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The wildland fire system and challenges for engineering

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ABSTRACT

Recent wildland fire disasters have attracted interest from a variety of disciplines seeking to reduce impacts of fire on people and natural resources. Architecture, insurance and reinsurance, city and county government, and engineering sectors have contributed ideas to mitigate or avoid damage during wildland fires. This paper examines the modern wildland fire system in terms of the historical context for wildland fire, primarily in the US, and discusses some of the characteristics of this system and its human culture that affect the potential impact of innovations and engineering technologies.

1. Introduction

Wildfires increasingly threaten human communities and natural resources around the globe. Although wildland fires have always occurred, and in fact are essential for sustaining ecological functions in many ecosystems in the US [1,2], a decade of dramatically increasing wildfire suppression costs and damages to communities is now attracting interest from different disciplines. It's not surprising that fire protection engineering has become more engaged in the wildland fire problem, because it has traditionally focused on the related discipline of fire in the built environment. There is also now interest by architects, structural and mechanical engineers, and insurance industries seeking to minimize damages and financial losses. The purpose of this paper is to examine the intersection of the current and historical culture associated with wildland fire with the potential contributions from these sources of expertise. Specifically, the intent is to address where and how such technical expertise can be expected to produce benefits.

2. Historical perspectives

The wildfire situation in the US today is but the latest point along the timeline of changing human activities, vegetation dynamics, and climate variations [3]. If we are seeking effective solutions to problems in the current wildland fire system, it's helpful to review some history as to how we arrived at this point, particularly in the United States. The term wildland fire system is used here to encompass interactions of people, fire, and ecosystems more expansively than what has traditionally been strictly considered "wildfire management".

Modern managers of wildland fire have acquired considerable experience in both suppression as well as use of fire. The uses of fire occurred first, having been employed by people in their practice of foraging and agriculture since prehistory [4]. Long before suppression was technologically feasible or presumed possible, fire was a routine farming technique for clearing forests and removing agricultural crop residues. Burning of post-harvest timber residues and organic ground cover prepares the soil surface for tree planting or natural forest reproduction. For millennia, native peoples of the Americas and Australia expertly used fire in managing their environment to obtain needed resources and sustenance [5–7]. Intentional human burning profoundly influenced the structure and distribution of vegetation as first encountered by European settlers to these continents. The cultural and traditional use of fire for land management, however, declined drastically after European contact (examples found in Ref. [8] for Appalachia [9], for California [10], for Canadian Rockies). The indigenous burning regimes that had long sustained humans and ecosystems in the US were replaced in the 19th century by an era of settlement–related fire disasters. Settlers and the timber industry carelessly cleared land and logged rapaciously near their communities, igniting fires that became notable for their huge sizes and human death tolls. The best-known examples in the US include the Miramichi fire of 1825 in Maine, followed by the Peshtigo 1871 (~2500 fatalities), Hinkley 1894 (418 fatalities), and Cloquet 1918 (453 fatalities) fires in the lake states. Railroads and slash burning contributed to the destructive 1910 fires along the Montana-Idaho border (87 fatalities). Canada had its own disasters, notably the Great 1919 fire of Saskatchewan and Alberta [11] which burned about 2 million hectares. These disasters have mostly been forgotten, making the recent fires only seem to be unprecedented.

Partly because of the human role in these wildfire disasters,

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professional foresters with the US Forest Service came to view wildfires as wasteful and damaging, and unnecessary to achieving the primary goal of timber management. By the early 20th century in the US, particularly after the 1910 “Great Burn” in Montana and Idaho, the Federal government began attempting fire control on lands remaining in the public estate [12]. The professional views on fire, which developed as principles of plantation forestry in Europe (principally Germany), transformed Federal fire policy. Irrespective of how different native forests of North America (and their fire-dependent nature) were from the German forest plantations, the US Forest Service began a dedicated program of fire suppression and persecuted the established burning practices of timber companies, foresters, and “woodsburners” in the southeast [13,14]. By the 1920’s settlement-era light burning traditions in west-coast states had been extirpated and the public adopted expectations of fire control as substitutes for historical fire uses. The strong culture of burning in the southeast [15] mostly resisted the new policies and prescribed fire remains widespread today [7,12,16].

