LEVERHULME

Centre for **Wildfires, Environment** and **Society**

‘Mid-term’ Report 2023

Leverhulme Centre for Wildfires, Environment and Society – 'Mid-term' Report

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Cover image: 'Playing With Fire' by Sophie De Pauw, University of Reading

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Introduction

The Leverhulme Centre for Wildfires, Environment and Society was established in 2019 with the aim to radically transform the scientific and practical understanding of wildfire, so that society can understand, predict and manage wildfire more effectively in the future.

Our collective expertise includes Earth system processes, numerical modelling, earth observations and data analytics, and geographies of land use. We were the first in the world to address the multi-scaled challenges of wildfire in a comprehensive, global and transdisciplinary context, bringing together all of these disciplines. Integrating approaches from the social and natural sciences, we are developing a new field of research in which understanding of the human, physical and ecological dimensions of wildfire will advance together.

During Phase I (years 1-5), our research has been organised into four strands focusing on major topics or regions of interest: (1) Fire in Global Systems; (2) Fire in the Tropics; (3) Fire in the North; and (4) Fire at the Wildland-Urban Interface.

These have been 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.

Fire in Global Systems

Fire in the Tropics

Fire in the North

Fire at the Wildland-Urban Interface

This report serves to summarise our activities during the first four years of Phase I (2019-2024), particularly focusing on year 4, and outline our approach to our second phase ('Phase II'), from 2024-2029.

Infrastructure and Governance

The Centre is a collaboration between Imperial College London, King's College London, the University of Reading and Royal Holloway, University of London, funded by the Leverhulme Trust from 2019-2029. We were officially established on 1st October 2019, which was celebrated with a launch event on 13th November 2019.

We have established our:

1) **Leadership Team** – consisting of one Director and five Associate Directors, representing our different partners across the social sciences and physical sciences. The Leadership Team meets, along with the Centre Manager, approximately every two months, and is responsible for research coordination across our capabilities and Research Strands, and for overall progress and success of the Centre.
2) **Centre Manager** – responsible for overseeing the operational and logistical needs of the Centre, and supporting the development of the research programmes, communications, networks and collaborations.
3) **International Advisory Board** – consisting of world-leading authorities on wildfire research and other areas central to our vision. Meeting approximately every 6 months, the Advisory Board plays the role of 'critical friend' to the Leadership Team, providing advice on research progress, plans, and resource allocation.
4) **Centre Spaces** – dedicated and branded office spaces both at Imperial College London (Chemistry Building, South Kensington) and at King's College London (Melbourne House, Strand Campus).
5) **Academic Research Team** – who supervise the Early Career Researchers and support the activities of the Centre. In addition to the six leadership team members, we currently have 14 academic staff. They are based within several departments at Imperial College London (Life Sciences, Physics, Centre for Environmental Policy, Mechanical Engineering (Imperial Hazelab), Data Science Institute, School of Public Health, and the Business School); at King's College London in the Department of Geography, and more recently in Engineering; at the University of Reading in the Department of Geography and Environmental Science; and at Royal Holloway in the Department of Geography.
6) **Early Career Research Team** – we take an inclusive approach to Centre membership. In addition to projects directly funded by our Leverhulme Trust grant, we include researchers based in our partner organisations who are working on wildfire, but who have different sources of funding (e.g. through new grants which we have won). This allows us to expand our scope, and develop a more diverse community with greater collective impact, whilst offering all those affiliated with our Centre with the same opportunities and support as

directly-funded members. We currently have 16 postdoctoral research associates (PDRAs) in our membership (12 directly funded, 4 affiliated) and 30 PhD students (17 directly funded, 13 affiliated). We also have 9 past members, including those who have now completed their PhDs.

7) **Affiliate Organisations and Groups** – with whom we work on an ongoing basis (see Partnerships and Collaborations)
8) **Working Groups** – a number of Working Groups (WGs) have been established, which support cross-partner and interdisciplinary working - including the: Equality, Diversity and Inclusion WG; Fire Governance WG; Arctic Wildfires WG; Earth Observation of Fire WG; and the Earth System Fire Group.
9) **Centre communications** – including a website, social media, and an internal and external mailing list. We regularly write short articles to share latest news and research findings.
10) **Programme of engagement activities** – including webinars, workshops, conferences and public events.
11) **Centre logo and branding templates –** promoting international recognition.

