Reimagine fire science for the anthropocene

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Abstract

Fire is an integral component of ecosystems globally and a tool that humans have harnessed for millennia. Altered fire regimes are a fundamental cause and consequence of global change, impacting people and the biophysical systems on which they depend. As part of the newly emerging Anthropocene, marked by human-caused climate change and radical changes to ecosystems, fire danger is increasing, and fires are having increasingly devastating impacts on human health, infrastructure, and ecosystem services. Increasing fire danger is a vexing problem that requires deep transdisciplinary, trans-sector, and inclusive partnerships to address. Here, we outline barriers and opportunities in the next generation of fire science and provide guidance for investment in future research. We synthesize insights needed to better address the long-standing challenges of innovation across disciplines to (i) promote coordinated research efforts; (ii) embrace different ways of knowing and knowledge generation; (iii) promote exploration of fundamental science; (iv) capitalize on the "firehose" of data for societal benefit; and (v) integrate human and natural systems into models across multiple scales. Fire science is thus at a critical transitional moment. We need to shift from observation and modeled representations of varying components of climate, people, vegetation, and fire to more integrative and predictive approaches that support pathways toward mitigating and adapting to our increasingly flammable world, including the utilization of fire for human safety and benefit. Only through overcoming institutional silos and accessing knowledge across diverse communities can we effectively undertake research that improves outcomes in our more fiery future.

Keywords: wildfire, climate change, resilience, wildland–urban interface, social–ecological systems

Significance Statement:

Fires can be both useful to and supportive of human values, safe communities and ecosystems, and threatening to lives and livelihoods. Climate change, fire suppression, and living closer to the wildland–urban interface have helped create a global wildfire crisis. There is an urgent, ethical need to live more sustainably with fire. Applying existing scientific knowledge to support communities in addressing the wildfire crisis remains challenging. Fire has historically been studied from distinct disciplines, as an ecological process, a human hazard, or an engineering challenge. In isolation, connections among human and non-human aspects of fire

are lost. We describe five ways to re-envision fire science and stimulate discovery that help communities better navigate our fiery future.

Introduction

Fire is a long-standing natural disturbance and a fundamental component of ecosystems globally (1). Fire is also an integral part of human existence (2), used by people to manage landscapes for millennia (3). As such, fire—or broadly biomass burning—can take on many forms: fires managed for human benefit or ecosystem health include prescribed or cultural burning, and response management beyond suppression; fires viewed as an immediate threat to human values are typically suppressed, and under increasingly extreme conditions have an increased chance of escaping suppression efforts. Fires can be ignited intentionally (e.g. prescribed or cultural burning and arson) or unintentionally (e.g. accidental human-caused or lightning-caused). They can happen in the wildlands and into human developed areas as in the wildland–urban interface (WUI). In the Anthropocene (The Anthropocene currently has no formal status in the Divisions of Geologic Time. https://pubs.usgs.gov/fs/2018/3054/fs20183054.pdf), the current era characterized by the profound influence of human impacts on planetary processes and the global environment (4), *fires from lightning and unplanned human-related ignitions (including arson; henceforth referenced as wildfires)* result in increasingly negative impacts on economic (e.g. loss of structures and communities), public health (e.g. loss of life, air pollution, and water and soil contamination), and ecological aspects of society (e.g. shifts in vegetation and carbon storage) (5).

Recent decades have seen a substantial increase globally in the length of fire seasons (6), the time of year when conditions are conducive to sustain fire spread, increased area burned in many regions, and projected increases in human exposure and sensitivity to fire disasters (7–11). Fire seasons are occurring months earlier in Arctic and boreal regions (12). In the western United States, the area burned in the 21st century has nearly doubled compared to the late 20th century, enabled by warmer and drier conditions from anthropogenic climate change, resulting in dry, flammable vegetation (13). Fire activity in the 21st century is increasingly exceeding the range of historical variability characterizing boreal (14) and Rocky Mountain subalpine (15) forest ecosystems for millennia. Unprecedented fires in the Pantanal tropical wetland in South America (16) and ongoing peatland fires across tropical Asia (17) exemplify the global scope of recent fire extremes.

Shifts in wildfire patterns **can** come with increasingly negative human and ecological impacts. Globally, dangerous smoke levels are more common as a result of wildfires (9, 10, 18, 19). The 2019 to 2020 Australian wildfire season produced fires that were larger, more intense, and more numerous than in the historical record (20), injecting the largest amount of smoke into the stratosphere observed in the satellite era (21, 22) and impacting water supplies for millions of residents (23). While extreme fire events capture public attention and forest fire emissions continue to rise (24, 25), the ongoing decline of burned-area across some fire-dependent ecosystems might have equally large social and environmental impacts. Global burned area has decreased by approximately 25% over the last two decades, with the strongest decreases observed across fire-dependent tropical savanna ecosystems and attributed to human interactions (26). Decreases across these systems are important, as maintaining diverse wildfire patterns can be essential for biodiversity or achieving conservation goals (27).

