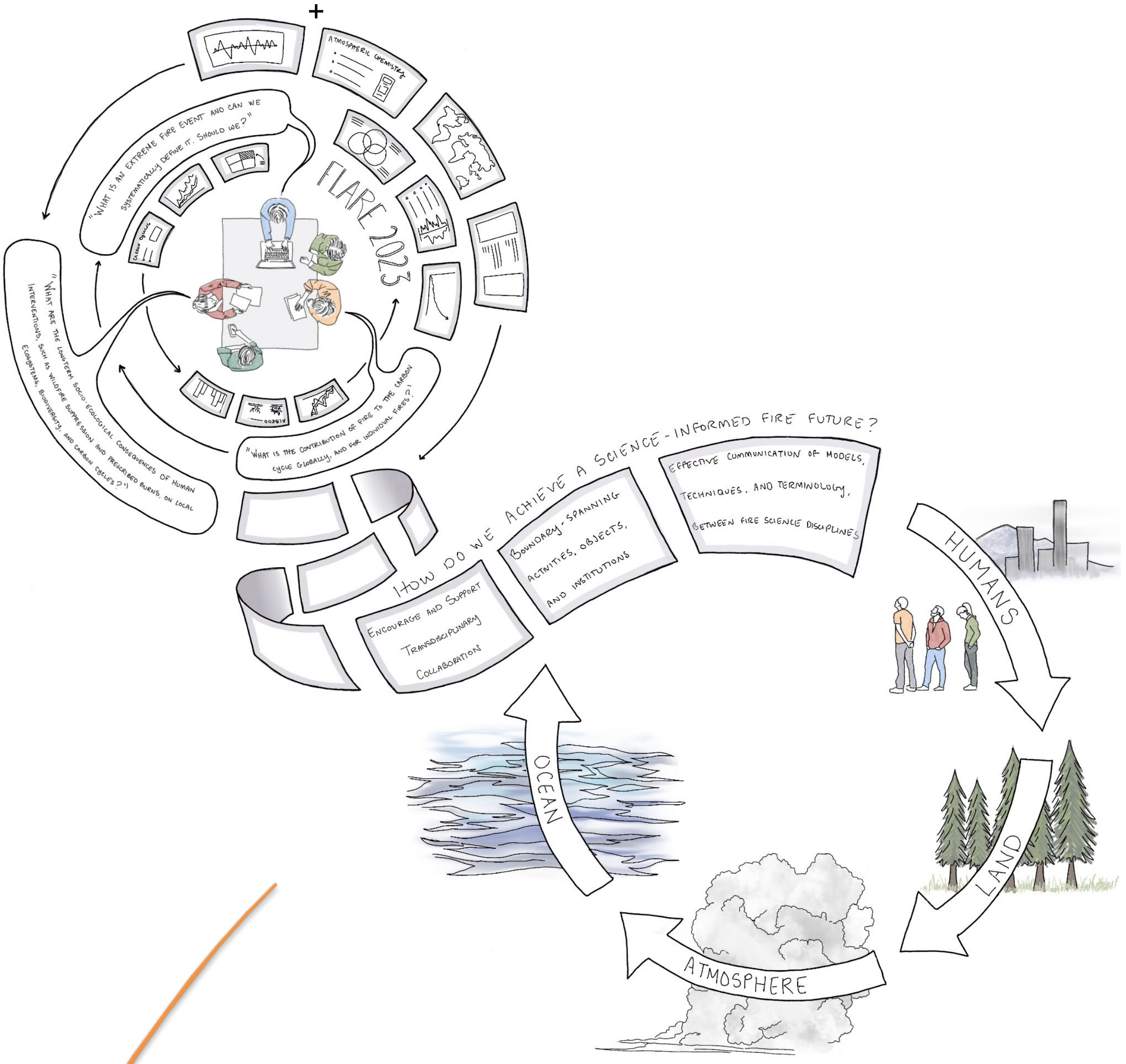
# The Fire science Learning AcRoss the Earth System (FLARE) Working Group



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# Igniting Progress: Outcomes from the FLARE workshop and 3 challenges for the future of transdisciplinary Fire Science

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## Table of Contents

# Executive Summary

Fire is a deeply integrated Earth System component. From the land to the ocean, from ecology to people, and from the past to the future: fire is a truly transdisciplinary research topic. However, integrated research across disciplines, institutions, and fire practitioners into its myriad connections throughout the Earth System and interdependencies with society is not well established. This creates barriers to a holistic understanding of how the rapid changes we are seeing in the fire regimes will impact the health of our planet and its inhabitants.

Diverse expertise from across the environmental sciences, humanities, and social sciences is needed to fully characterise and identify the main challenges facing fire science. The concept of FLARE is to design and develop a proactive approach to advancing transdisciplinary fire science, providing a framework for knowledge transfer of fire science to all disciplines. Recognizing the multidimensional nature of fire, the first goal of FLARE was to host a workshop that initiated collaborations across disciplines and expertise.

Building upon the momentum of a Future Earth COP27 side event on fire, the FLARE working group was launched at a workshop held online and in-person at the Bermuda Institute of Ocean Science (BIOS) in September 2023, providing a platform for discussing the latest scientific knowledge on fire. The workshop facilitated the promotion and integration of cutting-edge satellite data, on-site fieldwork, laboratory experiments, social science, mathematics, and modelling with the broad range of expertise essential for addressing diverse research questions related to fire. Striking a balance between contemporary research and a robust paleofire perspective, the workshop offered insights into how fire regimes have shaped and continue to shape the Earth System, particularly in response to climate change and human activities.

This white paper synthesises the many discussions held over the 3.5-day workshop. It presents the current state-of-the-science from land, atmosphere, ocean, social science perspectives. The workshop highlighted a poor constraint on our understanding of “future impacts of fires on the Earth System”, which stems from a lack of communication between relevant fields of expertise. In particular, a disconnection was identified between scientific approaches to understanding and characterising fire processes and the societal implications of fire events.

Workshop participants identified three main challenges that need to be addressed by the global fire community:

1. Unifying transdisciplinary research around common boundary objects, starting with "**The role of fire in the carbon cycle**”
2. Better characterizing “**Fire and extreme events**”
3. Taking a holistic approach to understand “**Fire interactions with humans**”

Each challenge is explored in dedicated sections with priority questions identified. Common themes that unite these challenges include the importance of transdisciplinary collaboration, encompassing the consequences of fire on society and on the Earth System, addressing communication barriers across the many disciplines involved in the study of fire, including different definitions and sources of uncertainties, and orientating physical science toward solution-based studies by adopting a more proactive approach to predicting fire behaviour and impacts. We explore these concepts within this white paper with suggestions designed to formulate a roadmap for fire science research over the next decade.

## Workshop Overview

Held from 18th–21st September 2023, FLARE gathered experts from disciplines across the Future Earth global research network. Experts in physical and social sciences, mathematics and statistics, remote sensing, fire communication and art, operational fire science, and fire management were all present. The workshop included participants representing 14 countries and with strong career diversity and gender equity composition. Increased participation from South America, Africa, Asia, and Small Island Developing States prone to fire, should be encouraged for future events. The workshop was held in a hybrid format, with 15 onsite participants invited to meet at BIOS (https://bios.asu.edu) and 22 participants online. The 3.5-day workshop included lightning presentations from each participant, 20 keynote talks, and 4 in-depth breakout sessions. Lively discussions led to a wide diversity of discussion topics (**Figure 1**).

**Figure 1: Workshop participant discussion themes.** Keywords (collected from Jamboard responses) arranged near the related challenge and examples of cross-cutting themes highlighted.

## An Early Career Perspective

Early Career Researchers (ECRs) form the majority of the scientific workforce and are a far more diverse cohort than established scientists. Yet, they also face many unique challenges in this career stage that can hinder research outcomes and professional success. To help identify some of these challenges, the FLARE workshop had an ECR-focused session dedicated to understanding what ECRs need from established scientists and what established scientists need from ECRs (see section "An ECR Framework for Future Workshops" for outcomes and "Methods" for how this perspective was established). This section summarises the ECR Perspective on FLARE and we also provide a framework for future workshops to achieve better ECR inclusivity in the final section of the white paper.

In general, ECRs consistently reported wanting to be included, mentored, and heard by established scientists within the scientific community. Established scientists reported the need for new ideas and different approaches to scientific problems that are often brought forward by ECRs.

ECR representation and participation was an important part of FLARE's goal of creating a multidisciplinary community to share knowledge on wildfires across Earth Systems, and FLARE achieved over 50% ECR representation in total. FLARE had many opportunities for ECRs to take leadership roles during and after the conference, including the coordination of this section and co-development of the challenges and themes presented herein. In a survey sent to ECRs who attended FLARE, participants felt included and heard due to these leadership opportunities, the small size of the workshop, and opportunities to network with established scientists in small breakout groups. Most respondents felt that FLARE created a relaxed and respectful environment where they could confidently identify as ECR, ask questions, and share their opinions. This environment facilitated high levels of successful networking and cross disciplinary learning for many ECRs. Participants also communicated that future work must be done outside of FLARE to fully integrate ECR in fire science, to ultimately make fire science more robust by supporting the next generation of fire scientists.. Online participants also felt they could successfully contribute to the workshop due to a combination of factors including online presenters and repeated online-only breakout groups, which allowed for rapport building and long-form discussions. Participants felt that established scientists within the larger scientific community often treat ECRs as a temporary resource, not as the future of science. Changing this perspective is essential to address the multidisciplinary problems within fire science.

Among ECRs there is a prevalent feeling of not having a strong ECR fire science network outside of FLARE. While communities do exist, they are often confined to specific countries, organisations, or institutes. To gain a comprehensive understanding of this issue, a table was compiled highlighting known initiatives in the ECR fire science network (Appendix i). This table illustrates the current landscape at the time of writing and underscores the need for more extensive networking opportunities beyond individual affiliations.

Minority groups (including Black, Latino, Asian, native peoples, Global South residents, women, LGBTQ+ members, disability groups, and other historically marginalised groups) share many of the same barriers. For these reasons ECR inclusivity efforts must be met with simultaneous efforts in minority inclusivity, equity, and diversity such that gains in the institutional inclusivity of ECRs are shared by minority groups.

## Background

The interactions between fire events, the Earth System, and humanity are complex. Fire interacts with communities, vegetation, and ecosystem services on land, but fire can also affect human health, land and ocean productivity, and weather and climate, in often contrasting ways, often at a distance from fire locations. Understanding these complex relationships requires expertise from across the geosciences and social sciences to fully appreciate and identify the main challenges that need to be addressed and the ways to overcome them. The impact of fire on terrestrial ecosystems has been studied for decades, and fire is now recognised as a critical ecological driver for structuring ecosystems and biogeochemical cycles[1]. However, the impacts of fire are multidimensional and can also be noticeable on freshwater systems[2,3], the atmosphere[4,5], marine ecosystems[6,7], the cryosphere[8], and on human health[9,10] and systems such as infrastructural damage. Changing trends in fire regimes (e.g., fire intensity or spatial organisation) in response to climate change (e.g., drought, loss of ice or snow, or changing temperature) and human activity (e.g., firefighting, deforestation, urban expansion, or land management), are altering interactions between fire and other components of the Earth System, including societies. However, quantifying past and future impacts of changing fire regimes on Earth and societal systems remains poorly constrained, due in part to a lack of communication between relevant fields of expertise.

While natural fire has occurred for hundreds of millions of years, since plants colonised the land, humans have modified these natural fire regimes profoundly. There is significant regional variation in the human driven evolution of fire regimes. Regime characteristics depend on their environmental identity and the associated chronologies of human history and culture[11–13]. Differences in the environmental and cultural identity of each region must be considered when analysing the frequency, seasonality, intensity, and severity of each fire event, to understand its origins and consequences. It would appear, however, that the human impact on all the planet's ecosystems today, sometimes achieved with significant time lags, has led to a global alteration in fire regimes, which, combined with recent, present, and future climate change, represent an unprecedented risk that is still very poorly understood. Human activities have become an inexhaustible source of wildfires. Changing climatic conditions further exacerbate the propagation of fires in many regions of the world, and the vulnerability of our Anthro-systems to such conflagrations becomes ever more evident year-on-year.

While the magnitude and frequency of extreme fire events have been increasing rapidly, particularly in extra-tropical and polar regions[14,15], and dominate the media discourse on fire[16], recent decades have seen a net decline in the global-averaged burned area as mapped by moderate resolution satellites, primarily driven by fire activity on the African continent[17,18]. The main reason for these opposing trends is that while climate change creates weather patterns that encourage the development of larger and more severe fires outside the tropics, tropical regions see a decrease in fires due to a rapid transition of natural grassland into managed pasture and agricultural fields[19]. However, a complete understanding of burned area changes is currently limited by the moderate resolution of many satellites that miss changes in smaller fires[20–22]. A better understanding of how climate, land cover changes, and human land management practices will drive the spatiotemporal distribution of fires in the coming decades is necessary to improve predictions of the impact of future fires on the Earth System and, ultimately, on society.

## Holocene Fire Trajectory

Although paleofire quantification tools are often limited in providing absolute measurements and temporal dynamics, the amount of biomass burnt during the last ice age has been deemed to be fairly low on a global scale. However, fire probably still played an important role in shaping many ecosystems, with some evidence suggests that the ecosystem stress induced by a drier climate with low $CO_2$ concentrations during the last glaciation was further compounded by fires, leading to alterations in vegetation distributions[23,24]. At the beginning of the Holocene, increasing temperatures favoured vegetation growth and the accumulation of fuel, whilst maximum summer insolation in the Northern Hemisphere favoured a season conducive to fires. In certain regions of the world, such as Southern Europe and North America, the accumulation of charcoal in sediments attests to repeated occurrence of fire events across these continents. At the same time, particularly in northern Europe, where temperatures, relative humidity, and vegetation types were not conducive to 'natural' fires, the occurrence of fires associated with the presence of Mesolithic populations seems to indicate anthropogenic origins. More interdisciplinary research is needed to understand the extent of these practices. While reasonably good paleo-records exist across Europe and North America, much less information is available to help understand how the tropical fire regime has been changing throughout the Holocene.

From the early to late Holocene, the temporal and spatial variability of fires are consistent with the conquest of land by human populations and the occupational choices made by human groups practising agro-pastoralism. Gradually, the combination of climatic conditions that were less favourable to fires and human activities that caused repeated fires, albeit on a smaller scale, led to a change in the fire regime, with less biomass burned but about a doubling in the frequency of events. The management and control of the environment using fire evolved during Protohistory and historical periods as practices, objectives, and environmental conditions, including climate, changed. The use of fire shifted from conquering new territories to maintaining them, with practices fluctuating based on regional histories, demography, and ecosystem constraints faced by populations.

There are significant variations between regions globally, dependent on their environmental and cultural identity, as well as the associated chronologies of human history. The environmental and cultural identity of each region must be considered when analysing the evolution and characteristics of each fire regime, the frequency, seasonality, intensity, and severity of each event, in order to understand its origins and consequences. It would appear, however, that the human impact on all the planet's ecosystems today, achieved sometimes with significant time lags, has led to a global alteration in fire regimes, which, combined with past, present, and future climate change, represent an unprecedented risk that is still very poorly controlled. Human activities have become an inexhaustible source of wildfires. Climatic conditions further exacerbate the propagation of fires in several regions of the world, and the vulnerability of our Anthro-systems to such conflagrations is evident.

## Satellite Era Burned Area Trends

Globally, burned area observed with moderate resolution satellite sensors (e.g., MODIS) has reduced by around one-quarter since 2001[17,18,20]. However, trends in the area burned by fires differ strongly with the scale and region of interest. The reported global trend in burned area is predominantly due to reduced fire events in the global savannahs, particularly in Africa, although this does not take into account the contribution of small fires (e.g., crop burning of a single field) not detected by MODIS but often detectable in medium to high resolution imagery - such as since 2016 using Copernicus Sentinel-2[22,25,26]. Reduced detection of burned area in Africa has been attributed both to economic development involving the expansion of agriculture[17,27] and to a change in the distribution of rainfall on the continent[28]. Burned area has also reduced in other parts of the tropics, such as in southern Amazonia in the early 2000s. However, in tropical forests, the trend in burned area is more tempered, with some areas seeing an increase in burning levels due to a trend towards drier conditions[29–31] and deforestation[32–35].