Image: Collage of past and present Centre members (including Affiliate members) from 2019-2023. We have created a strong sense of community in the Centre, which we continue to nurture.

Our Research

Objectives

Underlying all our research, across the four Research Strands, are four key objectives:

1. **Understanding Fire:** What social and environmental factors and feedbacks govern wildfire regimes, including the sources, frequency, intensity, timing, and spatial pattern of fire on the landscape, past and present?

2. **Predicting Fire:** How can we incorporate new biophysical understanding, social learning and realistic human-environment dynamics so as to model fire regimes and associated patterns of land cover change more accurately, credibly, and accountably?

3. **Quantifying Impacts:** How are people, the places and properties they value, and the resources and ecosystem services they rely on (including biodiversity, air quality, carbon sources/sinks, and climate), affected by wildfire and by changes in the regimes governing it?

4. **Living with Fire:** What does wildfire mean to different social groups, and what changes in fire regimes and associated landscapes and management practices would be culturally, politically, environmentally, and economically acceptable to whom – and why?

Meeting our Objectives

This following section reports on how we are meeting our objectives and how we are answering these key questions through our research to date. For each objective, we also demonstrate how our research aligns with our four main Research Strands of Phase I (Fire in Global Systems, Fire in the Tropics, Fire in the North, and Fire at the Wildland-Urban Interface). Many of our projects reach across multiple Research Strands, and answer multiple objectives, but we have organised our research in this report to correspond with the objectives and Research Strands to which they primarily align.

Objective 1 - Understanding Fire

What social and environmental factors and feedbacks govern wildfire regimes, including the sources, frequency, intensity, timing, and spatial pattern of fire on the landscape, past and present?

O1: Fire in Global Systems

- **A new database for palaeofire.** The Reading Palaeofire Database (RPD) has been developed, providing an expanded global resource to document changes in fire regimes from sedimentary charcoal records, enabling extensive re-assessments of global and regional palaeofire regimes. The RPD contains new age models to account for new radiocarbon calibrations and to facilitate more robust regional comparisons in past wildfires regimes.

- **A model of Halocene wildfire.** In the modern day, human influence is an important component in describing patterns of wildfire, which potentially complicates our understanding of the nature of the relationships between fire and its other drivers. Within the research literature there is disagreement regarding the importance of people in influencing wildfire in the past, with some research finding a limited role until relatively recently, and others finding a key role for people as far back as 7000 years ago in some areas. Through our palaeofire research, we have been aiming to establish whether relationships between fire, vegetation and climate during the Holocene can be modelled with or without human influence. We have been working towards a model of Holocene wildfire based on climate, vegetation and human drivers and are now finalising model input reconstructions.

- **Identifying wildfire drivers.** We have helped identify key drivers of global fire size and fire intensity, which is not something that had previously been achieved. We showed that where burnt area was driven by fuel availability and dryness, fire size was more limited by fuel continuity and fire intensity by fuel build-up.

- **Fire-vegetation interactions.** We have analysed how vegetation properties create different responses of fire to specific drivers (including fragmentation and human activities), in fire-adapted and non-adapted vegetation. We have further explored the impact of differential responses to human activities in fire-adapted and non-adapted vegetation, using our new empirical global model for burnt area.

- **Improving predictions of species diversity in fire-vegetation interactions.** Field measurements with Earth Observation (EO) data are inevitably useful for operational monitoring to help understand vegetation-fire interaction at the landscape scale. We have used such EO data to help predict species diversity and structure information affected by fires across tropical biomes. We found that seasonal optical derived vegetation indices that are sensitive to greenness, moisture content and fire severity gives improved predictions. However, although highly useful, EO data from optical sensors are affected by cloud cover and smoke during active fires. Microwave data are an alternative tool to resample data to monitor fire-affected vegetation conditions and its

recovery, despite the presence of cloud cover. We tested the level of agreement between these microwave data and field-sampled vegetation structural recovery of fire-threatened peat-rich ecosystem of Borneo, and found that dry season acquired microwave data gives better level of agreement.