Humans are fundamental drivers of changing wildfire activity via climate change, fire suppression, land development, and population growth (26, 28–30). Human-driven climate change is aggravating fire danger across western North America (13, 31, 32), Europe (33, 34), and Australia (35). Exacerbated by this increasing fire danger from heavy fuel loads and greater flammability from drought and tree mortality, human-caused ignitions increased wildfire occurrence and extended fire seasons within parts of the United States (28), and it is these human-caused wildfires that are most destructive to homes and property (36). Concurrent with these challenges is a growing recognition that Indigenous peoples have been living with fire as an essential Earth-system process (30). Although some Indigenous societies have lived in relatively low-density communities, others have lived at scales analogous to the modern wildland-urban interface for centuries, making Indigenous fire lessons relevant for the sustainability of post-industrial communities as well (e.g. (37)).

As wildfire danger increases, we are only beginning to understand longer-term postfire impacts. These include regeneration failure of vegetation (38, 39), changes to biodiversity through interactions with climate change, land use and biotic invasions (27), landslides and debris flows (40), contaminated water and soil (23, 41), and exposure to hazardous air quality for days to weeks in regions that can extend thousands of kilometers from smoke sources (9, 10, 19, 42). Increasing wildfire activity and associated negative impacts are expected to continue over the 21st century, as greenhouse gas emissions continue to rise (7, 43, 44).

The rapid pace of changing fire activity globally is a significant challenge to the scientific community, in both understanding and communicating change. Even the metrics we use to quantify "fire" come up short in many instances. For example, total area burned and ecological fire severity are useful for characterizing some key dimensions of fire, but often do not capture negative human impacts. For example, the 2021 Marshall Fire in Colorado, United States, was less than 2,500 hectares, but was more destructive, in terms of structures lost, than the two largest wildfires in recorded Colorado history, each of which burned approximately 80,000 hectares. The 2018 Mati Fire in Greece burned only 1,276 hectares, but destroyed or damaged 3,000 homes and was the second-deadliest weather-related disaster in Greece (11). While evidence suggests increasing aridity will lead to more burning (7, 32, 43, 45), the 2021 Marshall Fire and 2018 Mati Fire remind us that area burned is a poor indicator of the negative impacts of wildfires on the built environment.

Given the shifts in wildfire activity and its increasingly devastating impacts, the need to fund research and adopt policy to address fire-related challenges continues to grow. These challenges may be best addressed with coordinated proactive and collective governance through engagement of scientists, managers, policy-makers, and citizens (23). A recent United Nations' report recognized extreme wildfires as a globally relevant crisis, highlighting the scope of this challenge (46). To address this crisis we need to recast how we study fire as an inherently transdisciplinary, convergent research domain to find solutions that cross academic, managerial, and social boundaries. As society urgently looks for strategies to mitigate the impacts of wildfires, the scientific community must deliver a coherent understanding of the

diverse causes, impacts, management paths, and likely future of fire on Earth that considers the integrated relationships between humans and fire. Humans are not only affected by fire, but are also fundamental to its behavior and impact through our changes to the biosphere and our values, behaviors, and conceptions of risk.

The challenge of understanding the integrated role of humans and fire during the Anthropocene is an opportunity to catalyze the next generation of scientists and scientific discovery. It requires funding that develops collaborative, transdisciplinary science, dissolves disciplinary boundaries, and aligns research goals across traditional academic fields and ways of knowing. This represents an opportunity to build scientific practices that are respectful and inclusive of all, by creating spaces to share and co-produce knowledge between and among all stakeholders. Such practice demands multi-scale data collection and analysis to develop models that test our understanding, support safer communities, and provide long-term projections. By reinventing the training of scientists to reflect this transdisciplinary, multi-stakeholder, and data-driven approach, we can help revolutionize community practices and provide information needed by communities to be able to better live with fire—in all its forms—in our increasingly flammable world.

Here we identify five key challenges as a call to action to advance the study of fire as a fundamental aspect of life on Earth (Fig. 1).

1. Integrate across disciplines by promoting coordination among physical, biological, and social sciences.
2. Embrace different ways of knowing and knowledge generation to identify resilience pathways.
3. Use fire as a lens to address fundamental science questions.
4. Capitalize on the "firehose" of data to support community values.
5. Develop coupled models that include human dimensions to better anticipate future fire.

These challenges are a synthesis of discussions of a group of mainly US-based researchers at the National Science Foundation's Wildfire in the Biosphere workshop. The challenges of fire science extend beyond national borders, and our hope is that funding agencies, land stewards, and the larger fire science research community will join to address them. Within each call-to-action challenge we describe the nature of the challenge, address the social impacts, identify fundamental scientific advances necessary, and propose pathways to consider across communities as we address our place in a more fiery future (Table S1, Supplementary Material). Acting on these challenges will assist in better addressing the immediate impacts of fire, as well as postfire impacts (e.g. landslides and vegetation shifts). The focus on immediate needs is not meant to undermine the importance of longer-term impacts of fires, which in many ways are less understood, rather to highlight their urgency.

Discussion
1: Challenge: Integrate across disciplines by promoting coordination among physical, biological, and social sciences

Wildfire is a biophysical and social phenomenon, and thus its causes and societal impacts cannot be understood through any single disciplinary lens.