Throughout the remainder of the 20th century, rising technology in transportation and communication enabled the Federal government to develop a sophisticated fire suppression organization. Abundant appropriations by the US Congress for fire suppression, including the Civilian Conservation Corps during the Great Depression, had created an *emergency response culture* both inside and outside government agencies. Private business grew profitable by supplying equipment, firefighting apparatus (e.g. aircraft), and contract services. By the 1970’s, reasons for the inexorable upward trend of suppression costs and wildfire damages were recognized officially by the Forest Service and the National Park Service. The Forest Service acknowledged that fire suppression had wrought unintentional and undesirable effects on forests, fuels, and fire behavior [17,18]. The National Parks had earlier accepted fire as a required ecological process and began adjusting fire policy to allow both prescribed fire and managed natural fire in large wilderness parks of the west [19]. Essentially, suppression had been creating a positive feedback loop through fuel accumulation that fed increasingly destructive wildfires and, thus, further demand for fire suppression, etc. [20,21]. This awareness was preceded by decades of warnings by ecologists and foresters who had documented increasing density of forests, incidence of severe fires, accretion of fuels and landscape continuity – and not surprisingly, the hazard reduction benefits of prescribed fire [13,22,23]. Long before climate change was recognized, vegetation change was clearly recognized. Changes to fuels and wildfire behaviors were particularly noticeable in the forest types that had depended upon frequent fire to remove biomass fuel and maintain open forest conditions. Paradoxically, attempts to remove fire had led to destruction of forests that were once sustained by it. Research showed, however, that these effects could be reversed by application of forest management and prescribed burning [13,22,23].

This fire paradox [24] was addressed in a major 1978 Federal fire policy shift that identified fire as an essential process in healthy ecosystems [18]. The policy called for tight integration of fire objectives for restoring beneficial fire into land management. Revisions to the Federal Fire Policy in 1989, 1995, 2001, and 2009 all strengthened this direction and afforded wide latitude in managing unplanned fire. The reforms in policy direction were affirmed by the 2005, 2009, and 2014 Quadrennial Fire Reviews [25–27] and the 2014 Cohesive Strategy [28] which is intended to guide fire management across agencies and jurisdictions [29]. Although the National Fire Plan [30], inaugurated in 2000, more than doubled the annual appropriations for both suppression and hazardous fuel treatment, the emergency response approach to unplanned ignitions and wildfires remained preeminent. Part of the reason is the inherent dissonance between fire protection objectives and the ecological need for more fire [29]. The other reason was (and is) that fuel treatments including mechanical thinning and prescribed burning are expensive, must be periodically maintained, and offer mostly future benefits that are discounted by the uncertainty of realizing those benefits at some distant point in the future [31]. In other words, wildfires and wildfire disasters that don’t happen (the counterfactual) are a difficult benefit to measure or credit to land management activities today. Unlike fire suppression and emergency response, planned management (fuel treatment, harvesting, etc.) is heavily regulated by planning laws, including the National Environmental Policy Act (NEPA) for Federal lands, and by legal constraints imposed by state air quality standards [32]. Management plans can be appealed and litigated, but not emergency response.

Wildfire statistics have shown that more than 97% of all ignitions are suppressed before reaching 300 acres (about 120 ha) in size [33,34], leaving fires under the most extreme conditions to burn the landscape and 90+% of the annual fire area [35]. These proportions have remained roughly similar for a century, but fires are becoming larger in recent decades [36], and the costs of suppression are growing. With few exceptions, fires that can be suppressed are suppressed, and those that can’t be suppressed aren’t. Fire control is consistently attempted under all conditions with predictable failure at the extreme. The net result is that burning under mild and moderate weather has been reduced by 10’s of millions of hectares annually across the US [37,38] resulting in about 5 times less wildland burning on western US National Forests than historical rates [39]. If this current “wildland fire system” is producing the desired outcomes by allowing only extreme fires on landscapes and near communities, then no changes are needed. But if not, then new approaches or improvements will be essential; exactly which ones will, or can, be effective depends upon many external influences.