Outside of the tropics, many regions have experienced a notable increase in burned area, including the western US, east Siberian boreal forests, and Canadian boreal forests driven by increased dryness, changing fuel loads from changes in vegetation productivity, and different levels of human modification of the landscape[36]. A record level of burned area was observed across the pan-boreal forests in 2021, while the indications for 2023 are that Canadian fires burned an area ~7 times greater than the decadal average (https://cwfis.cfs.nrcan.gc.ca/report). Clearly, changes in fire regime are not spatially or temporally consistent with reduced fire in the grassland ecosystems contrasted by temperate and boreal forests where burned area is rising fast. Overall, global emissions of carbon from fires, as evidenced by atmospheric inversion, have remained approximately constant or increased slightly since 2001[37]. This can be explained by a rise in the impact of fire on regions where carbon is stored most densely – particularly forests. Increased emissions of carbon from fires in boreal and temperate forests thus potentially outweigh reduced emissions of carbon from fires in grasslands.

## Drivers of Change in Burned Area

The potential for fire to occur is rising under climate change. This is observed through increases in fire weather index – a catch-all measure that describes the flammability of landscape fuels and local meteorological conditions, and thus, the likelihood of a fire igniting and spreading. Increasing fire weather potential is expected to impact environments where ample fuel loads are present and where fuel dryness is the dominant control on fire (i.e., fuel moisture typically being the primary limitation to fire ignition). Prime examples of a sensitivity to climate include the temperate and boreal forests, such as those in boreal Canada, western Northern America, Siberia, and southeast Australia (**Figure 2 top panel**). In these regions dense fuel stocks become seasonally dry and flammable, a condition exacerbated during years with prolonged drought and episodes of extreme fire weather. Tropical fire is more diverse in its relationship with fire weather, with Africa showing low correlation while Southeast Asia shows some of the highest.

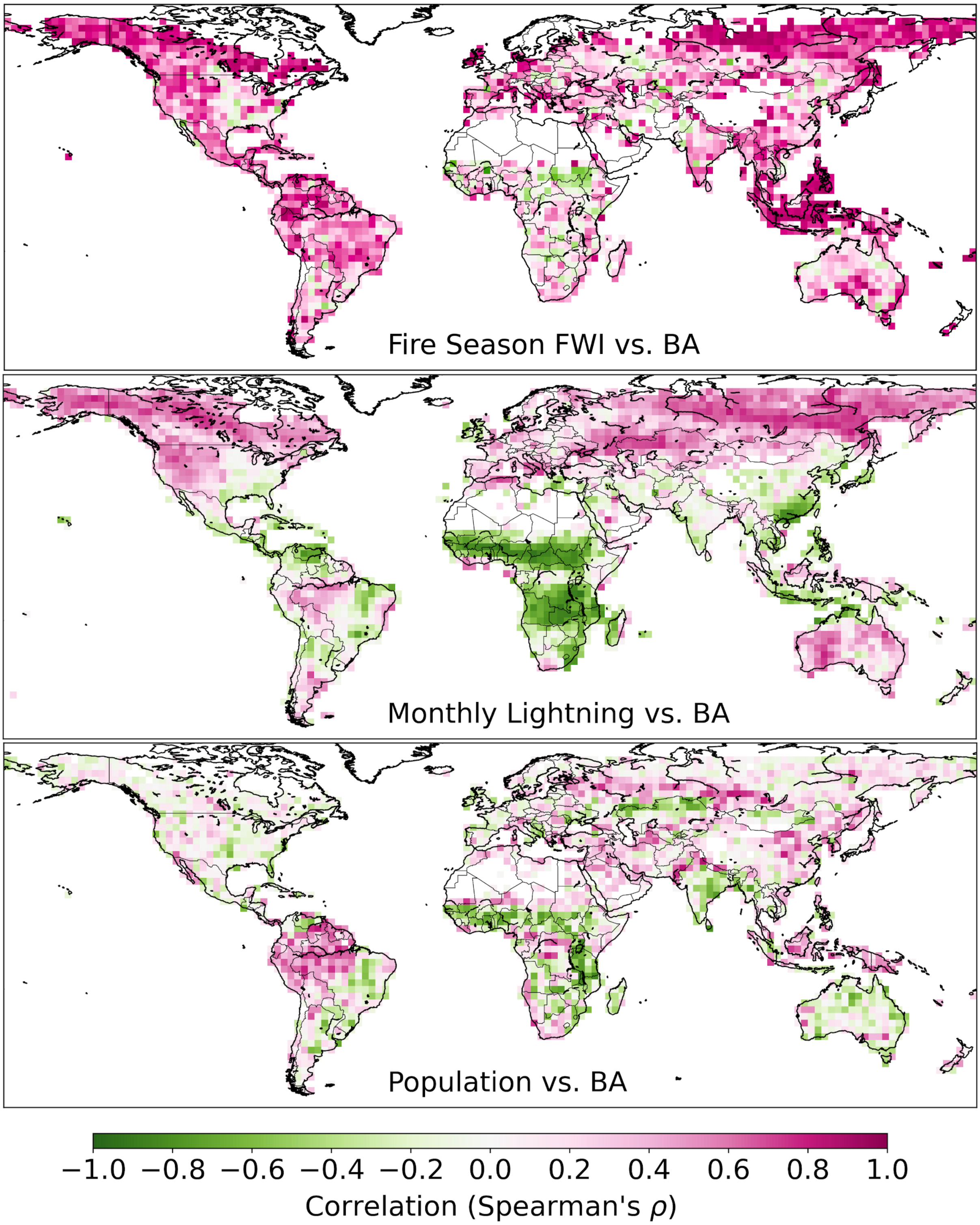


**Figure 2: Relationships between burned area and a selection of fire drivers**, reproduced from Jones et al. (18). Plots show the Spearman's rank correlation coefficient between a) the total burned area (BA) in the fire seasons between 2001-2019 (MODIS satellite observations) and the mean fire weather index (FWI)[38] in the fire season (top panel). b) monthly lightning flash density[39] and burned area (middle panel). c) population[40] and annual burned area 2001-2019, based on sub-grid variability in population density and burned area (bottom panel).

Sensitivity of fire burned area to human population is strongest in tropical regions (**Figure 2 bottom panel)**. For example, in tropical savannahs, people have a strong control on the location and frequency of fire ignition, and they also control the landscape heterogeneity by fragmenting savannas with agricultural areas that are generally more fire controlled. This is evident in the distinct spatial differences in correlation between lightning activity and burned area (**Figure 2 middle panel)** with positive correlations in forested regions with lower population density while the correlation is anti-phase in grassland regions with strong land management. In tropical forests, people also control ignition patterns and have fragmented and degraded forests that are not naturally fire-prone, leading to reduced forest resilience to drought and increased potential for fire during hot dry periods and at forest edges.

## Fire Regimes

A fire regime describes how fire, based on its specificities, interacts with ecosystems, and climate in a particular geographical area or ecological setting over a defined time period. This concept encompasses many attributes of fire including the type of fire, its frequency, size, seasonality, intensity, and severity as well as its impact on local vegetation, carbon cycling, and biodiversity. Many observations and modelling studies focus on quantifying burned area[18,41–43]. However, this is not enough to understand the broader implications of fires, and we must start considering all aspects of a fire regime to encompass human and ecological consequences and soil and vegetation responses that occur during and after a fire event[44]. Going "beyond burnt area" will allow us to explore the diverse impacts of fires on ecosystems, on the carbon cycle, and on trace gas emissions, delve into the complexities of extreme fire events[36] and recognize the significant role of humans in shaping fire regimes. A comprehensive understanding of fire regimes is also crucial for predicting future fire occurrences, understanding and preparing for their impacts, and fostering resilience in the face of evolving climate conditions and human interactions with fire.

## The Fire Science Tool Kit

A complete understanding of fire events requires integrated studies of the fire dynamics, the fuels complex and landscape that burns, the different impacts on societies and the climatological context in which fire occurs. Also essential is understanding the chemical composition of the fire products, including smoke, charcoal and ash. Some chemical species generated by fire can be harmful to life on Earth when exceeding threshold concentrations, for example ozone can damage plant function while small aerosol particles or metals are toxic to animal life, while others are nutrients, which, following redistribution via the atmosphere or water-transport, can fuel life in remote regions on land and in the ocean.

**Ground-based Sampling.** Understanding the state and composition of soil and vegetation before and after fire and the resulting pyrogenic materials generated is essential to assess fire impacts. This can be achieved through field-based measurement and sample acquisition. However, field-work is very time and resource consuming, resulting in collection campaigns both under-scaled and too short to comprehensively study the singular characteristics of each fire-prone ecosystem on Earth.

In addition to pre- and post-fire burn observations, the physicochemical characterisation of a fire while burning is essential, although challenging. Ground-based optical sensors can quantify some gas and aerosol species contained in the fire plume and, hence, be used to track the evolution of a fire's plume characteristics in near real-time. However, quantifying other elements in the fire plume requires laboratory analysis of samples. Aerosol samples are commonly collected by pumping ambient air through a filter substrate, which retains particles of a given size. However, the deployment of instruments close enough to a fire hotspot to collect representative samples represents an obvious danger for the operation material and the operator. In addition, fire events are highly episodic and complex to predict in real time, which makes planning effective field campaigns challenging. It is also difficult to obtain representative samples across the full range of fire types. While managed fires for experiments can be ignited, such experiments produce a limited number of samples. Several studies reporting fire plume sampling have been fortuitous, occurring during other field campaigns several kilometres away from the fire hotspot, highlighting how adaptability in experiment approach can provide additional knowledge. Similarly, long-term time series atmospheric sampling stations have captured emissions from fire events when placed near fire-prone regions. Because strong and turbulent winds characterise a fire event, measurements of the fire plume characteristics several kilometres downwind from the fire hotspot are likely to contain a blended signal of multiple atmospheric sources mixed together. A challenge remains to assess whether a collected sample is representative of the plume's chemical properties or whether the fire plume signal is to be dissociated from other atmospheric sources contained in the same filter sample. While difficulties in collecting robust field-based observations exist, this tool is essential to calibrate and validate remote sensing data and to inform models.

**Remote Sensing** is a vital tool in fire research as it provides a comprehensive and efficient way to monitor, detect, and analyse fires from a distal observation point. Remote sensing technologies use satellite, aerial, and ground-based sensors to collect valuable data on various aspects of fire detection, dynamics and fire history, such as burned area or active fires[20,22,45,46], fire frequency and timing, fuel load and moisture[47], combustion completeness, fire intensity[48,49], emissions and their transport[5,50,51], recovery post-fire, and the history of a fire's spatial extent. These technologies allow both assessment of the impact of fire on ecosystems and near real-time surveillance, to help early detection, assessment of fire severity, and to monitor post-fire recovery. Moreover, remote sensing can capture extensive and spatially diverse information, making it an indispensable tool in addressing transdisciplinary challenges associated with wildfires and incorporating ecological, climatic, and anthropogenic dimensions into comprehensive fire research endeavours.

Integrating different satellite observations of fire characteristics, spatially and temporally, allows the construction of a description of individual fires and their behaviour[52]. However, all satellite observations represent a sample of fire behaviour which needs to be analysed against the detection capability of each (combination of) instrument or sensor, including its spatial, spectral, and temporal resolutions. For example, the estimation of burned area from space varies as a function of the satellite data used and the algorithm implemented (**Figure 3**).

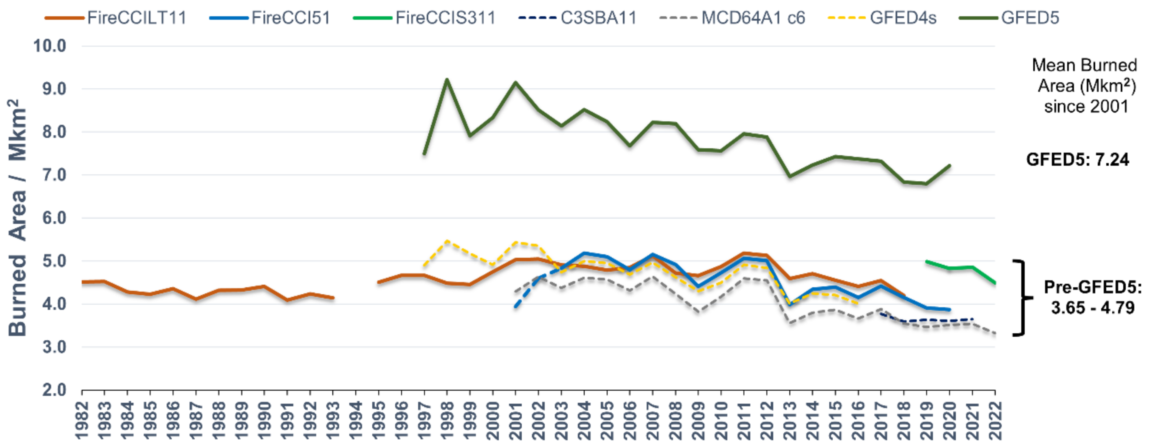


**Figure 3: Burned area estimates from satellites.** Grouped by Global Fire Emissions Database (GFED4s and GFED5)[20,53], estimates from ESA FireCCI[54], and from NASA's MODIS MCD64A1[46].

The 'fire' products generated from remote sensing data can inform ecosystem and atmospheric transport models to enhance our understanding of the complex interactions between environmental factors and fire behaviour[18,55]. However, information for emissions estimates, such as those provided by the Global Fire Emissions Database (GFED), relies partly on modelling of fuel load and combustion completeness, rather than direct observation[53]. Remote sensing approaches need to advance towards more direct observations of fuels (i.e., living biomass, litter, and woody debris), fuel consumption, and the combustion process.

**Fire Modelling.** The development of numerical and statistical computer models enables us to tackle questions in fire science that observations alone cannot address. For example, understanding the overall contribution of fires to the Earth System and carbon budget; how fires have changed over time and how they might change in the future with climate change; what controls fires and how changes in these controls might affect fires and ecosystems. There are many different types of modelling approaches to tackle the huge range of challenges in simulating fires, both natural and human driven. There is a great diversity in the scales addressed and the techniques used by fire modelling; from complex process-based models to simple empirical and statistical models; from modelling at the millimetre level to global scales; and from modelling minutes to millennia. Tailored ways of answering different research questions are a strength of the fire science community; however, this diversity also makes it difficult to integrate and communicate across different models, between models and observations and across different disciplines including fire management services and policy.

Process-based modelling plays a pivotal role in capturing the intricate mechanisms governing fire dynamics and the impacts on local vegetation through mortality, carbon storage, trace gas and aerosol emissions and, when incorporated into Earth System or climate models, the wider climate feedback[41,43,56,57]. These models vary in complexity. Most models simulate fire ignitions by people and lightning, and account for the effects of vegetation cover on fuel load, flammability, and moisture content when estimating burned area. More complex models also represent fire spread and extinguishment processes by incorporating detailed knowledge of environmental factors, fuel characteristics and dynamics, and the physics of fire behaviour. Human landscape changes are also becoming increasingly important in fire models.

The precision of a model relies heavily on accurate parameterisation, and thus, a comprehensive understanding of the physical processes behind it. The more feedbacks represented, the harder it is to constrain results, and the more uncertain model outputs become. Most fire models have skill at representing large scale burnt areas[42] and influences on vegetation composition and total emissions in the present day[58]. However, fire models struggle to represent extreme burning[29], and future projections of burnt area and emissions often wildly disagree[59]. This points to using mostly simple models for research. Nevertheless, complex models are likely to still be required to untangle extreme fires' complex relationship with the environment (e.g., vegetation and soil carbon transitions).

Empirical and statistical modelling approaches complement process-based models by offering pragmatic insights derived from field-based data. Empirical models draw on historical records and observational data to establish relationships between key variables, providing a more straightforward and data-driven perspective on fire dynamics[30,60]. Statistical models, on the other hand, employ mathematical frameworks to analyse patterns and trends within datasets, enabling the identification of key factors influencing fire occurrence, size, and behaviour[61,62]. Both empirical and statistical models are valuable for their simplicity and ability to handle uncertainties[33], offering practical tools for decision-makers and land managers. They require robust datasets for accurate parameter estimation and may have limitations when applied to novel or extreme scenarios, though recent advances in model optimisation and using empirical models alongside processes-based land surface schemes are starting to tackle this problem[36].