While studied for over a century, wildland fire science often remains siloed within disciplines such as forestry, ecology, anthropology, economics, engineering, atmospheric chemistry, physics, geosciences, and risk management. Within each silo, scientists often exclusively focus on fire from a specific perspective—fires as a human hazard, fire as a management tool, or fire as an ecological process. Collectively, we have deep knowledge about specific pieces of fire science; however, to move fire science forward and answer fundamental questions about drivers and impacts of fire, we must break out of traditional silos (e.g. institutional type, research focus, and academic vs. management) (47) to a more holistic and integrated approach across social (48), physical, and biological sciences, and including Traditional Ecological Knowledge (TEK) (49) (see Challenge 2).

Fire affects every part of the Earth system: the atmosphere, biosphere, hydrosphere, and lithosphere and plays a critical role in local to global water, carbon, nutrient, and climatic cycles by mediating the transfer of mass and energy at potentially large scales and in discrete pulses. Ecosystems and fire regimes are changing; we need to be prepared to anticipate tipping points and abrupt transitions to novel or alternative states. To fully understand the causes and consequences of shifting fire regimes, we must accept fire as a process with feedbacks between social and ecological systems while increasing respect among diverse communities (e.g. (50)). Rethinking collaborations across disciplines provides opportunities to determine shared values and goals (51) as well as new modes of practice that dismantle inequitable and exclusionary aspects of our disciplines (52). Team dynamics are particularly important in multidisciplinary collaborations given the varied experiences, expertise, and discipline-specific language used by team members. In many cases, these differences, in addition to the historical and systematic inequities within STEM (Science, Technology, Engineering, and Math) fields (e.g. (53, 54)) have kept disciplines siloed and some groups excluded (55).

We need to build upon the adaptive, integrated knowledge, and "use-inspired" approaches, such as those put forth by Kyker-Snowman et al. (56) and Wall et al. (57), by including empiricists, modelers, practitioners, and domain experts from broad disciplines where they are involved at every stage of data collection, idea development, and model integration. In this approach, the two-way exchange of ideas is emphasized in order to effectively incorporate domain expertise and knowledge into models of systems that can not only improve understanding, but eventually move toward forecasting capability (see Challenge 5).

2: Challenge: Embrace different ways of knowing and knowledge generation to identify resilience pathways

Fire is an intrinsic part of what makes humans human, such that all humans from diverse groups and perspectives can provide valuable insights; thus co-produced knowledge is a prerequisite to innovation in fire science.

Given the urgent need to reduce wildfire disaster losses and to promote pathways to live sustainably with fire, it is critical to integrate knowledge from across disciplinary, organization, and community boundaries (58). Knowledge coproduction offers a model that identifies and produces science needed to drive change (59) through iterative, sustained engagement with key stakeholders (60). Specifically, development of mitigation tools and strategies enables social–ecological systems to transform from a resistance mindset to a resilience mindset (61).
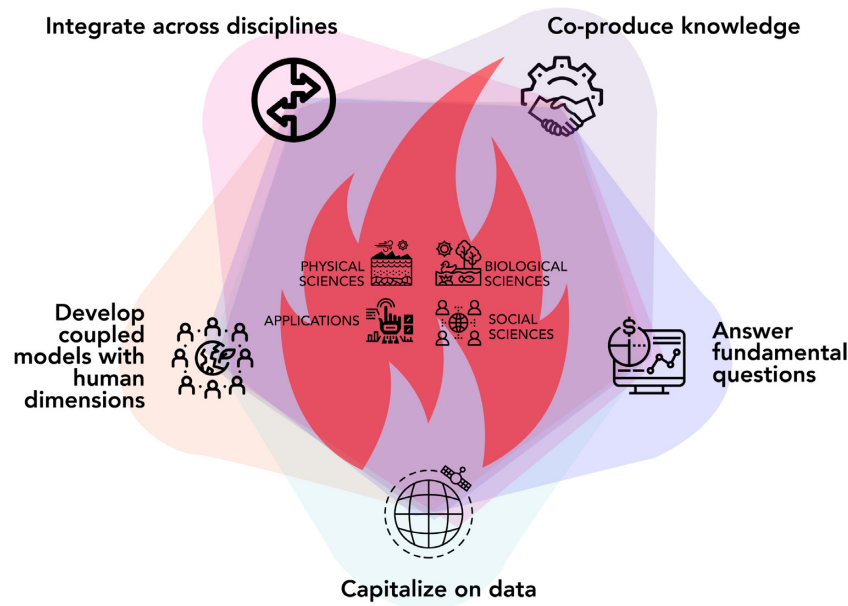
Fig. 1. We need a proactive fire research agenda to support human values and create safe communities as impacts from lightning and unplanned human-caused wildfires increase in the Anthropocene. Such an agenda will span multiple disciplines and translate understanding to application while answering fundamental science questions, incorporating diverse and inclusive partnerships for knowledge coproduction, capitalizing on the wealth of new and existing data, and developing models that integrate human dimensions and values.

There exist millennia of knowledge by Indigenous peoples of Tribal Nations that hold Traditional Ecological Knowledge (TEK) of ancient burning practices (62–66) used to maintain healthy ecosystems. Indigenous and non-Indigenous place-based societies, such as traditional fire practitioners in Europe and elsewhere, have used fire to safeguard communities, promote desired resources, and support cultural lifeways for centuries to millennia (37, 49, 67–72). Working together, scientists from diverse cultural perspectives can co-define resilience across ecocultural landscapes (73), using this knowledge to identify perspectives of resilience to wildfire (72, 74). Our fire science community needs to work with diverse communities to determine what is valuable, generating needed information on risk scenarios and potential resilience pathways in the face of a changing climate, while upholding data principles that respect Tribal sovereignty and intellectual property (75).