3. Wildfire risk and measuring success

Despite a century of rapid technological advances, wildfire losses continue to climb because of the concomitant contribution of several factors. Climate change is underlying a global trend in increasing wildfire activity [40], communities have encroached on fire-prone wildlands with vulnerable construction and little preparation for fire [41], and attempts at fire exclusion in lieu of land management have caused ecological changes. The global necessity of addressing climate change does not obviate the effectiveness of local and regional measures to reduce wildfire risk for communities and natural resources.

Rather than simply preventing wildfire disasters, success in wildfire management would be more comprehensively described as risk reduction [21]. *Risk* is the expected loss or expected net value change for a natural resource or developed asset [42]. Effects of fire on the functional value of natural resources and developed assets are of concern here [43], although risk is frequently used in association with operational safety of firefighters during incident engagement. While engineering to improve safety of fire responders has obvious value, we will see from the nature of wildfire risk that the value of risk reduction for both natural resources and developed property is not straightforward.

Risk is calculated as the product of probability (exposure) and magnitude of change (vulnerability or loss) [43]. One of the complicating factors in evaluating risk reduction investments is that wildfire exposure and the fire behavior at the time of impact is highly uncertain. It is therefore addressed statistically through the probability component of risk. Wildfire uncertainty derives from the nearly infinite variations in factors that determine fire occurrence, growth, and behavior across large landscapes. Specifically, ignition location and timing, fuel and topography patterns, and weather sequences all affect the direction and behavior of wildfires as they approach and impinge on any given location. Wildfire risk becomes dependent upon factors that may extend across the landscape for tens of kilometers. Historically, probability of wildfires burning a particular location in the US varies from less than 1/10,000 to greater than 1/100 per year [34,44].

Engineering improvements in wildland fire have traditionally attempted to reduce risk by targeting each of the two main components: reducing vulnerability of assets and decreasing exposure to fire. Reducing vulnerability of natural resources (e.g., forests, watersheds) is not traditionally an engineering concern and will be discussed in the context of fire benefits below. However, reducing vulnerability of structures and increasing defensibility in communities is aligned with traditional engineering disciplines and may be accomplished by upgrading building design and urban fire protection. A recent application of risk analysis has suggested that structure loss mitigation through implementing building codes for the Wildland Urban Interface (WUI) would yield expected benefit-cost ratios of about 4:1 [45]. More effort is clearly warranted to understand effectiveness and cost-effectiveness of various proposed solutions given the uncertain timing and characteristics of wildfire impact.

At present, engineering measures to reduce vulnerability and defensibility of developed property are compelling investments because they have been shown to be effective [20,47], align well with fire protection engineering for high-value assets, are technically feasible, and can be funded by private property owners individually rather than requiring organized or government investment at community or landscape scales. One caveat, which is not widely communicated, is that the capacity for active protection or defense of structures declines with the exposure rate (e.g. buildings exposed per hour). High home loss has recently occurred when fast-spreading wildfires grew large before impinging upon a broad swath of urban or semi-urban development. Exposure of thousands of structures to firebrands and other ignition sources in short time periods minimized the defense by fire departments which were preoccupied with evacuations or simply overwhelmed. Engineering to improve home ignition resistance must acknowledge that “defensible space” does not imply active defense will be possible during these wildfires [20]. More robust designs or active defense measures must be considered if home loss is to be avoided in large wildfire events.

Efforts to reduce risk by decreasing exposure to fire (probability) have included rapid fire detection, better mapping, employing new firefighting apparatus (for either faster response or more effective attack), collecting and utilizing data for decision making, and enhancing communications. But because current management is already successful in removing almost all fires from the wildlands [33], these investments can be expected to offer only minor marginal returns. Fires that escape suppression do so for a variety of reasons that are essentially immune to technological improvements. For example, wildfires escape and become large even with aggressive early initial attack when multiple ignitions occur in concentrated episodes and overwhelm the numbers of firefighting resources. Episodes of escaped fires can occur under both extreme and mild weather conditions at the time of ignition. A recent example was the 2017 Wine Country fire episode in northern California caused by powerline failures (Tubbs, Atlas, Nuns fire, etc.). Powerline ignitions have been particularly destructive because electric infrastructure is located close to populations and its failure is specifically caused by strong winds during hot and dry conditions (not independently of extreme fire-weather) [46]. Even for fires ignited one at a time, extreme weather and unmanaged fuel conditions often cause high fire spread rates impervious to suppression. The Hayman fire in Colorado escaped and burned 136,000 acres despite huge initial attack efforts (see documentation in Ref. [48]). The recent Kincade fire in Sonoma County (October 2019) is another example when extreme weather led to failures in initial attack and structure protection efforts. The conclusion here is that wildfires are inevitable because biomass from wildland vegetation is continually growing; incremental success in removing fire will be counterproductive in avoiding future fire disasters [20] because the underlying premise of controlling wildfire is itself ineffective compared to proactive alternatives [20,49,50]. Reducing probability of wildfire impact to communities will require managing wildland vegetation and fuel hazards, which concomitantly reduces vulnerability of forests, watersheds, habitat, and viewsheds.