The Fire Model Intercomparison Project (FireMIP)[41] was established in 2014 as an international community of modellers and experts in fire science, atmospheric chemistry, carbon cycle and ecology, and remote sensing. The aim is to strengthen the development of global fire models through a core set of simulations[43], which allow standardised model intercomparison and evaluation against observations[42]. The group meets annually to discuss progress in fire modelling across worldwide centres. The next phase of FireMIP is now through collaboration with ISIMIP (Intersectoral Impacts Model Intercomparison Project), where impacts attribution and future scenarios will be explored within the fire models.

## Our Challenge

The transdisciplinary nature of fire science necessitates a collaborative approach to answer research questions. The FLARE workshop, and activities like it, can act as a “boundary spanner” at the crossroads of knowledge creation, synthesis, translation, and application, bridging the dialogue between research and communities[63].

Three overarching challenges emerged from discussions during the FLARE workshop; each interconnected and underpinned by common themes. The following findings were compiled based on in-person and online talks and debate, collaborative Jamboard exercises, and breakout session discussions. The challenges revolve around the need to bring the community together on agreed common boundary objects. The first we identified is a deeper understanding of the role of fire in the carbon cycle across both space and time, second to address what is an “extreme fire”, both for science and for society, and finally to approach the long-standing and constantly evolving bilateral interactions between humans and fire more holistically.

Common themes that unite these challenges include the importance of transdisciplinary collaboration, recognising the societal and Earth System consequences of fire, addressing the many different definitions and sources of uncertainties, and adopting a proactive (short response) approach to fire science.

## Challenge 1: The Role of Fire in the Carbon Cycle

**Priority Questions decided by FLARE working group participants:**

1. **What is the contribution of fire to the carbon cycle globally, and for individual fires?**
2. **How can we collect observations more effectively, and how can a more comprehensive global record of fire data be created that combines detailed but sparse in-situ observations with broader remote sensing observations?**
3. **Do models incorporate the correct drivers of the carbon cycle and sensitivity to those drivers?**

Fire substantially influences and modulates the global carbon cycle through numerous processes, interactions, and feedbacks. Interactions can be direct, such as carbon emission during combustion, vegetation, and soil carbon loss, and indirect, such as when aerosols and gases in smoke plumes propagate through the Earth System, affecting weather, climate, atmospheric composition, and chemistry which in turn affect carbon cycle processes.

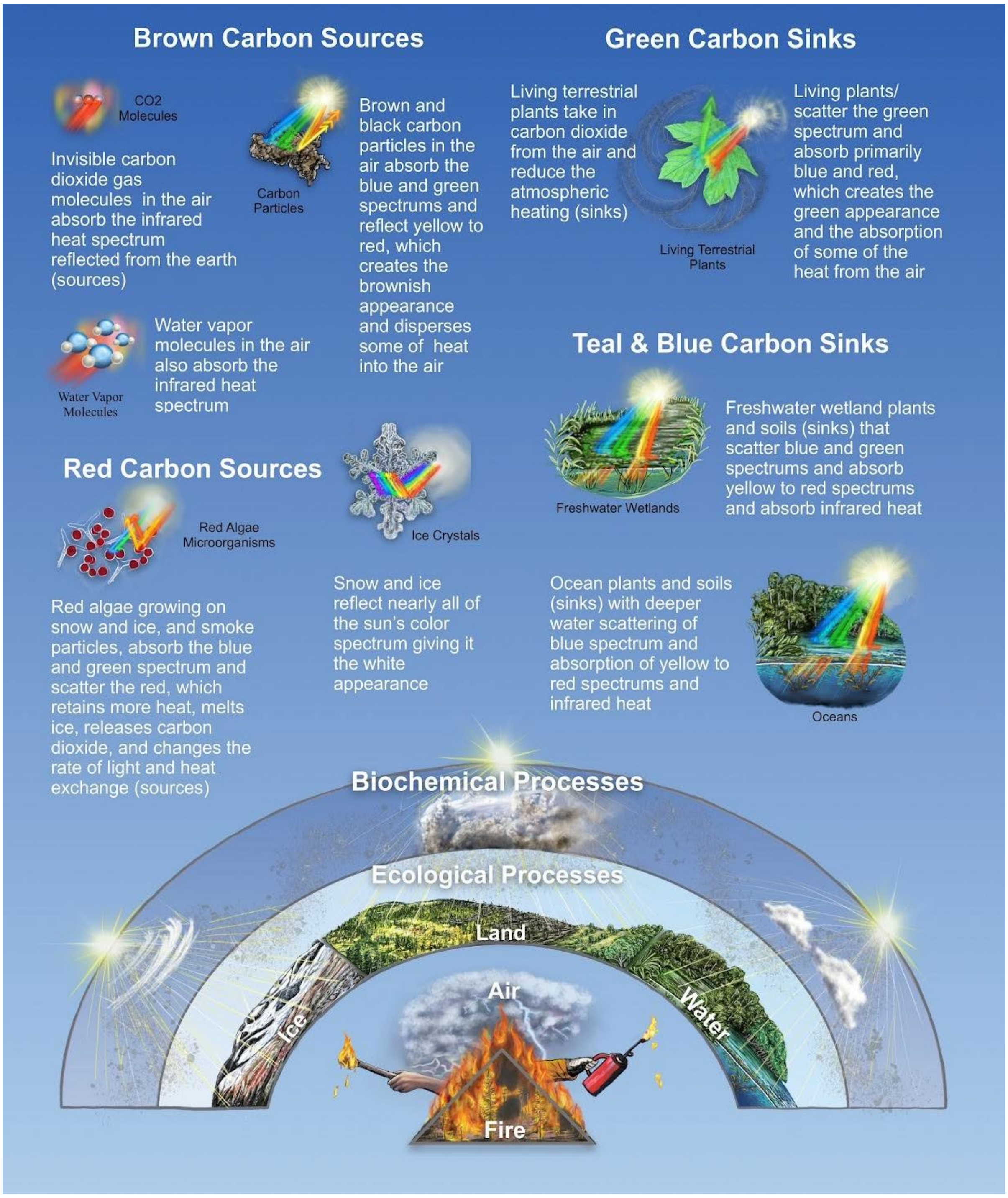
Some of these indirect interactions involve complex interactions between different components of the Earth System often over large distances that, while critical to how the Earth System is evolving, are extremely challenging to represent, model, and quantify, and often require interaction between different research disciplines and a holistic study approach.

The impacts of black carbon aerosol originating from a fire, for example, are observed across a range of distances from the fire. During transport, black carbon can warm the atmosphere by absorbing solar radiation and cool the atmosphere by acting as the seed for cloud droplet formation and thus increase cloud albedo. Once black carbon is deposited on ice or bare ground it can lower surface albedo[8,64]. Conversely, other aerosols emitted in a fire may counteract the effects of black carbon. For instance, organic carbon aerosols scatter incoming solar radiation while nutrient-bearing aerosols, like phosphorus or iron, can stimulate land and/or ocean primary production upon deposition. The indirect link to the carbon cycle being that fire can alter many aspects of the local environment, for both land and ocean biota, with a potential to change productivity and thus the carbon cycle. Furthermore, peat and permafrost act as huge carbon stores that are potentially at risk from changes in fire regimes[65] and will likely see major increases in burning over the next few decades[36]. Fires can act as a major driver of permafrost thaw, and a combination of climate warming, reduction in precipitation, and anthropogenic drainage can lead to increases in peatland burning.

Despite the many complex interactions fire has throughout the Earth System, fire is often viewed only as a negative and destructive process and one that solely acts as a source of atmospheric carbon. However, fire is a vital part of the healthy functioning of ecosystems, and many plants have evolved adaptations to – and indeed are reliant on – fire. For example, seed dispersal and resprouting in some species require heat from a fire to regenerate and reproduce[66–68]. Fire can also affect carbon allocation in plants, which influences heterotrophic respiration. When fire regimes change, these adaptations no longer confer an advantage, impacting carbon resilience and recovery after fire. This can be seen during and after an extreme fire event (**Challenge 2**), but also under reductions in fire. Well-intended human intervention to reduce fire in sensitive biomes or to decrease fire risk to humans can thus have unintended and significant negative consequences on vegetation and ecosystem health and hence the stability of carbon storage. Also, despite improved observations (Shen et al., 2023; Clarke et al., 2013), these crucial aspects of fire ecology and the impact on fire emissions and post-fire carbon recovery are largely unrepresented in models (Kelley & Harrison 2014).

In terms of the role of fire in carbon budget, the release of carbon only represents the very initial stages of the story, missing all the ways in which fire shapes carbon sequestration over different spatiotemporal scales, including vegetation regrowth, deposition of stable carbon particles (such as pyrogenic carbon), soil microbial enhancements, and post-fire nutrient fertilisation within remote terrestrial and marine ecosystems. Many of these processes can be important for carbon sequestration. For example, between 5% and 25% of all biomass burned is converted to pyrogenic carbon[69], and up to half of that pyrogenic carbon can remain stable in the long-term[70]. Globally, there is an estimated 200 Pg pyrogenic carbon in the top 2 m of soil[71] resulting from an annual production of 196–340 Tg pyrogenic carbon/year[72]. There is a clear need, therefore, to fully understand the role of fire in the carbon cycle in a holistic Earth System manner – one that explicitly considers different ecosystem dynamics and interactions with the Earth's energy budget over a wide variety of timescales (**Figure 4**).

Here we propose that the visualisation of carbon colours across the Earth System, incorporating a "rainbow effect", can be a thematic tool for unifying disciplines (**Figure 5**). Inspired by the USGS carbon rainbow, we recommend a modified visual theme that is rooted in information on each carbon colour category and its relevance to climate science with the goal to enhance transdisciplinary fire science. We suggest employing a carbon colour spectrum in relation to the solar light spectrum and heat exchange between air, land, and water. This broader thematic approach allows for the integration of water, clouds, and albedo into the fire cycle, establishing better visual connections with carbon sources and sinks, exploring both positive and negative aspects of fire and smoke within the light spectrum and living systems. For instance, examining the role of carbon particles in directly modifying the atmospheric energy budget with downstream impacts such as diffuse aerosol radiative processes altering photosynthesis rates within lower canopy vegetation. Different terrestrial, snow/ice, and aquatic systems are acknowledged for their distinct light, heat absorption, and reflection characteristics, also interacting with the carbon in smoke and ash.



**Brown Carbon Sources**

Invisible carbon dioxide gas molecules in the air absorb the infrared heat spectrum reflected from the earth (sources)

Brown and black carbon particles in the air absorb the blue and green spectrums and reflect yellow to red, which creates the brownish appearance and disperses some of heat into the air

Water vapor molecules in the air also absorb the infrared heat spectrum

**Red Carbon Sources**

Red algae growing on snow and ice, and smoke particles, absorb the blue and green spectrum and scatter the red, which retains more heat, melts ice, releases carbon dioxide, and changes the rate of light and heat exchange (sources)

Snow and ice reflect nearly all of the sun's color spectrum giving it the white appearance

**Green Carbon Sinks**

Living terrestrial plants take in carbon dioxide from the air and reduce the atmospheric heating (sinks)

Living plants/ scatter the green spectrum and absorb primarily blue and red, which creates the green appearance and the absorption of some of the heat from the air

**Teal & Blue Carbon Sinks**

Freshwater wetland plants and soils (sinks) that scatter blue and green spectrums and absorb yellow to red spectrums and absorb infrared heat

Ocean plants and soils (sinks) with deeper water scattering of blue spectrum and absorption of yellow to red spectrums and infrared heat

**Figure 4: Examples of fire-related carbon sources and sinks and their diverse interactions with the Earth's energy budget.** Schematic drawn from the discussions held during the workshop. Fire ignitions highlight examples of both natural (lighting) and human (fire brand and drip torch) sources.

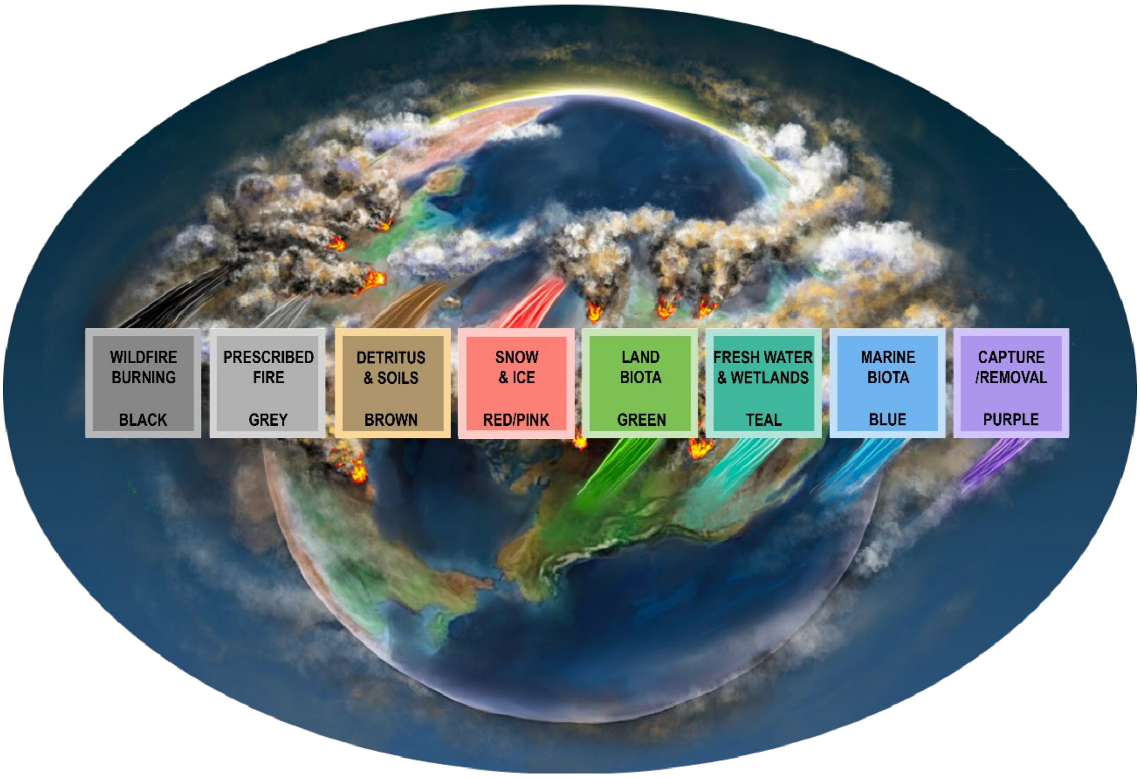


**Figure 5: Shining a light on the role of fire in the global carbon cycle.** To establish a cohesive relationship between carbon colours and their representation in transdisciplinary fire science, as well as their connection to human understanding akin to a rainbow, a depiction of the Earth was rendered with a series of boxes symbolising the “primary” carbon sources and sinks. The term “primary” is employed to denote key carbon cycle elements while also referencing predominant colours. Each source is accompanied by a colour band extending into the atmosphere, while each sink is portrayed with a corresponding colour band extending below into the Earth System. The “snow and ice” box represents fire-cryosphere sensitive processes such permafrost thaw and the role of black carbon in icesheet retreat, subsequently exposing the land and a reduction in pink algae that live in these frozen environments. The depiction includes clouds and smoke, helping associate carbon sources with their interaction within the atmosphere.

While there are impacts of fire on the carbon cycle that require transdisciplinary collaboration to help understand the processes, drivers and actors involved. To highlight this need, here, we go stepwise through some examples that span the interfaces between the land, atmosphere, ocean, and policy domains.

**How does fire impact the ocean carbon cycle?**

- Starting with the burn itself, we need to know how much vegetation of different types was consumed, an estimate of the biomass nutrient content, and the intensity of the fire to inform/estimate the plume height and its temporal dynamics.
- The injection of material into the atmosphere influences dispersal distance, trajectory, and lifetime in the atmosphere. We also currently have large uncertainties associated with the relative contribution of dust (soil) aerosol to total aerosol during and post-fire events.
- The next step to understand is the transport of the fire plume and its chemical transformation while in the atmosphere, affecting the bioavailability of nutrients contained in aerosols.
- Nutrient-bearing aerosol are then deposited onto ice or into fresh or ocean water bodies, via aerosol settling or precipitation, passing through a complex organic film at the ocean-air surface before becoming available in the ocean column for phytoplankton use.
- The final step is an understanding of the potential for a fire aerosol to induce a phytoplankton bloom, and the associated impacts on the marine food web and oceanic carbon storage.