We must accept fire as a social–ecological phenomenon that operates across multiple scales in space and time: fire acutely affects ecosystems, humans, and the biosphere; fire is a selective pressure and driver of ecological change; and humans, including various management practices, influence fire behavior and impacts. We need to understand where vulnerable communities are before wildfires occur, to build better, create defensible spaces around homes, reduce unintended human ignitions (e.g, downed power lines), and promote Indigenous management strategies and prescribed burning practices where they could mitigate disaster risk (37). Returning fire to landscapes and developing a culture of fire tailored to specific settings is increasingly seen as the most effective path forward. *We repeatedly converged on the need for "sustainable" strategies for human communities to coexist with fire and smoke to become more aligned with TEK. Our authorship group, however, reflective of STEM disciplines more broadly, consists of non-Indigenous scientists. This situation emphasizes the need to prioritize collaboration with Indigenous scientists and community partners in developing ways to adapt to fire in a changing world.*

It is critical to recognize the human role in using fire in the environment, and bring that into our understanding of adapting management for a more firey world. In turn, this can inform development of coupled models (see Challenge 5) representing fire as a human–biophysical phenomenon and can be used for management. To do so, we need to understand different value systems and develop metrics through co-production, thus collectively defining what success looks like for all stakeholders. This perspective provides scientific support for adaptive management and policy in the face of continuing human-caused change, including climate change. The resist–accept–direct (RAD) framework is explicitly designed to guide management through ecological transformations (76), a scenario increasingly likely with unprecedented climate change and enabled by fire. Because fire can catalyze social and ecological transformations, the RAD framework will be particularly useful for coming decades. Applying decision frameworks such as RAD requires incorporating human values, perceptions, and dynamism into fire management, within and beyond natural sciences (51, 77). Thus, the process itself offers potential for transdisciplinary innovation and inclusion of different ways of knowing (e.g. TEK) by requiring interdisciplinary engagement, including paleo scientists, ecologists, traditional knowledge holders, cultural anthropologists, archeologists, remote sensing experts, modelers, policy scientists, and community and government partners.

In addition to working across disciplines, we need to be aware of extant systems of oppression inherent in Western science (78). The lack of diversity among knowledge contributors in co-produced science and among scientists themselves fundamentally limits innovation, applicability, as well as being fundamentally unjust (79). Furthermore, as fire is a global ecosystem process, the research community should reflect a similar breadth in perspectives (80). However, fire science, not unlike many STEM fields, has problems with representation across all axes of identity, including gender, race, ethnicity, LGBTQA+, and disability (e.g.

81). For example, the majority of our authorship group work at US institutions, likely limiting the scope of our discussions. To change course, we need to interrogate our own practices and limit opportunities for bias. Providing clarity and transparency about and throughout decision-making processes (e.g. grants, job postings, and publications), training reviewers about bias, requiring the use of rubrics for all evaluations, and anonymizing application materials whenever possible, are all effective strategies to reduce gender and racial bias (82). Given the importance of representation, as a community we need to elevate a diverse group of role models (83), e.g. highlighting notable accomplishments of women-identifying fire scientists (84). To embrace diverse knowledge requires explicit consideration of equity in stakeholder participation and fire science recruitment and training from under-represented backgrounds.

3: Challenge: Use fire as a lens to address fundamental science questions

We should use fire to answer fundamental scientific questions within and across physical, biological, and social sciences.

Fire is a ubiquitous and pervasive phenomenon, historically studied and tested in natural philosophy and scientific disciplines (85). It is also an ancient phenomenon with strong impacts on the Earth system and society across scales. Thus, fire is an excellent subject for asking basic questions in physical, biological, and social sciences. Here, we present three fundamental science areas that use fire to understand change: (a) ecology and evolutionary biology; (b) the evolution of *Homo sapiens;* and (c) social dynamics.

Fire is a catalyst for advances in ecology and evolutionary biology, providing a lens to examine how life organizes across scales and how organismal, biochemical, and physiological traits and fire-related strategies evolve. Consequently, fire ecology provides a framework for predicting effects of dramatic environmental changes on ecosystem function and biodiversity across spatial and temporal scales (27, 86), especially where fire may have previously not been present or has been absent for extended periods (e.g. (87)). Research is needed that targets the synergy of theoretical, experimental, and modeling approaches exploring the fundamental evolutionary processes of how organisms and communities function in dynamic and diverse fire environments. Fire allows researchers to investigate the fundamental and relative roles of traits and strategies across plant, animal, and microbial communities (27), and evaluate the influence of smoke on the function of airborne microbial communities (88), photosynthesis (89), and aquatic systems (90). A focus on fire has advanced evolutionary theory through the understanding of the evolution of plant traits and subsequent influence on the fire regime and selective environment, i.e. feedbacks (91). Fire–vegetation feedbacks may have driven the diversification and spread of flowering plants in the Cretaceous era (92, 93). This hypothesis builds upon processes observed at shorter time scales (e.g. the grass–fire cycle; (94)) and suggests flowering plants fueled fire that opened space in gymnosperm-dominated forests. This functional diversity can be parameterized into land surface models (see Challenge 5) by using phylogenetic lineage-based functional types to characterize vegetation, and could enhance the ecological realism of these models (95). Critically needed is an understanding of the reciprocal effects of fire and organismal life history characteristics and functional traits that characterize Earth's fire regimes.