Compared to investments in suppression-related technology, engineering efforts in training and fundamental research receive far less interest. Enhanced training for firefighters, land managers, and the public, for example using 3D visualization, virtual reality, or computer simulation might aid in preparation and appreciation of conditions that present the greatest threat. Engineering attention to research concerning the physical processes driving wildland fire behavior is another area receiving limited attention but is the primary means of raising the level of technical knowledge for modeling and prediction of wildfires which cannot be gained from experience in fire use or suppression. Although reductions in wildfire risk may only be indirectly benefit from improvements in training, science, and modeling, they may be able to offer considerably more value than any of the efforts aimed directly at reducing vulnerability or exposure. The justification of this argument will require some explanation below of the wildland fire culture and incentives that currently exist.

4. Improving the wildland fire system

From the preceding sections it should be clear that wildland fires and their urban consequences present different challenges than fire protection solely in the built environment. These differences will be discussed as they occur in three principal areas:

1) Benefits of fire
2) Nature of expertise
3) Culture and Incentives

4.1. Benefits of fire

Wildland fire is distinguished from other kinds of fire by the important benefits it bestows in many ecosystems [1,2,12,13,15]. Ecosystems are always changing, and in fact, require change. The current biotic assemblages are accustomed to fire as a free-spreading agent of disturbance; fires of certain character and frequency renew, restore, and sustain ecosystem structure and function. In the domestic or built environment, however, free-spreading fires almost always have negative consequences. Except for warfare or criminal intent, who would want a fire spreading through their home or city? Fire used for heating, lighting, and cooking is primordial to human experience (and perhaps evolution) and it is doubtful that humans have ever desired their domesticated fires to do anything other than stay confined. Yet the ecological context for fire is exactly the opposite – fire is largely irrelevant to ecosystem function if it is not free-burning. Our instinctive reactions to free-spreading fire in homes and cities are not transferrable to wildlands. Nevertheless, our society and its wildland fire system try very hard to enforce the same discipline on wildfires as on candles and cookstoves.

Attempts to control wildfires have, as already explained, led to the current “tiger by the tail” situation in the US and elsewhere. Positive feedbacks from fuel accumulation drive even more expensive and futile efforts to rein in wildfires and unintentionally make the inevitable fires more and more destructive [20,21,51]. Huge investments in fire removal by suppression create an illusion of fire control that both encourages naïve and vulnerable development in wildlands and dims public awareness of the need for active management to mitigate inevitable fires (vs. “passive management”) [52]. Unfortunately, there are no substitutes for fire in ecosystem functions or fuel hazard reduction, but management plans for most public lands have yet to fulfill original policy direction [18,53] to include specific fire objectives for the amounts and behaviors of fire needed and strategies for use of lightning ignitions to achieve them. Much scientific research has confirmed that mechanical methods (e.g., thinning, logging) do not remove the specific fuel components essential to mitigating wildfire behavior (see summaries [54,55]) and could not be practical over the vast landscapes needing treatment in the US. The fuel supply for wildfires is primarily from decomposing duff, litter, downed woody material, small trees and brush or grass that are not commercially useful and exorbitantly expensive to remove manually. This is obviously true in grassland and shrubland ecosystems where there is no timber for harvesting. Solutions to the inevitability of wildland fire are to develop the expertise in the use of fire itself, allow fire to play a constructive role in land management as it had for millennia, and adapt our modern communities to the natural reality as our forebearers had done since ancient times. US Federal wildland fire policy supports these options and some land management agencies in the American southwest are attempting to implement them [56].