Understanding all these processes requires a synergy between land-based fire researchers, atmospheric scientists, Earth System modellers, observation scientists, and ocean biogeochemists at the very minimum.

**What is the role of fire in relation to climate mitigation policy?** When assessing the role of fire in the carbon cycle, it is essential to address the impact of fire processes (natural and anthropogenic) not just from the scientific perspective but also in the context of climate mitigation strategies including REDD+ (Reducing Emissions from Deforestation and Forest Degradation), the Glasgow Declaration on Forests and Land Use (https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/) and carbon credit calculations[36]. These policy statements and strategies aim to reduce carbon loss or restore carbon from many of the world's forests, generally need very detailed information in spatial and temporal resolution terms that is not the same as that used in global or regional budget calculations and are open to interpretation which has consequences for the carbon cycle[73].

These mitigation strategies also do not expressly consider fire as either an environmental process or a threat. As a result, mitigation schemes can lead to negative environmental consequences if implemented without caution; complete avoidance of fire can lead to overgrazing or fuel build-up, planting trees in inappropriate locations to restore carbon can lead to excessive fuel and more extreme fires and planting the wrong type of trees or not avoiding deforestation of natural forest assemblages may lead alteration in the established fire regime. Improving the methodology for assessing and understanding fire risks and requirements in different regions and ecosystems is essential to support global emission reduction goals and initiatives.

In addition to addressing the role of fire processes in mitigation schemes, there is also a need to ensure regional and global budgets incorporate mitigation schemes in their calculations and permit the impact of these schemes and their effectiveness to be quantified. Here, it is important to create links with Global Carbon Project activities (https://www.globalcarbonproject.org/), to define a 'budget of disturbance' not just on fire but also on other disturbances likely to affect mitigation schemes and to understand the feedbacks between disturbance processes such as insects, windthrow, dieback, and fire.

**Influence of fire on the carbon cycle and its implications for human activities and the environment**. The overall influence of fire on the carbon cycle and its implications for human activities and the environment also require social scientists and close communication with society and stakeholders. The relationship between people and fire is complex but understanding our interactions with fire is vital for fully comprehending fire in the Earth System and specifically on the carbon cycle. For example, people act as drivers of change in fire regimes through ignitions, suppression, land-use change, prescribed burning, and climate change.

Conversely, fire also affects people and the landscapes we manage in both positive and negative ways. As a result, a holistic understanding of how fire influences different components of the carbon cycle cannot be achieved without bringing biophysical, ecological, and social science communities and researchers together with stakeholders. Such collaboration holds potential for better comprehending fire-associated carbon emissions, their measurement, and their resonance with the environment and socio-cultural practices. Science needs to work proactively (within a reasonable time frame) to inform the management of fire events and related carbon emissions and assess human activities' impact on fire dynamics.

## Challenge 2: Fire and Extreme Events

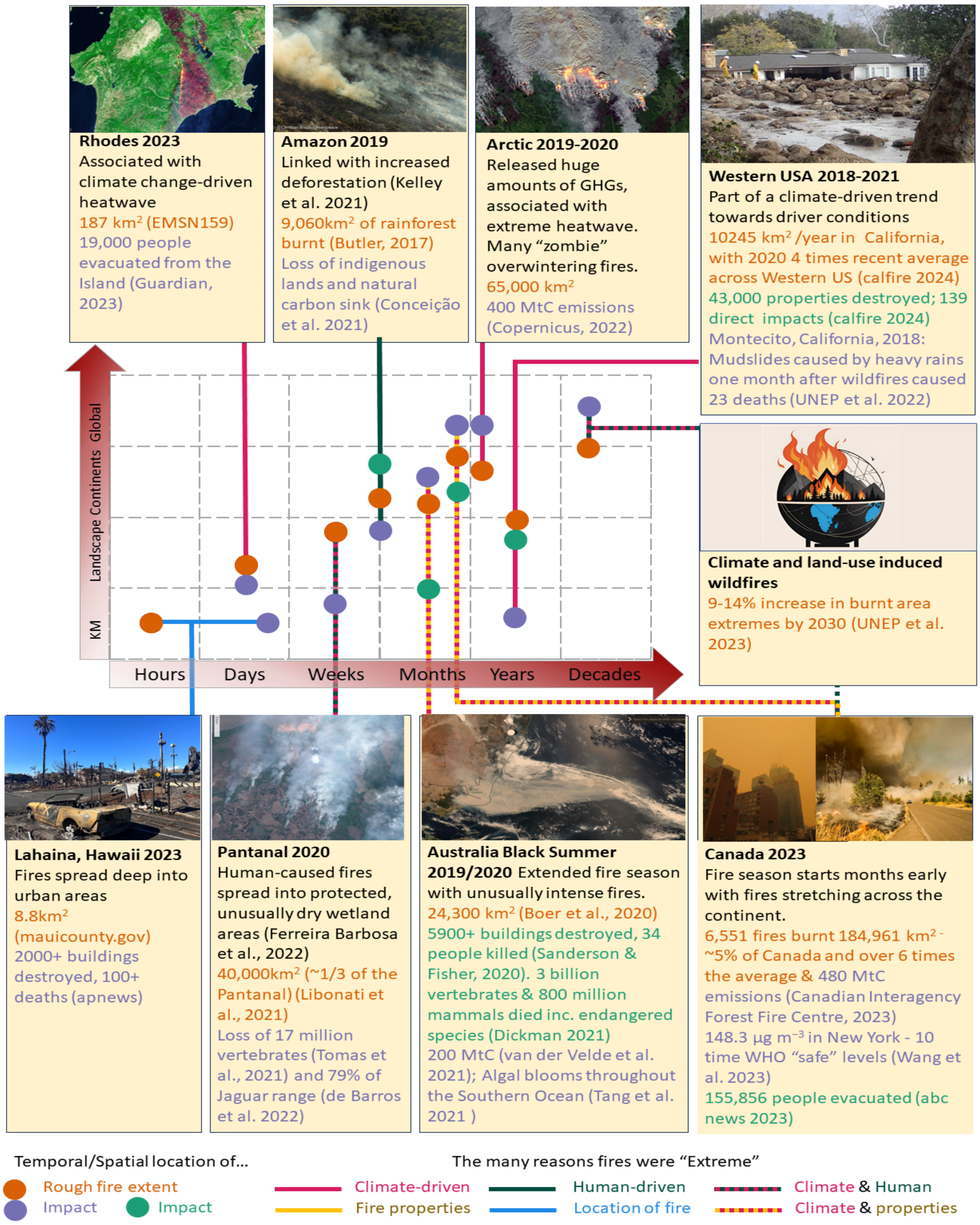
### Priority Questions decided by FLARE working group participants:

1. **What is an extreme fire event, and can we systematically define it? Should we?**
2. **How do fire-extreme events impact society and the Earth System, including plant communities, weather properties, air quality, and regional fire risk?**
3. **What climate model developments are needed to improve capability of fire models in capturing the strength and variability in extreme fire events?**
4. **How do extreme fire events influence carbon dynamics, both locally and globally, and what is their significant contribution to the global carbon budget?**

In recent years, the frequency and intensity of large-scale fire incidents have left an indelible mark on societies and ecosystems across the globe[36], exemplified by occurrences in Australia (2019-2020), the Amazon Forest (2019, 2020, 2022), the Arctic (2019, 2020), Hawaii (2023), Western US (2018-2021), the Mediterranean and across Europe (2022/2023), and in many more places (**Figure 6**). The manifestation of extreme fire events has become an alarming reality. Navigating the intricate web of factors contributing to these events, including climate change, human activities, and the complexities of attributing causality, presents a formidable challenge. Yet as the devastating impacts on communities and natural environments now repeat each year, the urgency to understand, define, and effectively address extreme fires has never been more pressing.

We must first identify what an “extreme” fire is and when it occurs. Different factors such as human activity, vegetation and climate can all impact the severity of fires in various regions, which can vary seasonally, annually, and decennially (decadally). Therefore, it is challenging to discern the influence of interannual variability from the impact of long-term landscape and climate changes on extreme fire occurrences. This complexity becomes a focal point for those hesitant or sceptical about attributing an individual fire event to climate change, especially given the observed decadal global mean decline in total burnt area from regular “non-extreme” fires. Therefore, it's crucial to have a nuanced understanding of how natural variability, climate change, and human activity interact to influence extreme fire occurrences across spatiotemporal scales.

When describing a fire, the word “extreme” needs to be clarified and, where possible, quantified, in context with specific aspects of the fire regime. A common and intuitive definition of extreme is the examination of the tails in a probability distribution (**Figure 7**). For instance, in the case of fires, this can involve looking at 1-in-*nyear*s events (e.g., 1-in-10, 20, or any other *nyears* of interest) likelihood of the fire weather index or burnt area under historic or pre-industrial climate. While this approach is useful for measuring the probability of changes in large fires on a broad scale, it fails to capture the diverse ways fires and their impacts can be extreme. “Extreme” can apply to both large and small-scale fires, from prolonged fires that consume vast areas of land, ignite vegetation, and release large amounts of carbon over several months or years to intense, yet sometimes small-scale, fires that spread rapidly and cause devastation to communities and infrastructure within a shorter period of hours to days. Furthermore, as fire events increasingly affect human well-being and economies, they are simultaneously gaining increased traction in a wide variety of media. The phrase "extreme fire events" has become prevalent in scientific and public media discourse. However, defining a globally “extreme” fire remains elusive in current scientific understanding. In this context, one would be right to ask what the meaning of “extreme” fire is on a global scale. "Was this an extreme year for fire globally?" is a common question asked to scientists almost annually as high-impact, headline-grabbing fire events start to happen each year. And one that we have not yet learned how to answer effectively.



**Rhodes 2023**
Associated with climate change-driven heatwave
187 km$^2$ (EMSN159)
19,000 people evacuated from the Island (Guardian, 2023)

**Amazon 2019**
Linked with increased deforestation (Kelley et al. 2021)
9,060km$^2$ of rainforest burnt (Butler, 2017)
Loss of indigenous lands and natural carbon sink (Conceição et al. 2021)

**Arctic 2019-2020**
Released huge amounts of GHGs, associated with extreme heatwave. Many "zombie" overwintering fires.
65,000 km$^2$
400 MtC emissions (Copernicus, 2022)

**Western USA 2018-2021**
Part of a climate-driven trend towards driver conditions
10245 km$^2$ /year in California, with 2020 4 times recent average across Western US (calfire 2024)
43,000 properties destroyed; 139 direct impacts (calfire 2024)
Montecito, California, 2018: Mudslides caused by heavy rains one month after wildfires caused 23 deaths (UNEP et al. 2022)

**Climate and land-use induced wildfires**
9-14% increase in burnt area extremes by 2030 (UNEP et al. 2023)

**Lahaina, Hawaii 2023**
Fires spread deep into urban areas
8.8km$^2$ (mauicounty.gov)
2000+ buildings destroyed, 100+ deaths (apnews)

**Pantanal 2020**
Human-caused fires spread into protected, unusually dry wetland areas (Ferreira Barbosa et al., 2022)
40,000km$^2$ (~1/3 of the Pantanal) (Libonati et al., 2021)
Loss of 17 million vertebrates (Tomas et al., 2021) and 79% of Jaguar range (de Barros et al. 2022)

**Australia Black Summer 2019/2020** Extended fire season with unusually intense fires.
24,300 km$^2$ (Boer et al., 2020)
5900+ buildings destroyed, 34 people killed (Sanderson & Fisher, 2020). 3 billion vertebrates & 800 million mammals died inc. endangered species (Dickman 2021)
200 MtC (van der Velde et al. 2021); Algal blooms throughout the Southern Ocean (Tang et al. 2021 )

**Canada 2023**
Fire season starts months early with fires stretching across the continent.
6,551 fires burnt 184,961 km$^2$ - ~5% of Canada and over 6 times the average & 480 MtC emissions (Canadian Interagency Forest Fire Centre, 2023)
148.3 µg m$^{-3}$ in New York - 10 time WHO "safe" levels (Wang et al. 2023)
155,856 people evacuated (abc news 2023)

**Figure 6: Examples of recent fires characterised as extreme in media and/or scientific reports and their impact across different spatial and temporal scales.** Extreme fire can happen over hours to years, affecting local people, ecology, oceans and other spheres of the Earth System. The colour of a dot links to the colour of text. Orange dots in the scatter plot show the scales/regions the extreme fire occurred. Sometimes, burnt areas can be distributed over many regions or countries, such as in the Amazon in 2019, while higher burnt areas can be more restricted with a single landscape or ecosystem, such as the Pantanal in 2020. Purple and green dots indicate the scales of their associated impacts (two colours as there can be >1 impact - see figure text for details). Bar colour represents the reason for the fire being considered extreme; however, even these categorizations (scales, climate or human driven, fire properties and location) capture only a subset of ways we see extreme burning.

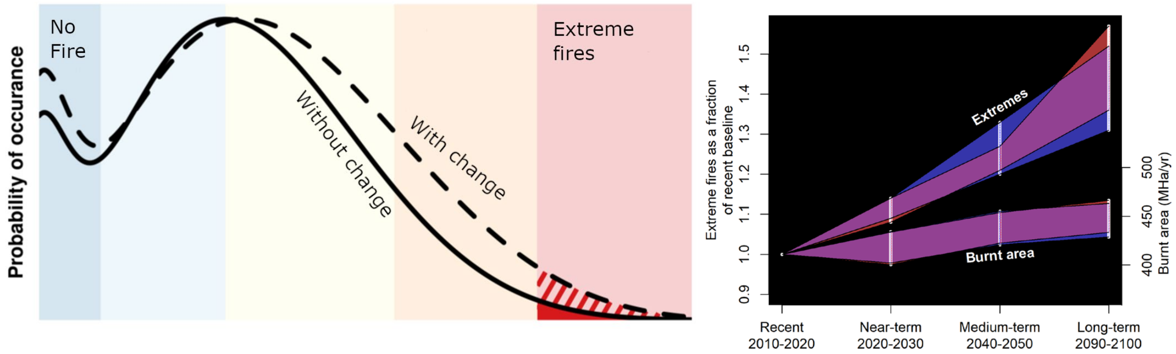


**Figure 7: Extreme fire occurrence.** The probability of extreme fire occurrence increases with human modification of the climate (left). The distributions can relate to space and/or time, depicting either the likelihood of an event over a given area at a point in time (e.g., for event attribution) or the frequency of different fire extremes occurring over a specified period (e.g., over 10 years). This relationship is often represented through probability distributions of different burning levels. The distribution relates various fire drivers to different likelihoods or frequencies of burning levels on the x-axis. The interpretation of extreme fire occurrences regarding spatial and temporal aspects will be further elaborated in the accompanying text. The presence of "no fires" in the distribution is due to the stochastic nature of fires. Sometimes, even under ideal burning conditions, no fires occur due to complexities such as the co-occurrence of ignitions, fuel availability, and wind conditions as considered within the observational or model framework. Modelling experiments can probe how the distribution tails (an extreme event) are influenced with and without changes in climate, land use, or other environmental conditions. The UNEP "Spreading Like Wildfire" report utilised this methodology in determining that global mean burnt area is likely to increase minimally in future decades, but extreme burnt area events (defined as a 1% likelihood of occurrence under present-day climate conditions) will likely increase by 1.4-1.5 times by the end of the century (right). The increase rate depends on the forcing level: RCP6.0 (red); RCP2.6 (blue). Analysis by Douglas I Kelley, Chantelle Burton, and Camila Mathison (UK Met Office). See UNEP et al. (36) appendix and https://ukesm.ac.uk/portfolio-item/likely-futures-of-global-wildfires/ for details.

Determining whether a year is extreme for a given fire event depends on various factors, including the observational scale, impacts on human health and infrastructure, firefighting resources and availability, and natural variation and event predictability. The interpretation also hinges on perspectives, impacts, and how society copes with the fire. Potential impacts include shifts in plant communities, atmospheric and weather alterations, increased air pollution risk on human health, infrastructure damage, mental health consequences, and long-term socio-economic repercussions.

For instance, during the 2019 and 2020 Northern Hemisphere summers, hundreds of fires burned across Siberia and Alaska, releasing over 400 $MtCO_2$ into the atmosphere[74]. In 2023, the Canadian fires contributed to the release of 480 MtC, approximately a fifth of that year's global fire emissions. On the other hand, the 2023 Hawaiian fires were most devastating within just a few hours on August 8th, when high winds pushed intense flames into Lahaina, resulting in over 100 deaths and destroying over 2000 properties. In some cases, events combine both scales, such as the Australian fires during the Austral Summer of 2019/2020. These fires were the most extensive in recent history[75], and many fast-moving individual fires destroyed over 5900 buildings, killing at least 34 people[76]. But the later fire season also had substantial impacts on the Earth System through large carbon and aerosol emissions (**Challenge 1**).