Fire provides an important lens through which we interpret major processes in human evolution. For example, the pyrophilic primate hypothesis (96) leverages observations from primatology (97) and functional generalization from other fire-forager species (98) to suggest that fire was critical for the evolution of larger-brained and big-bodied *Homo erectus* in sub-Saharan Africa by 1.9 million years ago. These populations relied upon fire-created environments and may have expanded burned areas from natural fire starts, all without the ability to start fires on their own. Fire-starting became a staple technology around 400,000 years ago (99), after which human ancestors could use fire in fundamentally new ways, including to further change their own selective environment (100). For example, at least some Neandertal (*H. sapiens neandertalensis*) groups in Europe used fire to intentionally change their local environment more than 100,000 years ago (101), and Middle Stone Age people (*H. sapiens sapiens*) in east Africa may have done the same shortly thereafter (3).

Fire illuminates social dynamics and can be a lens through which we examine fundamental issues in human societies, and even the dynamics of gendered knowledge (102). Specifically, fire questions convenient assumptions about population density and human–environmental impacts. For example, small populations of Maori hunter–gatherers irreversibly transformed non-fire-adapted South Island New Zealand plant communities when they arrived in the 13th century CE (103, 104), whereas large populations of Native American farmers at densities comparable to the modern WUI subtly changed patch size, burn area, and fire–climate relations in fire adapted pine forests over the past millennium (37). Similarly, in an ethnographic context much Aboriginal burning is done by women (105) and male uses of fire tend to have different purposes (106) with potential implications for varied social and environmental pressures on gendered fire uses, goals, and outcomes.

Answering fundamental fire science questions about evolutionary biology and the dynamics of human societies could help illuminate the role of humans in cross-scale pyrogeography. This is especially important in the Anthropocene as species, communities, and ecosystems arising from millennial-scale evolutionary processes respond to new disturbance regimes and novel ecosystem responses (107). Moreover, with increasing extreme fire behavior in many regions (16, 17, 35, 108), human societies must learn to live more sustainably with fire in the modern context (109). Fire is a catalyst for exploring fundamental questions and highlights the need for interagency fire-specific funding programs to support basic science. The direct benefits to society of fire research are well-acknowledged, but fire scientists are not organized as a broad community to argue for coordinated efforts to support basic science. Current fire-focused funding sources are usually limited to narrowly applied projects, while funders of basic science treat fire as a niche area. The result is duplicated efforts and competition for limited funds instead of coordination across an integrated fire science community.

4: Challenge: Capitalize on the "firehose" of data to support community values

We need funding to harness the data revolution and aid our understanding of fire.

The volume, type, and use of data now available to study fire in the biosphere is greater than ever before—a metaphorical "firehose" delivering vast amounts of information. Multidisciplinary science campaigns to study fire behavior and emissions are data intensive and essential for improving applications from

local, regional, to global scales (e.g. ABoVE (110), MOYA (111), FAS-MEE (112), FIREX-AQ (113), MOYA/ZWAMPS (114), and WE-CAN (115)). Observation networks supported by the US National Science Foundation (e.g. NEON, National Ecological Observatory Network, 116) and the Smithsonian sponsored ForestGEO plots (117, 118) are uniquely valuable for the duration and intensity of data collection. Additionally, there are dozens of public satellites, and even more private ones, orbiting the planet collecting remote-sensing data related to pre-, active, and post-fire conditions and effects, thereby facilitating geospatial analysis from local, to regional, and global scales (119, 120). Terabases of genome-level molecular data on organisms spanning from microbes to plants and animals are readily generated (121). Finally, laboratory, field, and incident data exist like never before, where in the past there was limited availability.

While these data exist, there are challenges with the spatial and temporal frequency and coverage and duration of observations. Airborne flight campaigns cover a limited domain in space and time, while geostationary satellites provide high temporal resolution with relatively coarse spatial resolution and polar orbiting satellites provide higher spatial resolution, but lower temporal resolution. These tradeoffs in resolution and coverage lead to different data sources providing conflicting estimates of burned area (122, 123). We need investment in laboratory and field infrastructure for studying fire across a range of scales and scenarios (124) and continued work comparing and accounting for biases across existing data streams. We must develop infrastructure and support personnel to collect real-time observation data on prescribed or cultural fires (125) and wildfires in both wildlands and the wildland-urban interface across scales: from the scale of flames (i.e. centimeters and seconds) to airshed (kilometers and hours), to fire regimes (regions and decades).

Furthermore, many measures of fire processes and impacts are inferred from static datasets (126), while fires and their effects are inherently dynamic; collecting observations that capture these dynamics, such as the response of wind during a fire event, would greatly reduce uncertainties in forecasting the impacts of fire on social–ecological systems. For fast-paced, local processes like fire behavior and the movement of water and smoke, we need more high frequency observations from laboratory and field-based studies, such as the role of flame-generated buoyancy in fire spread (127), to update empirical relationships, some established by decades-old research and still used in models (128, 129). For centennial- to multi-millennial processes covering regions and continents, we need paleoclimate and paleoecological data sets that cover the variation in fire regimes (e.g. low severity vs. high severity) across ecoregions (130, 131).