Humans have long demonstrated their technical ability to manage fire for ecological and their own benefits ([5–7,16]). The modern sociopolitical expectations of wildland fire resulting from expanding human populations and urbanization, however, place increasingly stringent constraints on fire uses in the form of regulations and laws, and cultural unfamiliarity with burning and aversion to managed wildfires [32,75]. Some relaxation of laws and regulations would certainly be helpful, but it has frequently been argued that only through demonstrated predictability and reliability will proactive fire management methods become accepted in the modern era [57,58]. Precise and reliable application of wildland fire would thus require developing expertise based on science in addition to fire management experience. But even this will be insufficient without social license, and unfortunately there has been little effort to increase public acceptance of fire for risk reduction despite long being proven as indispensable [17,19,59]. The unwillingness to utilize available but unconventional solutions has been associated with collapse of societies faced with climate change and environmental degradation – a situation not unlike what we see in wildland fire management today [60].

4.2. *Nature of expertise*

Unfortunately, the physical science basis needed for precise wildland fire application is poor [61,62], both in an absolute sense and by comparison to that found in fire engineering. Without additional knowledge of the physical basis for fire behavior we rely mostly on rules-of-thumb and individual experience to plan for and conduct managed fire and to train and educate professional analysts. Much of the education and expertise in wildland fire is ecological. The science of fire ecology is well developed and provides the foundation for setting management objectives in terms of fire frequencies and characteristics necessary to sustain the variety of ecosystems. Operational expertise is developed through practical fire management experience primarily from a career in suppression. But tactical firefighting itself does not develop analytical skills or produce the strategic abilities needed for planning and conducting risk reduction across landscapes and over time-scales of decades. The land management agencies, public, media, and elected officials (i.e., the wildland fire culture) cannot expect significant improvement in wildfire outcomes if they continue to rely upon fire suppression experience as the principal source of expertise in proactive fire risk management. A technical role for a “wildfire engineer” has not been recognized as essential in fire management, partly because the science of wildland fire is insufficient for such expertise, but also because there has been so little cultural value placed on strategic thinking in wildfire compared to tactical response.

The mainly suppression-oriented basis of contemporary fire management must eventually give way to more science-based proactive approaches if lands and communities are to be freed from the positive feedback cycle of the fire paradox. In order to do this within modern societal constraints, we must elevate the level and use of analytical expertise for designing, planning, and implementing active management strategies. It would be culturally impossible to simply return to the days of indigenous burning.

Three challenges are evident. First, the knowledge of physical fire science must be acquired. Second, practical methods and tools for using this knowledge and educating personnel must be developed. And finally, the benefits of having specialized knowledge accepted within the fire management culture must be appreciated and valued for the purposes of strategic planning and implementation. It is the latter challenge that may present the greatest hurdle because of the primacy of reactive suppression within the wildfire enterprise today. Even ideal advances of knowledge and tools would be little used if the culture and structure of fire management remains as it has developed for the past century [63].

As said earlier, there is currently no role for a “wildfire engineer”. Specialists who could accurately evaluate the dynamical interactions of fire, fuels, weather, and complex topography at local and landscape scales would be essential to planning and conducting proactive fire management on the 100’s of millions of hectares managed in the public trust. Most foresters and firefighters are unaware of the potential for strengthening strategic planning and operational implementation of active fire management by advancing knowledge and expertise of wildfire behavior. Most fire practitioners do not realize that the present state of knowledge only allows for qualitative correlation between mean fuel characteristics and potential behavior of thin linear flame zones. But large fires, rather than line fires, present the greatest threat to both natural resources and human communities and are well beyond current understanding, much less prediction. They are driven by atmospheric circulations induced by energy release over an extensive burning area and may be the most complex examples of the scientific challenge. But even simple behaviors have yet to be clearly explained [62,64]. For example, we can’t yet describe how line fires spread in various fuel types, how long energy is released in arbitrary fuel configurations, how solid phase combustion affects wildfire behavior, how to quantify smoke production from prescribed vs. wildfire, how live fuel (living foliage) ignites and burns, or simply describe the salient properties of wildland fuels as they affect fire behaviors [62,64].