What constitutes extreme can also be less obvious, but in ways that still have a large impact. Last summer's Canadian fires highlighted a shift in fire seasonality, which is a trend seen in many parts of the world[18], with large fires occurring weeks or months earlier than previously seen. This can lead to more destructive early burns occurring as typical fire management plans, such as prescribed burns, may not yet be applied, and wear out of person-power later in the year or stretching of limited resources for firefighting. Extreme impacts can also happen away from the fire's source, such as air quality degradation after the 2023 summer Canadian fires impacting residents in US cities, and the Amazonia 2019 deforestation fires, where smoke reached cities as far as São Paulo, more than 2700 km away[77]. They can also happen over periods beyond the fire, such as post-fire flooding in California[78] and increased river pollution from Amazon deforestation extremes[79]. The 2019-2020 Australian fire season was linked to increased nutrient supply through the emission of aerosols which have fuelled ocean productivity across the Southern Pacific (**Challenge 1**).

While the term "extreme" often carries negative connotations in relation to fires, it's essential to recognize that fire has historically been a critical part of natural cycles in many ecosystems worldwide, operating before human intervention. But this natural cycle is undergoing alterations or disappearing in many locations. Understanding historic fire regimes – the recurring patterns, frequencies, and characteristics of fires in a specific area or ecosystem over time, including seasonality, intensity, and human/ecological impact – is vital for evaluating if future fire projections fall outside the typical range of burning. This broader historical perspective, including periods such as the Holocene thermal maximum (~7000 years ago) or previous interglacial periods, provides invaluable insights into long-term fire dynamics and ecosystem responses. Such an approach aids in contextualising present-day extremes within the context of Earth's historical fire-climate relationships and understanding the potential impacts of future changes on fire occurrence and propagation. This is also vital for comprehending the broader implications of wildfires on biodiversity and landscape dynamics, including ecosystem and carbon resilience and recovery after a fire.

A formidable challenge for fire science is improving the accuracy in attributing the influence of both direct and indirect human activity and climate on the occurrence and propagation of extreme fires. Current fire models do not include all facets of the fire regime, thereby limiting the data needed for a detailed attribution of different drivers of extreme fires. Underutilised fire observations, including ecological data and ground-based firefighting records, are essential for contextualising extreme fires[56]. Paleodata, sourced from sedimentary charcoal records, pollen, and tree rings, offer insights into historical fire regimes beyond contemporary observations. Integrating these records with simulations aids in situating present-day extremes within the context of Earth's historical fire-climate relationships, including periods such as the Holocene thermal maximum (~7000 years ago) or previous interglacial periods[24,80,81]. Advancements in modelling and statistical techniques, such as machine learning and Bayesian Inference, help to identify broad-scale drivers of fire extremes. The effectiveness of such techniques relies heavily on the quality and robustness of the datasets used, emphasising their significance in addressing the complexities of extreme fire occurrences[29,33,55,62].

While these tools offer invaluable insights into drivers of recent extremes, we still lack the details required to determine exact, policy-relevant drivers or actions to assess specific future adaptations[29,36,42,82]. The increasing urgency to evaluate and inform the management of these fires highlights the complex interplay between anthropogenic factors and climate-induced conditions. The intricate relationship between these factors necessitates a holistic approach to understanding the dual influence of human actions and climate on the evolving nature of extreme fire events.

Fire is woven into a complex web of interdependencies with other extreme events, creating a dynamic, interconnected system. Changing patterns in drought and heat waves influence the onset and magnitude of a fire, as these environmental factors contribute to a heightened susceptibility of landscapes to ignition and rapid spreading of fire. In turn, the aftermath of a fire, marked by the removal of vegetation, sets a stage for secondary hazards. The diminished capacity of burned landscapes to absorb and mitigate water flow increases the likelihood of soil erosion, exacerbating the risk of landslides. Simultaneously, the increased runoff from rainstorms in the absence of vegetation cover intensifies the potential for flooding downstream[78] and degrading water quality[83]. These compound extreme events pose a heightened risk to the resilience of both human societies and natural ecosystems. Understanding these interdependencies is crucial for developing effective mitigation and response measures that address the multifaceted impacts of these compound extreme events on landscapes, communities, and the broader ecological balance.

The escalating frequency and intensity of large-scale fire incidents present a multifaceted challenge that extends beyond ecological impacts to societal well-being and economic stability. As we navigate the complexities of attributing extreme fire events to a changing climate and various drivers, it becomes evident that the term 'extreme' itself requires contextual clarification. From prolonged fire seasons consuming vast landscapes to rapid, intense blazes devastating communities; the spectrum of extreme fire defies a one-size-fits-all definition. The evolving nature of fire regimes, coupled with their intricate interdependencies with human activities and climate dynamics, underscores the urgency for transdisciplinary research. By incorporating insights from paleodata, ecological records, ground observations alongside remote sensing, and advanced modelling techniques, we may yet gain a more comprehensive understanding of extreme events in an extended time-scale context. However, the fire science community has still to find an effective way to ascertain and communicate useful information on extremes – a problem that occurs almost every year. This problem is becoming bigger than the community available to tackle it, and as well as working together, education and training for the next generation of fire scientists is critical for us to catch up. As we brace for the future, informed by the lessons of the past, addressing the complex interplay between anthropogenic factors and climate-induced conditions becomes paramount. Only through proactive efforts in research, public awareness, and effective policy-making can we strive towards mitigating the many impacts of extreme fire events on ecosystems, communities, and the broader ecological balance.

## Challenge 3: Fire's Interaction with Humans

### Priority Questions decided by FLARE working group participants:

1. **What are the long-term consequences of wildfire suppression policies on ecosystems, including biodiversity and the carbon cycle? Is this policy sustainable in the context of global change?**
2. **How do prescribed fire, farming fires, and fire protection practices impact local ecosystems and the carbon cycle?**
3. **How do we convert modelling output into applicable field solutions to fire management?**
4. **How best to incorporate local knowledge into global fire dynamics?**
5. **To what extent can the diversity of human impacts be translated into models at both regional and global scales?**

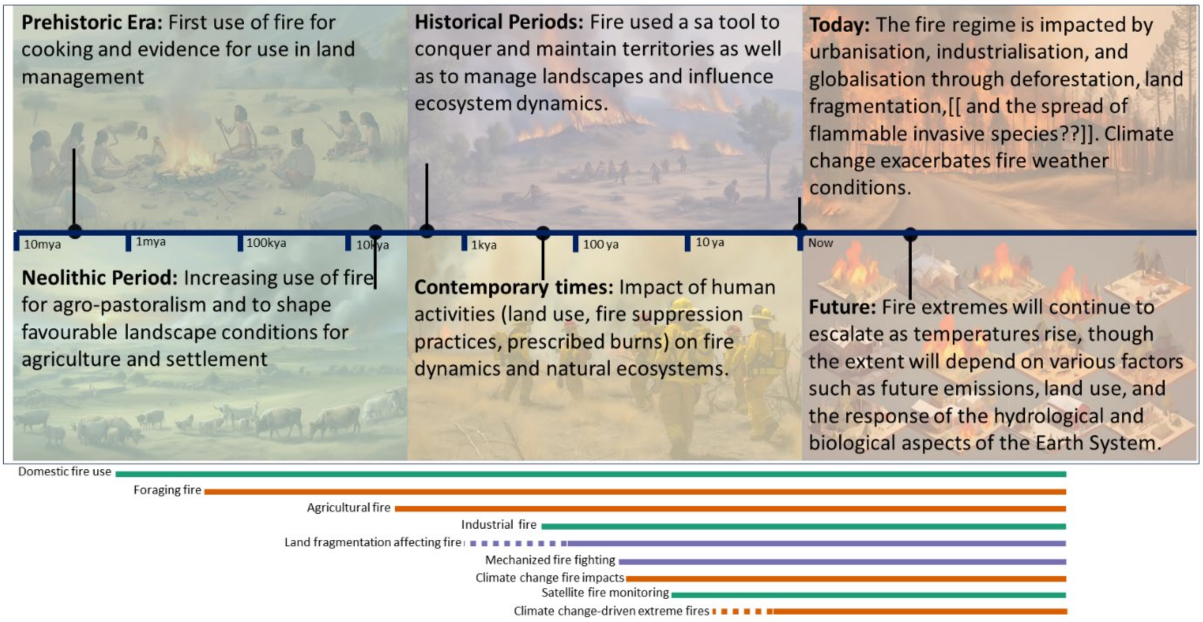
Fire is an integral aspect of human experience, spanning hundreds of thousands of years. Regardless of the chosen region, compelling evidence reveals the historical use of fire by humans[84]. Originally serving basic needs like heating and cooking, fire swiftly transformed into a tool for shaping, transforming, and controlling the surrounding environment. Fire allowed humans to modify the dynamics of local vegetation, facilitating easier access to attractive environments and promoting the dynamics of certain plant resources and game. In contemporary times, human activities significantly impact the distribution, timing, and variability of fire event characteristics across the world, including incidence, size, severity, and duration. As a tool, vegetation fire plays a pivotal role in creating and sustaining intentionally designed ecological niches by human groups. Yet, despite the increasing influence of humans on global fire dynamics through time, quantitatively characterising the role of humans in fire science remains challenging due to numerous aspects that defy straightforward statistical assessment or process modelling.

Prior to the establishment of permanent settlements by human populations and the adoption of agriculture in the Neolithic period, the use of fire by human populations, whether in open ecosystems such as grassland or savannah, or in more forested ecosystems, is relatively difficult to identify, characterise, and quantify. Substantial changes in the fire regime without any change in environmental conditions (i.e., climate and land cover), but contemporaneous with new forms of human occupation, may be an indirect indication of the role of these populations.

Evidence becomes clearer with the emergence of Neolithic cultures when data is most consistent with the environmental use of fire by human populations. For example, seven to eight thousand years ago in Europe a reversal in climatic dynamics has been clearly recorded in temperature reconstructions and ecosystem dynamics. While data shows that climatic changes made conditions less favourable for fires, sedimentary signals from this period reveal more frequent fires concurrent with population expansion. This led to a change in the fire regime, with less biomass burned but about a doubling in the frequency of events. Managing and controlling the environment using fire evolved during Protohistory, and historical periods as practices, objectives, and environmental conditions (including climate) changed. The use of fire shifted from conquering new territories to maintaining them, with practices fluctuating based on regional histories, demography, and the differing ecosystem constraints faced by populations.

Fire in the Anthropocene is fundamentally a socio-ecological phenomenon. For example, an estimated eighty-four percent of fires in the United States are ignited by humans[85] and human intervention on the landscape through activities such as land use and management practices, fire suppression, and prescribed and cultural burning can significantly alter climate-driven fire regimes. Human efforts to suppress wildfire's impact on landscapes and communities can however result in more destructive fire behaviour and escalating fire risk[86]. In short, humans, advertently and inadvertently, are increasingly dominant factors in explaining whether, when, and the frequency that fire occurs, how large and intense fire ignitions become, and what type of fuel is subsequently consumed even before considering humans' role in climate change. As a result, efforts to forecast the future impact of fire on the global carbon cycle require analysts to make educated guesses about what humans are going to do, how communities and governments will respond, and how this activity will affect fire regimes now and in the future.

The societal and economic impacts of fire need to be considered. To achieve this, it is crucial to hear the voice of people and communities exposed to fire, including Indigenous groups, farmers, fire-exposed communities, ground-based firefighting organisations, field researchers from a diverse range of countries where fire is a major seasonal event, and other key stakeholders such as grassroot organisations. When building such discussions, ensuring that low-income countries are represented equitably, and their knowledge is shared and accredited fairly is also important. Throughout the process, it is essential to use the FAIR (findable, accessible, interoperable, reusable) and CARE (collective benefit responsibility) principles to democratise the accessibility to fire research. By doing so, fire researchers can better ensure that fire research is relevant and actionable at large. Additionally, such transdisciplinary interaction efforts for knowledge generation will be transferred to the next generation of fire scientists, stakeholders, and the public.



**Prehistoric Era:** First use of fire for cooking and evidence for use in land management

**Historical Periods:** Fire used a sa tool to conquer and maintain territories as well as to manage landscapes and influence ecosystem dynamics.

**Today:** The fire regime is impacted by urbanisation, industrialisation, and globalisation through deforestation, land fragmentation,[[ and the spread of flammable invasive species??]]. Climate change exacerbates fire weather conditions.

**Neolithic Period:** Increasing use of fire for agro-pastoralism and to shape favourable landscape conditions for agriculture and settlement

**Contemporary times:** Impact of human activities (land use, fire suppression practices, prescribed burns) on fire dynamics and natural ecosystems.

**Future:** Fire extremes will continue to escalate as temperatures rise, though the extent will depend on various factors such as future emissions, land use, and the response of the hydrological and biological aspects of the Earth System.

**Figure 8:** Timeline of human interactions with fire.

As part of the discussion on human impacts of fires, the perception of an extreme event needs considering (**Challenge 2**) and this can often differ between the local population affected by the fire and a global perspective based on the extent of the burned area or the magnitude of fire emissions. Using 2023 as an example, while fire events like Lahaina (Hawaii) and Rhodes (Greece) left devastating local impacts on society and ecosystems, their limited influence on the global carbon budget and the absence of a large-scale ecosystem response may not warrant their classification as “extreme” on a global scale. Conversely, 2023 fires across Canada, with global consequences on the carbon cycle and substantial ecosystem responses, could be considered as “extreme” on a global scale. Though they led to large evacuations and losses to the economies, the death toll in themselves was not as extreme as in Hawaii. Under these different perspectives, the notion of an “extreme” fire year for 2023 is hard to determine when considering all these fires collectively. It also prompts the question of the period for assessing a “baseline” for fire activity in highly fire-prone regions with fire-return intervals extending beyond satellite, and the human lived experience of a few decades.

Perhaps the most evident health risk of fire for humans is smoke, a public health and regulatory issue for most communities and countries. Smoke from wildland fires is an acute form of air pollution that can be seen as a product of a natural disaster. On the other hand, smoke from prescribed burning can be seen as a more avoidable incidence, whereby burners have more (albeit not total) agency in preventing smoke from impacting communities. There is also an enforcement issue, while governments may ban prescribed burning for improved air quality, farmers may not comply with regulations. For example, in India 44 to 98 thousand premature deaths per year are attributed to smoke inhalation from prescribed burning, despite government bans on the practice. It is currently unclear how smoke emissions will change and affect air quality under future climate change scenarios, and there are many ever-evolving variables that will affect future emissions. This is because smoke emissions are governed by several variables that will continue to evolve as the climate changes, including fuel source, meteorological conditions, and burn intensity. There have been substantial improvements in fossil fuel related air quality across the US and Europe over recent decades. However, these gains are likely to be offset by the increasing number, size, and severity of wildfires in coming decades[87–89]. Fire mitigation practices like prescribed burning may also affect the total magnitude of smoke emissions and alter composition. For example, to help combat increasing fires the United States Forest Services is planning to burn over 20 million acres over the next 10 years (USFS, 2022), but how prescribed fires impact wildfires and their emissions has yet to be quantified. These confounding factors impede the ability of researchers to predict future air quality levels and protect human health accurately.

In addition to $PM_{2.5}$, fire emissions are a source of many other pollutants including $NO_2$ and NO and, through formation processes, ozone that negatively affect human health. In addition, increases in other toxic compounds such as lead, mercury, and other gas-phase hazardous air pollutants have been observed in fresh and aged wildfire smoke[90–93]. For example, hexavalent chromium, a known carcinogen, has also recently been shown to be present in wildfire ash and may be present in smoke[94]. Additional research is needed to quantify the presence of these toxic compounds in emissions near the fire and in long-ranged transported smoke to understand the potential human and public health effects of rising fire activity.

How do we represent human fire use in interactive fire models beyond population density-dependent ignition functions? Such efforts must consider human impacts on the landscape, such as fragmentation, forest structure, speciation, fuel and land management practices, roads, logging, dams, etc., both legal and illicit.