We need technologies that collect data relevant for better understanding fire impacts on ecosystems and humans. New technology (e.g. ground-, air-, and space-borne lidars, radars, [hyperspectral] spectrometers, and [multispectral] radiometers) would enable measurements to help characterize surface and atmospheric structure and chemistry and better understand human land cover and land use in conjunction with fire impacts on air and water quality, ecosystems, and energy balance. We must use molecular techniques to capture the direct and indirect effects of soil heating on soil organic matter composition (132), belowground biological communities (133, 134), organism physiology (135), and ecosystem function processes (136). Finally, laboratory work can help better understand the mechanisms of heat transfer (137, 138), firebrand ember generation, behavior and transport

(139, 140), atmospheric emissions (141), and transformation of fire plumes (115).

One challenge is that these data are not well-integrated for studying fire disturbance, as many were not specifically designed to examine the causes or effects of fire within an integrated social–ecological construct. For example, the use of diverse sets of multi-scale (tree, patch, local, and regional landscape) and multi-proxy records (pollen and charcoal, tree-ring fire scars, tree cohort analysis, inventories, photographic imagery, surveys, and simulation modeling) can be used to determine structure, tree-species composition and fire regimes (72, 142), and departures from historical ranges of variability (15, 143). However, this type of integrated historical data across a spatiotemporal continuum is not readily accessible to fire scientists, policy-makers, and communities. Current capabilities of remote sensing measurements of vegetation properties (144) are also not easily ingested as relevant information for more traditional fire models (145). Finally, there is limited access to global datasets of research-quality event-based data (24, 146–149), which is necessary to advance the understanding of human and biophysical processes of fire.

Many of these data are housed in disciplinary databases, such as the International Multiproxy Paleofire Database (150), which can be challenging for nonspecialists to access and use. We need to compile and merge these diverse data across spatial (m^2 to Earth System) and temporal (milli-seconds to millennia) scales to support integration across disciplines, research groups, and agencies. Previous work provides an extensible framework for co-aligned airborne and field sampling to support ecological, microbiological, biogeochemical, and hydrological studies (112, 151). This work can be used to inform integration and coordination of data collection across platforms (field and remotely sensed), scales (flame to airshed), and systems (atmosphere, vegetation, soil, and geophysical), to establish a network that will produce long-term, open-access, and multi-disciplinary datasets related to fire science. This effort requires a reevaluation of how we collect data, ensuring we do so in ways that address key societal needs (e.g. aiding in human adaptability and maintenance of biodiversity). It highlights the need to coordinate across laboratory, field, and model-based research in designing future campaigns to develop, not only a common platform, but also a common language and coordinated data management across disciplines. Standardized data collection (e.g. observables, units, and so on) and protocols for quality control, archiving, and curation will be essential to merge existing datasets (90) and create new ones.

In support of increased utility, we need to establish and use common metadata standards and a community of practice for open algorithms and code, informed by the FAIR data principles making data and code Findable on the web, digitally Accessible, Interoperable among different computing systems, and thus Reusable for later analyses (152), and data literacy communities such as PyOpenSci (https://www.pyopensci.org/) and ROpenSci (https://ropensci.org/). Implementation of FAIR principles are complemented by the CARE (Collective benefit, Authority to control, Responsibility, and Ethics) principles that protect Indigenous sovereignty and intellectual property (75). This requires not only building coordination among federal agencies, but also with state, local, and Tribal governments and institutions. Such a community of practice, exemplary of ICON (Integrated, Collaborative, Open, Networked) science principles and practices (153), would facilitate more frequent collaborations across disciplines and lead to convergent research and data-intensive scientific discovery.

By compiling and merging diverse datasets, we can remove barriers to searching, discovering, and accessing information across disciplines, thereby accelerating scientific discovery to understand drivers and impacts of fire, helping support the development of more fire-resilient communities. There is considerable potential to harness this data revolution and explore cross-disciplinary research in the form of biomimicry adapted from long-term parallels from flora, fauna, and Indigenous peoples' responses to fire (154), management planning with Potential Operational Delineations (PODs; (155)), and digital twins (156) that use coupled models including human dimensions (see Challenge 5) to adapt and test historical parallels and potential solutions for human communities and broader social–ecological systems.

5: Challenge: Develop coupled models that include human dimensions to better anticipate future fire

To better anticipate future fire activity and its impacts on and feedback with social–ecological systems, we must develop coupled models that integrate human- and non-human dimensions.

We need modeling frameworks that better represent fire in a social–ecological system, and that can be applied across multiple spatial and temporal scales spanning wildland–rural–urban gradients (8, 11, 20). Such frameworks should capture differences between managed and unmanaged fire as they relate to: preceding conditions, ignition sources (28), fire behavior and effects on ecosystems, humans, and the biosphere. Making this distinction between managed and unmanaged fire in modeling is essential to characterizing changes in the natural system due to the influence from human behavior (26). Fire has been a primary human tool in ecosystem management (30), and thus unraveling the variability in human–fire interactions over space and time (see Challenges 2 and 3) is necessary for understanding fire in the biosphere (26, 30, 69). There are multiple types of models that can benefit from better accounting for human interactions.