The required knowledge can only be obtained once research into physical processes ultimately explains wildland fires sufficiently to develop expertise. Knowledge is itself required for educating wildfire specialists to a level well beyond practical “training” in operational use of models. Research efforts in the past decades have been preoccupied with fire modeling, neglecting the science of fire behavior. Similarly, there has been little attempt to define user needs for models or understand the requirements for modeling in wildfire decision making. Improved modeling must be suitable for use by wildfire analysts (not only those holding a Ph.D. in engineering) and produce results that are informative to decision makers.

The wildfire system is obviously different from the system in which fire engineering operates in modern society. Although firefighters exist in both contexts, the construction industry naturally values engineering expertise for building design and selection of materials. Fire protection engineering is responsible for analyzing hazards and developing building standards that protect both the people and the developed property from fires. Financial and economic forces incentivize investment in mitigation or prevention and disincentivize poor performance (e.g., insurance costs, criminal and civil law). By contrast, wildland fire is mostly a government-funded enterprise involving emergency firefighting response. Feedbacks that could incentivize beneficial investments and penalize damaging activities are minimal. Technical expertise primarily derives from experience with emergency fire suppression rather than from a scientific foundation for proactively managing the key biological and human components of the system.

4.3. *Culture and incentives*

As explained above, the existing wildland fire system, or more explicitly, the human culture that is coupled with the natural system, has developed over a century to be mostly skeptical of fire benefits and strongly supportive of emergency fire response. The wildfire culture has been characterized as a “socioecological pathology” [65] that is maintained and reinforced by incentives [32]. The *culture* derives from interaction among four primary groups: fire management agencies, media, elected officials, and the public (Fig. 1). Culture tends to be resilient because no individual group is independent of the influence of the others. This influence exists via formal interactions with laws and regulations or informally via media or direct communications. Changes

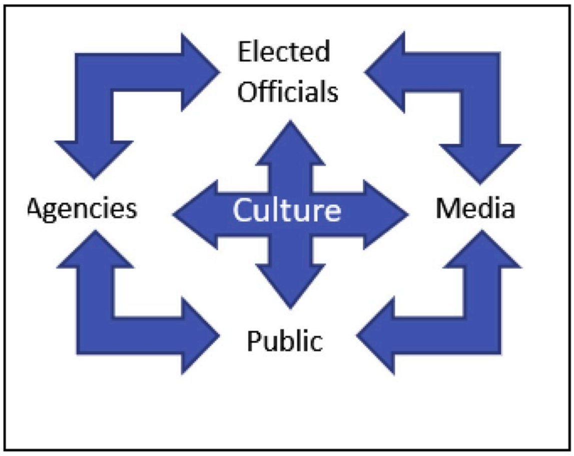

Fig. 1. Wildland fire culture is defined by interactions among land management agencies, the public, elected officials, and the media.

introduced by one group are vetted relative to the prevailing paradigm. Engineering solutions for example, that reinforce the paradigm will be welcomed and those that challenge the paradigm will not.

The prevailing paradigm can be summed up as a set of *beliefs* where 1) all fires are damaging and potential natural disasters, and 2) suppression is necessary, sufficient, and effective for protecting communities and natural resources. This is clearly a belief system, rather than a fact-driven analytical system, as evidenced by its strengthening throughout the same century that growing science and data demonstrated its fallacies. Thus, it's not surprising that new and improved data and science that contravene such beliefs are poorly received. But perhaps the most challenging characteristic of the wildland fire culture is that it elides responsibility except when blame can be assigned for starting a fire [66]. There is no accountability for individual and collective actions (or inactions) which perpetuate the cycle of disaster (land management, suppression, construction, zoning, etc.), and thus little incentive for any group to avoid continuing to play their cultural roles. By contrast, accountability in the built environment incentivizes fire safety in design, construction, and maintenance, not just preventing ignition. Sentiments that wildfires are "acts of God", everyone did the best they could, and bad things happen sometimes, aid in the denial of responsibility after wildfire disasters. The existing wildfire paradigm discourages change to the system because these efforts would involve assuming responsibility – first for challenging the well-accepted paradigm, then for success in delivering the promised outcome, and finally for any externalities of those actions.