Incorporating the human dimension into a global assessment of the impact of fire on the carbon cycle (**Challenge 1**) requires us to delve deeper into characterising socio-cultural norms, assessing the impact of humans as causers and managers of fires, and understanding the role of humans in maintaining ecosystems using fire. Humans can also be drivers of fire extremes, as highlighted during the 2019 Amazonia fires while management may help us mitigate and adapt to the projected increase in global extreme events.

As fire science is applied in diverse contexts, policymaking is an illustrative example of its practical use. When integrating the human component into fire modelling frameworks, it is crucial to consider how scientific insights can be effectively translated into policies. This involves addressing differences in the temporal and spatial scales at which each operates; policies may be operating on different timeframes and geographical extents than observational studies or modelling. Policies often operate on a comparatively shorter temporal scale, necessitating a case study framework that spans local to global contexts and subsequently circles back to local considerations. This cyclic approach allows for a nuanced understanding of policies' varied impacts and implications in different contexts, enforcement capability, and human behaviour change. Conversation across partnerships becomes paramount, facilitating a collaborative and transdisciplinary exchange of knowledge that appreciates the multifaceted nature of challenges and solutions related to increasing fire risk. Moreover, community engagement emerges as an additional aspect of this process, providing valuable insights and lessons that can help inform policy formulation and its implementation. Thus, the comprehensive discourse encompasses incorporating the human dimension into models and translating scientific findings into policies, contextualising these policies through case studies, active community engagement, and fostering meaningful dialogues across diverse partnerships. Such frameworks will need careful designing and prompt implementation.

## Data Reliability and Model Enhancement

Fire research relies on robust data collection and dissemination, and ongoing efforts to enhance predictive models. A continuous improvement of the compatibility between data and models is imperative for advancing our understanding of fire dynamics. This involves the community adopting both informal ways of linking models and observations, such as comprehensive model evaluation[41,42,57–59], and more formal approaches, such as informatics techniques like inference, artificial intelligence, and data assimilation methods which update model parameters or structures to improve the model's representation of historic burning[36,55,61,62,95]. These efforts help identify points of strength and limitation in models – identifying fire science questions a model has the skill to answer robustly or where caution in interpretation may be warranted. To improve the reliability of data, develop more sophisticated models, and expand the tools available for fire research, it is necessary to collaborate across disciplines. This means creating strong frameworks for collecting diverse data and prioritising the development of models that can integrate important observations. Working together in this way is crucial for achieving greater predictive accuracy, implementing proactive fire management strategies, and developing comprehensive mitigation measures.

Initiatives such as FLARE, designed intentionally to bring together scientists from remote sensing, in-situ, and paleo-data collection realms for direct discussions with fire modellers, play a key role in understanding the strengths and limitations of modelling and observations. This promotes appropriate comparisons when combining data and models[41], crucial for directly addressing challenges, such as those documented here, and where they intersect: fire regimes beyond burnt area, diverse carbon feedbacks from extreme fires, and the evolution of fire under changing climate and people's interaction with the land.

Clear communication of the uncertainties and applicability of current data sources is essential for comprehending the multifaceted role of human interactions in fire dynamics. Key observations, including fire radiative power, active fire counts, burned area, fuel load, plume composition, injection height, fire severity, combustion completeness, and nuanced categorisations of fire types, form crucial factors for refining models. The question to keep asking is whether existing models can effectively leverage such key observations and if the data to characterise fire within these models is readily accessible. Addressing this question will involve thoroughly exploring available observations used in fire research alongside evaluating the tools essential for refining models and addressing uncertainties. As fire emerges as a global concern, ensuring open access of data for all (e.g. conforming to FAIR and CARE data sharing principles) becomes integral to its use, equity, and transparency.

Integration of data can come from many alternative sources besides remote sensing products, including in-situ and ground-based observations and data from the past. Paleofire data offers the much-needed perspective for understanding changes to fire regimes, their causes, and their effects on the timescale of ecosystem change rather than human lived experience. While a single fire event occurs over a relatively short period, the parameters and conditions that cause fires and their consequences take place over a much longer period. The repetitive nature of the events characterises the fire regime, with their seasonality, intensity, and severity. This frequency can occur on time scales ranging from several years to several centuries or millennia. Changes in seasonality, intensity, and severity are the result of decadal to secular dynamics in climate, ecosystems, and land uses. However, observational data on past fire regimes and their shifts often lacks spatial representativeness, is incomplete and less well-resolved than present-day satellite data. There is therefore a challenge in linking datasets to models in ways that account for uncertainties. Establishing smart retro-observatories that bridge the present and the past is a promising approach to document the range of potential values by capturing variability over time.

Fire models have greatly improved in representing many crucial aspects of fire across the world, largely due to incorporating observations. Fire models coupled with vegetation and land surface schemes can capture large scale patterns and some key trends in fire behaviours and their direct impacts on carbon emissions, while empirical and statistical models are starting to represent extremes. However, there are many areas where fire models still poorly perform. These include capturing the full extent of fire-driven feedbacks within the carbon cycle (**Challenge 1**), representing extremes in a coupled system (**Challenge 2**), or human and fire interactions particularly local scale controls on fire related to land use (**Challenge 3**). Performance issues can be due to a range of missing processes and over-simplifications, but also due to incorporating complexity beyond the requirements of the model – i.e., the unwieldiness of early rate of spread models when representing coarse fire distribution on decadal timescales (Hantson et al, 2016). This severely limits our understanding of the future change in the risk of wildland fire. FireMIP and Jones et al. (18) have summarised a range of opportunities for improving fire models.

**Enhanced Use of Computational Tools:**

- ❖ Implement techniques such as machine learning and data assimilation throughout all phases of model development, including formulation of empirical fire model structures, parameter calibration, and model evaluation.
- ❖ Explore various machine learning algorithms such as generalised linear models, logistic regression, general additive models, random forests, or neural networks to estimate fire activity.
- ❖ Explore uncertainty quantification through Bayesian inference and Maximum Entropy Concepts, which can bridge the gap between Machine Learning methods and numerical modelling techniques.

**Optimization Through Data-Model Integration:**

- ❖ Improve global process-based fire models by integrating strict data-model integration approaches.
- ❖ Targeting model evaluation towards validating the model for specific research questions.
- ❖ Consider alternative and potentially stronger predictor variables for fire regime beyond predefined empirical fire model structures.

**Model Calibration and Recalibration:**

- ❖ Calibrate fire models against observed data and recalibrate optimal fire models when coupled to DGVMs to address biases in simulated vegetation properties.
- ❖ Utilise various climate, vegetation, and human predictor variables during calibration to identify important predictors and their underlying relationships.
- ❖ Calibration and refinement should be specific to the model and problem the model is trying to tackle.

**Addressing Challenges in Model Optimization:**

- ❖ Mitigate overfitting challenges by using multiple satellite burned area reference datasets with varying methods and detection algorithms.
- ❖ Be mindful of limitations and, wherever possible, incorporate uncertainties in satellite burned area products and charcoal records during model tuning and validation.

**Improved Representation of Human Controls on Fire:**

- ❖ Move beyond simplistic representations of human controls based on population density by incorporating more sophisticated socioeconomic factors.
- ❖ Explore the addition of "agent functional types" to fire enabled DGVMs to represent diverse human impacts on fire.

**Improved Representation of ecosystem impacts and recovery from Fire:**

- Using ecological statistical techniques would greatly benefit data-model integration.
- Time series analysis of observations and model responses post fire should be more routine.

**Effective Integration of Regional Models:**

- ❖ Foster collaboration between social scientists, economists, and natural scientists to integrate lessons from regional models into global models.
- ❖ Explore the use of regional parameter values for human ignitions and suppression in DGVMs as a "quick win" to improve model performance.

**Incorporating Human Infrastructure in Models:**

- ❖ Map human infrastructure effectively in models to improve ignition modelling, especially in semi-remote regions where ignitions often centre around transport routes and infrastructure.

**Careful Assessment of Ignition Schemes:**

- ❖ Assess the impact of different lightning schemes on simulated patterns and trends in fire activity across fire enabled DGVMs.
- ❖ Consider the improved availability and accessibility of lightning observations for evaluating the performance of lightning models.

**Improving Fire Spread Model Representation:**

- ❖ Account for physical barriers, such as lakes, roads, and utility corridors, in fire spread models to better represent the constraints on the spread of surface fires.
- ❖ Explore the feasibility of representing the density of physical barriers in fire enabled Land Surface Models.

**Understanding Topographic Effects on Fire Spread:**

- ❖ Conduct more research to understand the impact of topography, slope, and aspect on fire spread across different environments before incorporating these effects into fire enabled DGVMs.

And opportunities for improving observational data include:

**Standardisation and Specification:**

- ❖ Specify and standardise observations to enhance their quantitative and global comparability.
- ❖ Promote standardisation of protocols for acquiring new data among the community of experts, striving for interoperability and continuity.

**Advancements in Characterization:**

- ❖ Support and conduct ongoing research to further characterise past fire regimes, utilising both traditional methods and geochemical approaches.

**Diversification of Indicators:**

- ❖ Encourage the diversification of indicators in paleodata research, leveraging geochemical methods alongside traditional approaches like tree rings and sedimentary charcoal records.

**Maintenance of Public Databases:**

- ❖ Allocate adequate resources to maintain and regularly update public databases (e.g., https://paleofire.org that provides free access to data on past fire proxies).

**Accessibility and Openness:**

- ❖ Ensure open access to databases, welcoming new data streams, encouraging continued interest in the field.

**In-Depth Classification of Data:**

- ❖ Conduct in-depth classification of data within databases to decipher their potential use and facilitate broader utilisation.
- ❖ Develop new tools, including machine learning and AI, for data mining and data meaning leveraging.

**Investment in Research:**

- ❖ Invest in research initiatives to transform existing databases from storage facilities into genuine resources for the broader scientific community.
- ❖ Advocate for the upgrading of existing databases as research objects,

enhancing their usability for a wider audience.

- Develop retro-observatory experiments to better constraint deep-time data integration into models.

**Complexity and Limitations in Carbon Cycle Data:**

- Acknowledge the complexity and limitations in the state of the art regarding data on the role of past and future fires in the carbon cycle.

**Need for Tangible Quantifications:**

- Highlight the necessity for tangible quantifications in the field, recognizing the current prevalence of assumptions in discussions on the role of fires in the Earth System.
- Decrease uncertainty in satellite derived essential variables (burnt area, biomass, etc.)
- Integrate knowledge of more physical based, smaller scaled models into global models

## Communication and Education

Fire is a dynamic force with the potential to significantly impact different areas of human existence, ranging from physical infrastructure and economy to social structures and human health. Navigating the complexities of the interactions between fire and human life demands not only effective but also sensitive communication with various stakeholders. This includes the public, civil representatives, and the media. Such communication efforts should delve into the dual role of human activities in igniting fires and the reciprocal role of fire in shaping the world in which we live.

Effective communication of the distinction between a climate-driven fire regime vs a perturbed or controlled one effectively with those outside the field of fire science is also critical in preparing local communities for potential impacts and informing policy and the wider public on the implications of fire extremes threat to communities and the global climate[96]. Therefore, a more complete public understanding of fire events requires proactive efforts from the scientific community to provide information and disseminate evidence as events, whether extreme or not, unfold.

In our pursuit of fostering effective communication regarding fire, especially in the context of building trust-based relationships, we have explored two questions and provided answers from different perspectives.

**Building Effective Communication Channels with Stakeholders:**

- **Media Engagement:** Recognizing media communication as an integral part of research activities is crucial. It necessitates funding commensurate with its significance. Media inquiries often exhibit biases towards local risks, simplistic causation, and unrealistic expectations from research outcomes. The incorporation of prescribed fire as part of the solution in managing larger wildfires further complicates communication strategies compared to other natural disasters. The high uncertainties surrounding observations, models, and understanding intensify the challenge. Scientists can proactively respond to these challenges by ensuring their institutional websites are not only up to date but also carry public-friendly explanatory information about their fire research. Scientists also have a duty in communicating knowledge directly to the public through outreach initiatives, and if these are directly managed the message can be both expedient and monitored. Moreover, accessible contact details, collaboration with press offices, and responsiveness on social media platforms can enhance communication effectiveness. The sharing of photos, videos, and graphics, where possible, can also be effective communication tools to catch public attention.

- **Fire-Prone Communities Engagement:** Adopting a proactive approach within fire-prone communities involves addressing common issues collaboratively. Inter-regional collaboration becomes crucial, allowing regions unfamiliar with frequent fires to learn valuable lessons from those experiencing increased fire occurrences. Some communities integrate fire into their livelihoods, but the risk of fires escalating beyond control poses a potentially escalating hazard that the community is not prepared for. Collaboration between fire scientists, specialists, and these communities is vital, emphasising the development of applications such as early warning systems and fire danger rating systems. Addressing transboundary smoke haze pollution, exemplified by an early warning system in Southeast Asia, underscores the need for collective efforts. Initiatives like the Fire Management Research Network (FMRM) strive to bridge the gap between applied management and academic work, particularly in South Africa and townships.

**Communication vs. Education:**

- Communication is a facilitator of Education, possessing a capacity-building component that can pave the way for formal educational initiatives. However, for communication to effectively function as an educational tool, it must align with education timescales. Education demands a long-term commitment, relying on the development of partnerships and relationships across communities to foster understanding. While communication often aligns with the news values of the media, which tend to shift focus once the fire season concludes, education requires sustained efforts. Trust and active listening are imperative for learning to occur, distinguishing it from more superficial communication that entails a one-way flow of information from experts to audiences. An example is South African volunteer firefighters working on outreach in townships in Cape Town where educating the fire-prone community is essential.
- Establishing a shared lexicon is fundamental to effective communication and collaboration within fire science, and across different stakeholders, including the media, the general public, and fire-prone communities. Defining a common vocabulary ensures that researchers, practitioners, and stakeholders converse in the same language, facilitating knowledge exchange and the development of comprehensive fire management strategies. While some terms associated with fire science have set definitions used across disciplines, other terms have, to date, been used either interchangeably or for different purposes (**see examples in Appendix iii**). Harmonising terminologies and promoting a clear understanding of fire-related concepts can enhance the coherence and impact of our collective efforts in addressing the complex challenges posed by fire.

# A Path Forward

The escalating visibility of fire as a consequence of climate change and human land management poses novel challenges in effectively communicating shifts in fire regimes. While we cannot yet predict where or when the next extreme fire will happen, there is consensus in the community that humanity will see more and larger impacts in the coming years[97]. The escalating occurrence of “extreme” fires, coupled with the anticipation of heightened impacts on both ecosystems and societies, necessitates a shift from reactive fire science to proactive measures before and during a fire season.

Anticipating the future of extreme fire events is vital to effective adaptation to a rapidly evolving climate with new environmental conditions. However, this task is inherently challenging and riddled with uncertainties, as stated above. The intricate interplay among landscape dynamics, emissions, and climate responses adds layers of complexity to making accurate predictions. The uncertainties encompass how human activities, such as land-use practices and socio-economic drivers, will impact landscapes, emissions trajectory, and climate responses and the nuanced ways in which these elements interact [IPCC WG2]. The evolving nature of fire regimes, shaped by both anthropogenic and natural factors, necessitates a delicate balance in understanding these interactions. Despite the considerable uncertainties, certain model projections provide glimpses into future fire extremes with some confidence. Current models indicate a persistent rise in both the frequency and intensity of fire events in many extra-tropical regions over the coming decades (**Figures 6 and 7**). This trend is attributed to climate warming and the rapid transformation of landscapes under human exploitation[36]. Indicators derived from empirical and process-based models, and recorded incidents and observations of fire weather and burnt area, are collectively signalling a global increase in wildfire. These assessments extend beyond mere considerations of global burnt areas, accounting for the evolving intensity of fire emissions and a poleward shift in their latitudinal distribution.

Traditionally, fire science has responded reactively, often initiated by chance encounters or significant fire events. Moreover, the dissemination of scientific findings typically lags the fire event, taking months or years for research to reach the public domain. To address this, an urgent call arises for a proactive and anticipatory approach, wherein fundamental questions posed by society are identified and key metrics, such as emissions and attribution of fire drivers, are reported. This proactive stance also involves early communication of patterns associated with phenomena like El Niño, enabling affected communities to prepare adequately. It also requires us to look ahead over the next decades and ask where and how society can prepare for increased extreme frequency ahead of when the next devastating fire occurs.