First, an improved forecasting system is needed to project both managed (e.g. prescribed burn and wildfire response) and unmanaged (i.e. wildfire) fire spread and smoke behavior, transport, and transformation (112). This can aid society's strategic and managed response to fire in terms of community resilience (47, 74). Models of fire behavior and effects span spatial and temporal scales, but fundamental to each is the consideration of fuels, vegetation, and emissions. We must work to capture fuel heterogeneity, including the physiological dynamics that influence vegetation fuel loading (157), fuel moisture (158, 159), and the flammability of live and dead vegetation (160, 161). Fuel moisture and its variation in space and time have the capacity to alter fire behavior (162) and ecosystem vulnerability to wildfire (163). Currently, most models do not capture both these types of fuels *and* plant physiological dynamics, despite both influencing fire behavior, effects, and subsequently land surface recovery. Several wildfire propagation models exist ranging from empirical to process-based (127, 164), but they either entirely focus on wildlands (112, 164) or pertain to limited aspects to wildfire behavior in communities focusing on interactions among a group of structures (165) and not on the heterogeneous landscapes of the wildland-urban interface (166, 167). We are making significant advances in capturing the impacts of fire on winds during an event (164) as well as on local weather conditions (168, 169), which both have the capacity to alter fire behavior and path. Advances in analytical approaches are making it possible to model community vulnerability (170) and risk (171) from a fire propagation perspective while accounting for the interaction

between structures (172). However, to date, we do not have consensus on a model to assess the survivability of individual structures from wildfire events, as available urban fire spread models are not designed for these communities and underestimate the fire spread rate in most cases (172). Developing such models is vital for determining how to manage wildfire risk at the community level.

Second, land surface models, which simulate the terrestrial energy, water, and carbon cycle, often represent fire occurrence and impacts, but omit key aspects or are parameterized in a simple manner (173). As such, there is a need to develop fire models within land surface models that integrate fire behavior and effects representative of the social–ecological environment within which humans interact with fires and subsequently influence impacts to terrestrial energy, water, and carbon cycles. The current generation of fire-enabled land surface models demonstrate that a lot of uncertainty is due to how the human impact on fires is currently characterized, and exemplifies the need for a better representation of human dimensions within global fire models (174–177). Relationships between people and fire are driven by interactions between the social environment in which humans act (e.g. livelihood system, land tenure, and land use), the physical environment (e.g. background fire regime, landscape patterns, and land management legacies), and the policy sphere. The current generation of fire-enabled land surface models are not able to represent fire in this social–ecological environment, and thus struggle to capture both historical changes in global fire occurrence (26), as well as how these changes have impacted ecosystems and society with sufficient regional variability in the timing and type of human impacts on fires (174, 175). Additionally, current land surface models do not represent mixed fuel types between natural vegetation, managed land, and the built-environment, which influence fire spread, characteristics, and impact directly. Land surface models rarely include the effects of fire on organic matter (i.e. pyrogenic organic matter production (178), or the nonlinear effects of repeated burning on soil carbon stocks (179)). As this likely plays an important role in the net carbon balance of wildfires (178), these omissions may amount to oversights in estimates of the impact of fires on carbon stocks (180). While land surface models often include simplified postfire vegetation dynamics for seed dispersal and tree seedling establishment, competition during succession, formation of large woody debris, and decomposition (e.g. (157, 181)), they exclude the influence humans have on these processes through land management.

Third, fire-enabled Earth system models, which seek to simulate the dynamic interactions and feedbacks between the atmosphere, oceans, cryosphere, lithosphere, and land surface (as such incorporate land surface models), use a simplistic representation of fire simulating aggregate burned area rather than the spread and perimeters of individual fires (182). This is a challenge for projecting the broad-scale impacts of fire on ecosystem resilience and functioning, because the temporal and spatial patterns of fire that vary as a function of managed vs. unmanaged fire, underpin whether and how ecosystems recover (183, 184). This further affects smoke emission speciation, formation, and behavior of greenhouse gases, aerosols, and secondary pollutants that affect the climate system (185, 186) through the absorption and scattering of solar radiation and land surface albedo changes. Our limited understanding is due in part to challenges related to representing this complexity and the resulting processes and impacts within and across interacting model grid cells.

There is a need for the infrastructure to implement and nest models across multiple scales, linking from fine to coarse

temporal and spatial scales and including a two-way coupling to allow interaction between models. This would, for example, allow Earth system models to better capture changing vegetation and fuels through time, as modeled in land surface models; this in turn would help modelers capture finer-scale dynamics such as interactions between fire and weather and human interactions with individual fire events (e.g. suppression efforts). Reducing uncertainties across scales provides an opportunity to use data-assimilation to benchmark against multiple types of data at sites, for various scales, fires (prescribed/cultural and wild), and under variable conditions (see Challenge 4). Advanced analytics in machine learning and artificial intelligence can help ease computational complexity (187–189) in such an integrated framework.