Fuel management in the western US is a prime example, where those who conduct prescribed burning and forest thinning are burdened by environmental, legal, and logistical hurdles and are held to high standards of performance. They are minimally rewarded for success (in accomplishing the burn or mitigating future wildfires) and roundly condemned for failure (escaped fires, smoke production, or limited impact on future fires) [67]. The counterfactual of the avoided future disaster does not compel action as does the perceived threat of an active fire today. However, different cultures inside and outside the US show that these obstacles are not necessarily inherent or universal. The southeastern US engages in widespread prescribed burning for hazard reduction that is supported by legislation [7,15,16]. Australia examined alternatives following the 2009 Black Saturday fire disasters that took the lives of 173 people north of Melbourne. This transformative event [21] precipitated an inquiry by a Royal Commission and resulting laws mandating increased proactive "fuel reduction burning". But implementation has been compromised by controversy [68] and the bushfire disasters of 2020 now occurring in southeast Australia have renewed attention on the needed level of hazard reduction [69].

Some of the incentives in the wildfire culture are difficult to overcome through proactive measures. Firefighting is incentivized by pay and status [70]. Media coverage of wildfire favors scenes of firefighting, community destruction, human drama, and accusations which may exacerbate problems rather than aid in framing solutions [68,70–72]. Media interest in prosaic uses of fire for ecological or hazard reduction benefits (except for scrutiny of escaped prescribed burns) is rare and often focused on specific projects rather than the magnitude of the fire management challenge. Government appropriations for firefighting equipment support the perception of action by elected officials, government fire services, and private vendors, leading the public to expect aerial firefighting demonstrations, for example, during wildfires irrespective of technical justification [73,74]). By contrast, proactive hazard mitigation is disincentivized [75]. Liability laws penalize those who start fires (either accidently or from escaped prescribed fire) vs. the owners of land with fuel that feeds fires [32,66,76,77]. Air quality regulations restrict prescribed burning [67,75] but do not punish management neglect of fuel accumulation that produce acute smoke exposure during wildfire conditions [78]. Environmental protection laws for public lands require detailed and expensive plans for mitigation [75] but activities during wildfires are unrestricted (i.e., burnouts, mechanical harvesting, and bulldozer fireline construction).

In sum, it is uncertain whether engineering investments to reduce wildfire risk can overcome cultural predilections for emergency response. There are also no guarantees that increased scientific expertise and education will opportune beneficial fire use. But it is certain, that without such investments, modern society will remain incompatible with wildland fire.

5. Conclusions

This brief review attempts to highlight some of the systemic obstacles facing the use of engineering and technological solutions to wildfire problems. For many years, sociological and technical reforms have been proposed that would offer clear benefits to ecological and human wildfire management. But the wildland fire culture challenges the use of new ideas, and even old ideas, that contravene the emergency response paradigm. Engineering solutions to reduce vulnerability of buildings and other infrastructure to wildfires face few technical obstacles, but costs for both new construction and retrofitting, difficult enforcement of implementation, and uncertainty of benefits, impede widespread adoption of changes in building design and materials. Engineering to improve suppression, although readily welcomed in the current system, will likely offer little long-term benefit, since almost all fires that can be suppressed are already suppressed. Not only is wildfire suppression ineffective for preventing home loss in large fires, but suppression itself does not qualify as a viable land management strategy, since it is biophysically unsustainable and ecologically destructive in many fire-dependent ecosystems; biomass accumulates each year until it is inevitably burned during the roughly 3% of wildfires that reliably escape initial attack suppression. The opportunities for changing wildfire outcomes, measured as reduced risk to both developed and ecological values, are principally achieved through proactive fire management rather than emergency response. With concomitant efforts to obtain social license, engineering must be encouraged to focus on research that increases the knowledge of wildfire behavior, develops modeling tools for strategic planning application, and then improves the education and training of wildfire professionals who could design and execute proactive fire management strategies [79].

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.

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Appendix A. Supplementary data

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