Following fire incidents, crucial questions emerge, and the fire science community can play a pivotal role in providing answers. Collaborating with grassroots organisations, planners, and fire-fighters, fire scientists can contribute valuable insights for resource allocation in mitigation, preparation, response, and recovery[36]. This proactive approach must align with the needs of end-users, addressing short-term fire weather information to long-term climate trends, all the while considering the impact of human activities on fire dynamics. The creation of an annual report, summarising major fire events and advancements in understanding fire-related dynamics, is proposed as a step in this direction. These reports would work as a dissemination method, as well as push towards assessment tools that can obtain critical information of fire drivers and impact with a much-shorter lag time. Co-developing products and climate services with end-users further enhances preparedness for evolving fire regimes.

Priority questions in the aftermath of fires that we as a community should be prepared to answer include:

- Are these fires unusual / extreme?
- Are changes due to climate change or other human activities?
  - Considering ignition, spread, intensity, seasonality, and other environmental conditions.
- Will we see more in the future and why?
- What can we as individuals and as a community do about it?

As the demand for answers in fire science intensifies, the limited number of experts presents a significant obstacle. The capacity and will to undertake challenges, such as identified in this white paper, is the most crucial element of all if we as a community are to achieve a proactive approach. The solution lies in expanded training opportunities that foster and grow the next generation of fire scientists – and why the ECR perspective and leadership roles should continue in initiatives such as FLARE. While transdisciplinary groups like FLARE can be positioned to pioneer more proactive science at the international level, there is a pressing need for access to fire science education for students. Courses in fire science need expanding across academic institutions, to reach the level of access that is more commonly seen for other extreme events such as volcanology, earthquakes, or hurricanes/tornadoes. Additionally, there is a need for dedication and willpower to tackle these challenges head-on, a challenge that needs funding and resources allocated to the discipline in an equitable way. This includes allocating resources to draw on and enhance fire science in regions of the world often overlooked in international collaborations yet often the most affected by fire, including in South America, Africa, and Small Islands Developing States prone to fire. The urgency of the climate crisis and its manifestation in the form of increasing extreme fire events requires a commitment to proactive measures, including the production of annual reports, collaboration with end-users, and the integration of transdisciplinary efforts. This commitment to proactive science extends beyond addressing immediate concerns to strategically planning for the future, thereby ensuring a resilient and well-prepared global response to the changing dynamics of fire regimes. As the fire science community grapples with increased demand on its resources and complexity in the science, building capacity and fostering a collective will to embrace challenges are paramount for achieving sustained progress in understanding, managing, and mitigating the impacts of fire on ecosystems and societies.

As we consider how fire science can inform societal and policy choices, we understand that we can do more together through collaboration, discussion, and co-production than alone. To achieve change and live more sustainably with fire, we must build a culture of safety and trust that empowers voices across academic, managerial, sociological, Indigenous, and cultural boundaries[98,99]. To this end, FLARE was intentional in bringing together a transdisciplinary community to discuss the future of integrated fire science. Indeed, the workshop gathered science expertise ranging from field observations (both on land and on the ocean), atmosphere scientists, paleo-experts but also Earth System modellers and remote sensing experts. In addition, FLARE hosted participation from the head of a ground-based volunteer firefighting organisation, social scientists, and artists.

Despite large efforts to gather as many of the fire-relevant disciplines and stakeholders as possible, this FLARE event still deplored the absence or underrepresentation of several relevant entities. Amongst them were:

- Policy and decision makers.
- Stakeholders including local and national land management and firefighting agencies responsible for the implementation of prescribed burning.
- Educators and historians.
- Indigenous and traditional ecological knowledge practitioners
- Autochthonous communities.
- Journalists and other media writers.

Future activities are encouraged to include this expertise as the community grows with a focus on increased participation from South America, Africa, Asia, and those Small Island Developing States prone to fire.

## An ECR Framework for Future Workshops

The final section in this white paper is written by the ECR community that attended. Here the FLARE ECR outlines a suggested framework for achieving ECR inclusivity at future workshops, one that involves fundamentally changing how the research community thinks about ECRs. Instead of a temporary resource, ECRs must be recognised as the future of research at every institution. In terms of actionable items to do this, we recommend:

- Ensure high ECR participation: Actively encourage and prioritise ECR involvement in workshops by implementing targeted outreach, mentorship programs, and inclusive selection processes. This not only broadens representation but also enriches the overall research landscape.
- Establish avenues for ECRs to assume leadership roles, providing them with platforms to showcase their expertise and contribute meaningfully to the research community. This could involve organising dedicated sessions, panels, or workshops led by ECRs.
- Implement a robust online forum: Develop and maintain a comprehensive online platform that serves as a central hub for ECRs to connect with other ECRs and with recognised researchers, share ideas, and collaborate beyond the confines of physical workshops. This virtual space can foster ongoing discussions, resource sharing, and networking opportunities.
- Ensure small environments: either maintaining a small conference size or creating small environments within a larger conference, such as breakout groups. These settings facilitate meaningful interactions between established scientists and ECRs, promoting mentorship, knowledge exchange, and a sense of community.
- Seek specific feedback from ECRs: post-workshop or post-conference, actively ask detailed feedback from ECR participants to understand their experiences, challenges, and suggestions as those can be very different from other research communities. This information can inform continuous improvement, ensuring that future events are more tailored to the needs of ECRs.

By embracing this comprehensive framework, we aim to cultivate a research culture where ECRs are not only included but recognized as vital contributors, thereby fostering a more dynamic and collaborative future for the scientific community.

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## Methods

The goal of FLARE from the beginning was to reflect a broad spectrum of views and opinions on the future of fire science. To support that effort, we used a series of different tools and approaches to gain the insights reported in this white paper.

On the first day, each participant presented a lightning talk of their research and interests. This helped in creating a space where everyone's research angle was shared. Following talks each day had three in-person breakout sessions of 4-5 people and one online breakout session. Questions were pre-designed, and responses were recorded by Early Career researchers and on Jamboards. Over the 3.5 days following questions were asked:

- If we were to do fire science again -from scratch – how would we do it differently? What would be our design principles? – This was asked at the first and end of the meeting.
- What does your discipline need to go forward / what challenges do you face? Key take insights from your own discipline
- What can your discipline provide to others? Key take-aways
- What are the weaknesses and strengths of our research (approach and tools) for understanding wildfire across the Earth System?
- If money were no object, what tools would you develop to do what and why?
- How can we be more strategic in the way we develop and use our tools?
- How are tools unknown, unused, misused, or misunderstood, and why?
- What are your priority opportunities for improvements to fire science?
- What information is important for policymakers, social scientists, communities in wildfire-prone regions, and the general public to understand?
- Are there any geographical differences to scientific approaches – disconnects, tools for fire science – that need to be highlighted so science can progress more quickly?
- Based on what you've heard the last three days, where is the disconnect?
- What is your number one challenge?
- During the workshop, participants added the following questions for breakout groups that:
- We have green carbon and blue carbon. What other colour carbons should we think about? What numbers are there? And how confident are we in them?
- How do we institutionally enable more interdisciplinary collaborations?
- What takeaways/insights from the past three days are important for bio-physical science to understand?

ECR met several times at FLARE to coordinate their notes and prepare for an in-person talk on the final evening. The talk was given in person and facilitated a discussion between ECR and established scientists about barriers that face ECR.

On the final day a summary session highlighted commonalities in the discussions. This was the foundation from which the 3 Challenges were identified. After the meeting three separate channels of investigation were undertaken in parallel to identify challenges and see if they supported those identified on the final day. The first was an analysis of the responses recorded on the Jamboards **(Figure 1; top panel**). The Jamboard responses were categorised into overlapping but distinct challenges by hand and independently using large language model AI. The second analysis was to review the in-person notes taken over the full course of the meeting (45 pages in total). These were categorised by hand and summarised in **Figure 1** (bottom panels). The third analysis involved reviewing the online participation notes and Jamboards responses. All channels of analysis identified the same three challenges (carbon cycle, extremes, and human interactions with fire). To validate our sorting, we loaded the Jamboard responses into ChatGPT3.5 (OpenAI 2023) and asked the following questions:

> "*We asked a workshop of fire scientists the following series of questions (identified with a "*") and below are participant responses. How should we cluster these into three linked but largely distinct main challenges? And what are the common themes that link these challenges?"*

ChatGPT likewise identified these challenges:

- Understanding the Carbon Dimension of Fires
- Human Interaction with Fire
- Addressing Societal "Bad" Fires

The final challenge text in this report was then refined through feedback from workshop participants as the text for each section was developed.

All research questions in this report were likewise a product of this analysis with additional questions added from the community while writing the first draft. Once all questions were defined, we undertook a poll of FLARE participants to identify which ones are a priority for each challenge. Each FLARE member was asked to identify the top research question to them and also 2-3 secondary research questions. Approximately half of FLARE participants took part in the poll (n=20). Each top question was assigned a value of 2 while secondary questions were assigned a value of 1. These were summed for each question and if the sum of points was equal to or greater than n/2 (i.e., 10 or more) the question was flagged as a research priority and placed in the box under each challenge title.

After the meeting, 6 ECR members (one-third of all ECR attendees) met on Zoom 4 times to create an ECR perspective survey and to compose this section. The survey asked ECRs about their perspective on the workshop and how it compared with other workshops. It was sent to all attendees and answered by 7 ECR respondents. The survey information and discussions over Zoom were used to compose the section on the Early Career Perspective and the Future Workshop suggestions.

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## Appendix i: Initiatives, events, and platforms for fire science transdisciplinary research, collaborations, and ECRs.

| Initiatives/ Organizations/ Funding | Location | ECR Opportunities |
|---|---|---|
| Joint Fire Science Program https://www.firescience.gov/index.cfm<br>The Joint Fire Science Program provides funding for scientific studies associated with wildland fire, fuels, and fire-impacted ecosystems that respond to the emerging needs of land managers, practitioners, and policymakers. | USA | |
| WMO VFSP-WAS https://community.wmo.int/en/activity-areas/gaw/science/modelling-applications/vfsp-was<br>The VFSP-WAS aims to enhance the ability of countries to deliver timely and quality vegetation fire and smoke pollution forecasts, observations, information, and knowledge to users through an international partnership of research and operational communities. | Global | |
| IGAC BBURNED https://www2.acom.ucar.edu/bburned<br>BBURNED aims to better quantify the current understanding of the uncertainty and variability in biomass burning emission estimation and determine how to more accurately represent atmospheric chemistry resulting from fire. We will be a conduit to coordinate and organise the international scientific community to improve understanding of the current and future impacts of wildfires, prescribed burning and agricultural fire on public health and climate by addressing the uncertainties in atmospheric chemistry processes influenced by biomass burning. | Global | Many opportunities for ECRs to participate in and contribute to working groups |
| The Leverhulme Centre for Wildfires, Environment and Society https://centreforwildfires.org/<br>We seek to understand what factors govern wildfire regimes, including the sources, frequency, intensity, timing, and spatial pattern of fire; develop ways of predicting fire risks that include new biophysical understanding and account more reflexively for human-environment dynamics; quantify the impacts of fire on natural processes and human systems, including | UK-based; projects worldwide | Online/hybrid thematic workshops on all aspects of fire science - not necessarily ECR-centred but are excellent in terms of capacity building in ECRs |

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| assessing their influence on future climate, economic consequences and wider cultural meanings; and develop ideas for living with fire, which includes recognition that some wildfires are beneficial for ecosystem function and livelihoods, and humans use and control fire for many purposes within landscapes.<br>The Centre's day-to-day work is organised into four strands focusing on major topics/regions of interest: Fire in the Tropics; Fire in the North; Fire at the Wildland-Urban-Interface; Fire in Global Systems. These are being pursued through interdisciplinary, collaborative and participatory research, from the local to global scales, and by training a large cohort of early career researchers, thus nurturing a new generation of fire scientists. | | |
| International Paleofire Network<br>https://paleofire.org<br>The International Paleofire Network (IPN) aims to advance our understanding of the controls and impacts of fire in the Earth system on a wide range of spatial and temporal scales.<br>IPN drives the Global Paleofire Database (GPD) is to provide the scientific community with a global paleofire dataset for research, documentation and archiving.<br>The aim of the GPD is to provide the scientific community with a global paleofire dataset for research and archiving sedimentary records of fire.<br>The GPD (formerly GCD) has been founded by the Global Paleofire Working Group of PAGES and is now managed by the International Paleofire Network (IPN) in collaboration with several partner universities over the world.<br>The science emerging from the IPN is mainly:<br>- the creation of a public-access database and an international research community with multiple-authored papers describing observed spatiotemporal changes in fire at global and regional scales (e.g. time series and maps).<br>- Global and regional syntheses which enable the examination of broad-scale patterns in paleofire activity, creating a framework for exploring the linkages among fire, Human, climate and vegetation at centennial-to-multi-millennial time scales and allowing for evaluation of fire model simulations at regional to global scales.<br>The computer infrastructure associated to the GPD is hosted at and managed by the staff of the Maison des Sciences de l'Homme et de l'Environnement (MSHE; UAR 3124 CNRS-UFC) at the Université de Franche-Comté (Besançon, France). | International<br>Open database<br>PAGES affiliated | IPN looks to meet the growing needs of interdisciplinary ECR fire scientists by developing research projects, in collaboration with stakeholders, that employ the open-access Global Paleofire Database, statistical tools, and state-of-the-art models to address questions about long-term fire-regime variations and their feedbacks on species, ecosystems, and climate. |
| PAGES DiverseK Working Group | International | |

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| https://pastglobalchanges.org/science/wg/diversek/intro<br>The DiverseK working group is a network of environmental and social scientists working to develop recommendations for the most pressing environmental and social justice issues.<br>Goals<br>- Establish a clearer methodological and ethical basis for the integration of diverse knowledges.<br>- Support conservation needs in co-production with stakeholders.<br>- Re-assess current environmental policies based on the new integrated knowledge. | Strong Global South focus | DiverseK WG aims to create a multi-disciplinary framework that provides key scientific advice for policy recommendations on terrestrial ecosystems, in line with Future Earth's mission to foster international effort for a more sustainable planet. DiverseK welcomes people interested in environmental policies related to restoration, fire impacts, carbon stocks, forest management, biodiversity, and livelihoods - ECRs are encouraged to be involved. |
| Pyrolife ITN-developed International Symposium<br>https://pyrolife.lessonsonfire.eu/events/pyrolife-international-symposium/<br>The goal of this symposium therefore was to create new international links across scientific fields and disciplines, in order to get a better view on what Integrated Fire Management should look like across Europe and internationally. While this symposium represented the scientific kick-off of the Pyrolife ITN training network, researchers and interested parties from other institutes were warmly invited to watch this symposium, to allow broader and deeper connections to take root. | | |
| FireMIP<br>https://www.senckenberg.de/en/institutes/sbik-f/quantitative-biogeography/qb-projects/firemip/<br>The Fire Model Intercomparison Project is dedicated to strengthening the development of global fire models through a systematic comparison of current approaches and providing robust insights on global fire dynamics and impacts using an ensemble of coupled fire-vegetation models.<br>At the core of the project are standardised model simulations of modelling groups from all over the world and annual meetings where in-depth discussions, not only between modellers but also with experts in atmospheric chemistry, fire ecology, and groups generating observational datasets, are the drive and basis to refine the project goals. FireMIP is an international, unfunded initiative, started in 2014 | Global | |
| State of Wildfire | UK operated | This is a very new initiative and would |

