and for suppression efforts when needed. Not only do we have to develop missing knowledge, but we must find ways to get it to those that need it. As outlined by Ref. [6], there are cultural, social, and political issues that still must be addressed that are not necessarily our realm of expertise, but certainly create barriers to the adoption of any new knowledge or tool that we need to break through.

7. Concluding remarks

Wildfires don't have to be disasters. Most ecosystems need some kind of fire, but it needs to be the right kind of fire. Aggressive fire suppression only delays the inevitable, saving the fuel to burn in the worst possible conditions. Allowing "good fire" is critical for promoting ecosystem health (and the related ecosystem benefits like water), but it can also potentially reduce fire exposure to some communities. Regardless of whether the fire is "good" or "bad" however, fires will still inevitably impinge on communities, so the communities need to be ignition resistant to prevent the fire from becoming a disaster (and turning a WUI fire into an urban conflagration). Restoring "good fire" requires understanding fire behavior well enough to produce the desired fire effects, whether that is fuel reduction or ecological health benefits. Due to the complex nature of the wildland fire system [6], research and tools are desperately needed to bolster decision making and public acceptance. This paper outlined a number of "known unknowns" and opportunities to improve the current models and tools. Commentary was also provided that highlighted the importance of carrying out fundamental experiments, curiously making observations, questioning assumptions, and the openness to discuss unexplained phenomena. The current attention towards wildland fire is a result of the evolution of fire safety engineering out of the built environment into the natural one. Unlike the built environment, however, fires in natural vegetation require a much more nuanced approach. It is hoped that this paper generates awareness of these nuances within the fire safety engineering field so that we can all contribute to the wellbeing of our communities *and* ecosystems.

[3] As explained in Ref. [244], "Kufu is not just thinking with the head, but the state when the whole body is involved and applied to the solving of a problem … This is where the intellect can go no further … One must go deeper yet, but how? This "how" is kufu."

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

I have benefited greatly from the wealth of knowledge of all that work or have worked at the Missoula Fire Sciences Lab. Without them, I wouldn't have as deep of appreciation for the full context of wildland fire, especially fire ecology and fire management. Mark Finney and Jack Cohen in particular have been especially helpful. I would like to specifically thank Sharon Hood, LaWen Hollingsworth, and Nathan Kahla for their comments on the draft manuscript. I also want to thank the National Fire Decision Support Center for funding me and all the other great fundamental fire science research at the Lab over the last 15 plus years.

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