Nested, coupled modeling frameworks that integrate across physical, biological, and social systems will not only enhance our understanding of the connections, interactions, and feedbacks among fire, humans, and the Earth system, but also enable adaptation and resilience planning if we create metrics to gauge the response of social–ecological systems to fire (e.g. (126, 190)). These metrics would include fire impacts on ecosystem services, human health, ecosystem health, and sustainable financing through policies on fire suppression, air and water quality, and infrastructure stability. Recent progress in understanding the characteristics of western United States community archetypes, their associated adaptation pathways, and the properties of fire-adapted communities (191, 192) should be explored across a diverse set of communities and used to inform such metrics.

Metrics for risk and resilience would need to be incorporated in these nested, coupled models that include human dimensions so that projections before, during, and after a fire could allow for informed decision-making. Risk includes not only the hazard, or potential hazard, of fire, but the exposure (directly by flame or indirectly from smoke) and vulnerability, as susceptibility, to be negatively impacted by the hazard; all of which are different for managed vs. unmanaged fire (20, 108, 143). Using models to quantify risk could, for example, guide planned management shifts from fire suppression to increased use of prescribed burning as an essential component for managing natural resources (143, 193, 194), but is currently challenging to implement due to smoke effects (195). Next-generation, integrated human–fire models are necessary to help managers both locally, those who use prescribed fire near communities (125, 196), and regionally or nationally, those who report emissions. While such a comprehensive framework would address the specific needs of different stakeholders and policy-makers, it would also be accessible and broadly comprehensible to the general public (e.g. fire paths forecast), similar to existing national warning systems for hurricanes and tornadoes. A focus on community resilience to wildfires expands the definition of risk beyond human impact to consider ecological and biological risk more holistically, as well as their role in a coupled social–ecological system. Integrating human behavior and decision dynamics into a nested modeling framework would allow for another dimension of feedback and interactions. Thus, integration of data and processes across scales within a nested, coupled modeling framework that incorporates human dimensions creates opportunities to both improve understanding of the dynamics that shape fire-prone systems and to better prepare society for a more resilient future with increased fire danger.

Conclusion

Now in the emerging era of the Anthropocene, where climate change and decoupling of historical land management have collided, society needs large-scale investment in the next generation of fire science to help us live more sustainably in our increasingly flammable world. Fire is a complex phenomenon that has profound effects on all elements of the biosphere and impacts human activities on a range of spatial and temporal scales. We need a proactive fire research agenda. Fire science has been reactive in that it responds to agency opportunities and conducts research in response to past fires. It is essential that we transition from this reactive stance to proactively thinking about tomorrow's needs by acknowledging and anticipating future fire activity. This next generation of fire science will require significant new investment for a center that synthesizes across disciplines (Challenge 1), is diverse and inclusive (Challenge 2), innovative (Challenge 3), and data-driven (Challenge 4), while integrating coupled models that consider human dimensions and values (Challenge 5) (Fig. 1; Table S1, Supplementary Material).

One cause of current fragmentation within the United States is the narrow focus of major funding sources. Funding currently targets short-term goals, on small, single-Principal Investigator-led research, usually aimed at one aspect of fire science; it should target a holistic reimagination of our relationship with fire entirely, across academic, managerial, and social boundaries. This will create a broader and deeper understanding of the multifaceted nature of fire, with less focus on case studies and more focus on case integration. International projects funded by the European Commission have implemented a multi- and interdisciplinary approach, but can still be improved. Support for applied research will be most effective by aiming at both short- and long-term applications and solutions. There are active and prominent discussions on the need to fund fire science across government, local, and Indigenous entities that are all vested in understanding fire. These investments will be critical to advancing our ability to generate new insights into how we live more sustainably with fire. Fire will continue to have enormous societal and ecological impacts, and accelerate feedbacks with climate change over the coming decades. Understanding, mitigating, and managing those impacts will require addressing the presented five challenges to inform how we serve environmental and social justice by sustainably living and interacting with fire in our natural world.

Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

Authors' Contributions

All authors—J.K.S., J.K.B., R.T.B, P.E.H, C.I.R, D.W.S, E.N.S., T.B., M.M.B., J.B., Sa.B., So.B., K.D.B, P.B., R.E.B, B.B, D.C., L.M.V.C., M.E.C., K.M.C., S.C., M.L.C., J.C.I., E.C., J.D.C., A.C., K.T.D., A.D., F.D., M.D, L.M.E., S.F., C.H.G., M.H., E.J.H, W.D.H., S.H., B.J.H., A.H., T.H., M.D.H, N.T.I., M.J., C.J., A.K.P., L.N.K., J.K., B.K., M.A.K., P.L., J.L., S.M.L.S., M.L., H.M., E.M., T.M., J.L.M., D.B.M, R.S.M., J.R.M, W.K.M., R.C.N., D.N., H.M.P., A.P., B.P., K.R., A.V.R., M.S., Fe.S., Fa.S., J.O.S., A.S.S., A.M.S.S., A.J.S., C.S., T.S., A.D.S., M.W.T., A.T., A.T.T., M.T., J.M.V., Y.W., T.W., S.Y., and X.Z. designed and performed the research; and J.K.S, J.K.B., R.T.B, P.E.H, C.I.R, D.W.S, and E.N.S. wrote the paper.

Data Availability

All data is included in the manuscript and/or supporting information.

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