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| The "State of Wildfire" is a new initiative that aims to answer the questions that fire scientists are frequently asked as new fire extreme events emerge.:"How much was climate involved?" "Was the fire caused by humans?" "Who is affected?" "How does this year compare to previous years?" "Will we witness more fires like this in the future?" and "What measures can we take to prevent or prepare for them?" The questions are rightly asked by the public, media, non-governmental organizations, fire management agencies, and policymakers, but every year, the fire science community struggles to find answers to these questions.<br>The "State of Wildfire" group plans to publish its first annual report later this year, which will examine the significant fire events of the previous year, analyze their causes and impacts, and predict their likelihood as we continue to alter the land and climate in the future. However, the report will only be part of the story. Over the next few years, the tools used will be developed and improved to provide near-real-time information during fire events, offering invaluable insights while people pay attention. Ultimately, this report will be the vehicle that will make the advances and hard work of the fire science community relevant to a world eager for answers as we learn to coexist with the occurrence of fire extremes. | With Global collaborators. | welcome suggestions and feedback on how to support ECR research. |

| Events | Location | ECR Opportunities |
|---|---|---|
| IGAC ECR Conference<br>[https://igacproject.org/icacgp-igac-2023-ecr-online-conference](https://igacproject.org/icacgp-igac-2023-ecr-online-conference)<br>Online conference for early career researchers (ECRs) in atmospheric chemistry research around the Globe | Online, global, biannual | |
| FES congress (Fire in the Earth System)<br>[https://firecongress.eu/](https://firecongress.eu/)<br>Hybrid conference with scientists, citizens and practitioners to share information, ideas and goals to use fire as a tool to achieve sustainability. | Europe/ Global | |
| EUMETSAT Future Focus – Wildfires<br>The workshop will address the current status and advances in monitoring wildfires from space; role of satellite data in wildfire forecast, monitoring and emission estimate; impact of fires on the wider ecosystems and climate. | Global/ Possibly hybrid | |
| BBURNED and iLEAPS<br>will host a joint 2-full-day workshop on biomass burning/fires that will be focused on the themes of variability and uncertainty in fire emissions, atmospheric | Global, hybrid | |

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| chemistry and processes, and modelling. We aim to identify fire uncertainty related questions and preliminary/ongoing science and kick off a multidisciplinary special journal issue.<br>14-15 September 2024 Hybrid / Kuala Lumpur, Malaysia | | |

| **International Platforms and Communities** | **Location** | **ECR Opportunities** |
|---|---|---|
| iCACGP-IGAC<br>https://www.ecr-igac-icacgp.org/<br>Facilitate networking and career development for ECRs in the atmospheric chemistry community. | Global | ICACGP-IGAC Early Career Scientific Steering Committee |
| PAGES<br>https://pastglobalchanges.org/ecn/intro<br>Facilitate networking and career development for ECRs in the paleosciences. | Global | PAGES ECRs |
| Association of Fire Ecology<br>https://fireecology.org/<br>International organisation dedicated to improving the knowledge and use of fire in land management. | Global | ECR Award<br>Mentoring Program |
| The International Association of Wildland Fire (IAWF)<br>https://www.iawfonline.org/<br>Professional membership association dedicated to uniting the global wildland fire community. | Global | |
| iLEAPS<br>https://ileaps.org/<br>Facilitate networking and career development for ECRs studying physical, chemical, and biological processes through the land-atmosphere interface. | Global | Active Early Career scientist network supporting webinars, conferences side-events, and opportunities to participate in the steering committee. |
| SOLAS<br>https://www.solas-int.org/<br>Facilitate networking and career development for ECRs in the surface ocean lower atmosphere community. | | Active Early Career Scientific Steering Committee. Summer school and workshop activities. ECR peer mentorship being planned. |

# Appendix ii: Future Research Questions

## Challenge 1:

- How can regional to global carbon emission inventories be validated and improved?
- What data do we currently have on fire, fire processes and impacts, over what time periods and regional scales?
- How can we use paleoenvironmental archives of fire to better understand the historical and contemporary carbon dynamics related to fire, and how they are affected by changes in climate?
- How much do we understand of how fire impacts land and/or ocean vegetation/biota functioning?
- How can we best incorporate available observations into models, and integrate them over different scales?
- What is the role of fire in climate mitigation carbon sequestration projects?
- What is the contribution to carbon budgets over different timescales; over what timescale and under which environmental conditions could a fire become carbon neutral?
- How do future changes influence global climate, allowable emissions, and temperature mitigation ambitions?
- To what extent is fire a maintenance factor for biodiversity/ecosystem stability?
- Where is changing fire regimes pushing ecosystems into new formats?
- What methodologies are reliable for assessing wildfire risk within the context of climate intervention initiatives, and how does fire play a role in global climate policy?
- How do fire-evolutionary traits affect the carbon cycle? Can we incorporate ecological and evolutionary concepts into carbon cycle models for better carbon response variability?
- Taking all the aspects of how fire impacts the global carbon cycle, is fire a net carbon source or sink?

## Challenge 2:

- How can we model or statistically determine from observations direct human ignitions compared to natural ones?
- Can different models with varying spatiotemporal scales work together to assess extreme fire events?
- Can we harmonise or distinguish between fire driven by societal needs vs driven by climate change?
- If extreme is defined as a function of a chosen baseline, over what time horizon should we consider fire extreme events? Human lived experience? Centennial? Longer?
- Which observational tools are best to assess if a given year is extreme at the local, regional, or global scale?

- Can we use regional and local dynamic models of the Earth System, driven by future climate warming, to predict fire occurrence and indicate if a currently defined extreme will remain an extreme event or more likely to become the norm?
- What is required to put in place a set of tools that allows fire assessment to be done rapidly for any region and how best to translate this analysis into key unambiguous messages for multiple audiences (public, local populations, media, institutions, governments etc)?
- How good of an indicator are historical extreme fire events of future extreme fire events?
- To what extent can international collaboration enhance our ability to predict, monitor, and respond to extreme fire events, considering their transboundary nature and shared consequences?
- What communication channels are needed between fire modelling groups and other fields?

**Challenge 3:**

- How can we characterise socio-cultural norms – community fire use/suppression/extinction or loss of populations/community structures/knowledge?
- Is it possible to distinguish and quantify the impact of fire set by humans directly vs indirectly?
- How can we improve our understanding of the impact/risk of permanent and emerging settlement in fire-prone regions?
- Can we or do we need to harmonise the management and understanding of "societally bad" fires with biophysically extreme or unusual fires, especially concerning their effects on carbon emissions and the carbon cycle?
- How does recent and historical land management and land use alter fire activity in different regions?
- How do shifts in the global economy influence national and regional land use policies and practices? How is climate change likely to alter these patterns?
- What are the different policy logics and regimes which shape and constrain fire management action across countries? What explains variation in these regimes? Do these regimes have differing socio-ecological consequences for different landscapes?
- What are the different ways of knowing and relating to wildfire across communities? What are the consequences of this variation for fire outcomes? What political, economic, and cultural factors help explain this variation?
- Is the escalating human factor of wildfire different in different countries? What explains this variation?
- How does industrial and technological expansion in the developed countries affect the economic and environmental practices (e.g., fire practices) of developing countries, where the economy is based mainly on the expansion of primary activities, such as agriculture and forestry/logging? How do these external influences impact the economic and ecological sustainability of these nations?

# Appendix iii: Discussion on Fire Science Terminology

This table provides a starting point for discussion on commonly terms used in fire science that may need further definition or mean different things to different researchers or practitioners.

| Word | Advancement | Definition and discussion | Source (when known) |
|---|---|---|---|
| Active Fire/Hotspots | misused | Often used terms related to fire counts. Active fire or hotspot comprises a detection in a remotely sensed pixel of a excess temperature above the nominal background temperature. The term is not specific to wildfire or vegetation fire but also includes any form of temperature excess e.g. flaring. | |
| Anthropogenic fire | Needing definition | Anthropogenic fires" is difficult to define precisely due to the broad spectrum of human activities that can lead to fire ignition : human-influenced fires can occur as intentional burning for agriculture, accidental ignition from industrial activities, or changes in land use practices. The distinction between naturally occurring fires and fires ignited by human actions can be blurred, especially in regions where human activities are deeply intertwined with natural processes. This highlights the challenge of categorizing fires solely as either natural or anthropogenic and urges a refined definition of fire regimes. | |
| (Open) Biomass burning | Set definition | the burning of living and dead vegetation. It includes the human-initiated burning of vegetation for land clearing and land-use change as well as natural, lightning-induced fires. | https://earthobservatory.nasa.gov/features/BiomassBurning |

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| Burned area | Set definition | area characterised by deposits of charcoal and ash, removal of vegetation, and alteration of the vegetation structure due to wildfire. This term is equivalent to the fire's spatial 'extent' and is specifically detected based on changes in the spectral signature ("blackening") of the land surface due to deposits of charcoal, ash, removal of vegetation. | https://burnseverity.cr.usgs.gov/glossary |
| Burned Area Boundary | Set definition | boundary defining the area burned by a fire. In the context of satellite-based post-fire burn severity mapping, burned areas are typically delineated using remote sensing indices and/or spectral data, and may include unburned "island" areas. Boundaries are also mapped manually using a Global Positioning System (GPS) mounted on a helicopter, where the pilot obtains boundary georeference points by flying the burn perimeter or fire managers walk the burn perimeter or use infrared photography. | https://burnseverity.cr.usgs.gov/glossary<br>Kolden and Weisberg. 2007. *fire ecol*. doi.org/10.4996/fireecology.0301022 |
| Combustion completeness | Misused | combustion completeness is synonymous with combustion efficiency/burning efficiency. Needs a unique definition or these terms should be rationalised | |
| Combustion/burning efficiency | Needing definition | for vegetation fire combustion efficiency is defined as the fraction of available biomass or fuel consumed and often also termed burning efficiency. | Seiler and Crutzen. 1980. *Clim Change*. doi.org/10.1007/BF00137988 |
| Extreme fire | Needing definition | "extremes" are to be reported within a global, regional or local context. Extreme fires could be associated with a major release of greenhouse gases to the atmosphere at a global scale or could relate to a heavy destruction and casualties toll on a small island scale. Discussions are ongoing on how to define an extreme fire. | |
| Fire "risk": | Misused | "risk" includes the probability of an event (hazard) to occur (depending on several forcing factors) as well as the possible impact of the event, or in other way, the vulnerability of the ecosystem or society to the fire disturbance<br>e.g., if a system is well resilient, the risk associated with fire is zero ; if the system is not resilient but the probability of fire ignition is very low, the risk is also low | |

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| Fire activity | Misused | recommendation is not to use this term which is judged too “vague”. ‘Fire regime’ could be used to talk about fire in a system over time ; ‘fire event’ to refer to a single event, and ‘fire occurrences’ to mention multiple events. | |
| Fire behaviour | | this term seems to be used as a catch-all term for the properties of individual fires with connotations to extreme properties (rate of spread, intensity, rapid directional changes, pyroconvection) but has no set definition (lacks clarity) | |
| Fire counts or "number of fires" | Misused | thermal anomalies from satellites are often described as "fire counts" or "number of fires" ; however one fire event can lead up to several hundreds “fire counts”. The “number of fire” or “fire counts” should therefore not be used to tally the number of fire event occurring at a time | |
| Fire Emission Factor | Set definition | quantification of the amount of pollutants [gases] released per mass of biomass burned | Urbanski et al. 2013. *ACP*. doi.org/10.5194/acp-13-7241-2013 |
| Fire Radiative Energy | Set definition | the emitted radiant energy released during biomass combustion | Kaufman et al. 1996. in *Global Biomass Burning,* J. Levine (ed), MIT Press. |
| Fire Radiative Power | Set definition | the rate of outgoing thermal radiative energy coming from a burning landscape fire, integrated over all emitted wavelengths and over the hemisphere above the fire. | https://www.copernicus.eu/en/access-data/copernicus-services-catalogue/satellite-fire-radiative-power# |
| Fire cycle or Fire return interval | Set definition | time in years cumulated fire area equal to 100% of the defined area studied | |
| Fire frequency | Set definition | number of fires per unit of time in a defined area (vegetation type, ecosystem, biome) | |

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| Fire intensity | Set definition | amount of energy or heat release per unit time or area during the consumption of organic matter | https://burnseverity.cr.usgs.gov/glossary |
| Fire interval | Set definition | time between two fire events or two (geological) episodes of fire events in a defined area | |
| Fire regime | Set definition | used in fire ecology ; the 'fire regime' includes features related to space (type of fire, extent) and time (fire frequency, interval, cycle and seasonality), and its effect on a particular type of vegetation or ecosystem (fire severity). A purely physical (fire intensity, heat, duration, and size of the flame) component can be added to this definition. | Hely and Alleaume. In *Dryland ecohydrology* doi.org/10.1007/1-4020-4260-4_16<br>Keeley. 2009. *International Journal of Wildland Fire*. doi.org/10.1071/WF07049 |
| Fire severity | Set definition | degree of alteration of vegetation and soil (% mortality, depth burned) ; loosely, a product of fire intensity and residence time. | https://burnseverity.cr.usgs.gov/glossary |
| Fire Temperature | | Fire temperature depends on the type of vegetation that burns with typical ranges for 600–1500 degrees C. | Wooster et al. 2003. *Remote Sensing of Environment*. doi.org/10.1016/S0034-4257(03)00070-1 |
| Forest fire | Needing definition | A fire which occurs in a forest, as often (but not systematically) defined as an environment where tree cover exceeds 30% of the vegetation. This term is sometimes used in place of 'wildfire' | |
| Fuel complex | Set definition | the amount and arrangement of the fuels present in the fire's fuel bed | |

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| Fuel load | | fuel load includes the quantities of duff, litter, fine-woody debris, and coarse woody debris (logs) and is usually expressed in kilograms per metre squared (kg m–2). | https://www.fs.usda.gov/rm/pubs/rmrs_gtr225.pdf |
| Global fire | Needing definition | this term remains ambiguous as it lack specificity on “what” is global (the burnt area, the impacts on the Earth system or on large scale societal interactions). Questions were raised on whether this term has a meaning (and should it be used) | |
| Megafire | Needing definition | emerging concept commonly used to describe fires that are extreme in terms of size, behaviour, and/or impacts, but the term’s meaning remains ambiguous. Currently, some definitions may indicate a threshold size to a regional extreme, whereas other definitions incorporate other traits such as the intensity or the rate of spread of the extreme fire. | Linley et al., 2022. *Global Ecology and Biogeography.* doi.org/10.1111/geb.13499 |
| Mitigation | Set definition | set of actions used to mitigate the behaviour of an ignited fire event. Different from fire ‘prevention’ | |
| Natural fire | Needing definition | while the "natural" aspect could either be related to the ignition cause (natural or human), to the spread conditions (which can be human controlled) or to the environmental settings (including anthropogenic climate change), the least ambiguous examples of a natural fire is that ignited by lightning which spreads without direct modification by human (although the properties of these fires can be altered by human induced climate change and landscape modification) | |
| Plume Injection Height | | In intense fires smoke tends initially to be transported vertically or semi-vertically close by the source region, driven by the intense heat and convective energy released by the burning vegetation. The column of hot smoke rapidly entrains cooler ambient air, forming a rising plume within which the fire emissions are transported. The height in the atmosphere the plume reaches, injection height, is controlled by the plume dynamics, which are driven by both the energy re- leased by the fire and the ambient atmospheric conditions (both stability and humidity) | Paugam et al. 2016. *Atmos. Chem. Phys.* doi.org/10.5194/acp-16-907-2016, 2016. |

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| Prescribed Fire | Set definition | any fire ignited by management actions to meet specific objectives sometimes including a pre-planned prescription authorised by land/fire management authorities. | https://burnseverity.cr.usgs.gov/glossary |
| Prevention | Set definition | set of actions applied to prevent ignitions or limit fire spread before a fire event. Different from fire 'mitigation' | |
| Pyrome | Set definition | regions that can be classified together on the basis that they share a common fire regime - that is, similar fire frequency, size, intensity, severity, or bioclimatic and human drivers. | Archibald et al. 2013. *PNAS* doi.org/10.1073/pnas.1211466110 |
| Pyroconvection | Set definition | a process where intense heat from wildfires generates convective activity. The heat warms up the air which rises, carrying water vapour and creating powerful updrafts. When the uplifted air cools, it has potential for powerful downdrafts. The uplifted water vapour can condense to form pyrocumulus or pyrocumulonimbus clouds which can produce thunderstorms and lightning. Updrafts and downdrafts associated with pyroconvection contribute to unpredictable fire behaviour, including changes in fire rate of spread or direction, while additional ignitions can result from lighting or the uplift and transport of hot embers. | |
| Small Fire | Needing definition | | |
| Type of fire | Needing definition | vegetation layer impacted the most by the flames and the heat (ground, surface, understory, crown). Also used to characterise the type of vegetation burned (grassland, forest, crop…etc.) | |

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| Wildfire | Set definition | wildfires are often considered a separate type of fire from "landscape fire's", and defined as "an unusual or extraordinary free-burning vegetation fire which may be started maliciously, accidently, or through natural means, that negatively influences social, economic, or environmental values | Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. Nairobi |
| Zombie Fire | Needing definition | Zombie fires are those that can hibernate in the cold, smouldering underground for months on end. They are not characterized by roaring flames but by plumes of smoke seeping from the ground. | |