- **Modelling the effects of wildfires on atmospheric composition.** We have evaluated the current understanding of wildfire activity and its effects, specifically on atmospheric composition and the earth's energy budget, from pre-industrial times to the present day, through a thorough examination of the relevant literature. We have also performed simulations with the Earth System Model EC-Earth for the whole globe, which allows us to test the effect of emissions originating from wildfires. We are conducting simulations with the full emissions input data and also by excluding the wildfire emissions only. By estimating the difference between the two simulation sets, we are able to compare the concentrations of critical pollutants in the atmosphere (such as carbon monoxide and aerosols) and isolate the ones that originate from wildfires only. Our first global simulations were an important step towards better understanding and further development of the model. This will allow us to proceed with confidence to improve the representation of wildfires in the simulations.

- **Improving emissions estimates in the laboratory and in the field.** We successfully set up our Combustion Chamber at KCL to simultaneously collect both remote sensing and smoke measurements of fires. These have been used to find new relationships in fire characteristics and smoke composition. We also successfully conducted an airborne campaign studying wildfires in Northwestern Ontario, Canada, in August 2023, during the country's most intense fire season on record, with an area almost the size of the entire UK burning in a single year. Novel techniques which we developed for improving emission estimates in laboratory fires (taking into account how much is flaming vs smouldering) will be tested on data taken from these real-world, Canadian fires. Ultimately, the aim is for these methods to be applied to satellite measurements, which shall help to improve the accuracy of global emissions estimates.

- **The first global behavioural model of human fire use and management**. We have developed WHAM!, the first global behavioural, or 'agent-based', model of human fire use and management. This model is based on a literature meta-analysis of human fire use, and so draws together understanding of how human-environment dynamics influence fire regimes in a systematic way. We have integrated this model with the JULES-INFERNO biophysical model to allow the interactions between social and environmental influences on fire regimes to be explored. We have quantified the relative impact of climate, landscape fragmentation, human fire use and suppression on change in global fire regimes. We have also used WHAM! to provide an example of how human-Earth system modelling can support better definition of the potential for land-based carbon dioxide removal in achieving net-zero.

- **Anthropogenic drivers of fire regimes at a global scale**. We have collected and begun analysing global data on fire practices within smallholder and subsistence-oriented livelihoods, using both the literature and a survey of academic and practitioner experts. So far, these data have helped us to answer questions about: (i) trends in fire use and the drivers of these; (ii) how fire use purposes (e.g., driving game for hunting, clearing land for agriculture) are linked to patterns in the seasonality, size, and frequency of anthropogenic fires; and (iii) the types of policy instruments

that directly and indirectly govern fire use. Our findings contribute to broad scale understanding of the anthropogenic drivers of fire regimes. Furthermore, interdisciplinary collaboration between social scientists and climate scientists in the Centre has allowed us to link case study data about months of burning to climate data to look for patterns in the seasonality of anthropogenic fire use globally.

O1: Fire in the Tropics

- **Drivers of fire regimes in the Brazilian Amazon.** There is an urgent need to better understand what drives fire regimes in the Brazilian Amazon and to inform solutions to reduce wildfire frequency, given rising deforestation and forest degradation in the region, the existence of strong feedback between fires, deforestation and climate that could lead to massive forest dieback, and the limited impact of past environmental policies. Our analysis to date has showed that fires are becoming less frequent in the most well-connected parts of the Brazilian Amazon going through a process of agricultural intensification, while fires are becoming more frequent in the most isolated areas of the region and forests far from agricultural lands. Protected areas and indigenous lands are essential to reduce fires in the region.

- **Relationships between wildfires and tropical cyclones.** We investigated the interactions between tropical cyclones and fires, which have been overlooked in the study of hazard interactions until recently. Tropical cyclones can promote or enhance fires by setting up favourable atmospheric conditions either locally via their own circulations or remotely by altering large scale atmospheric circulations, the latter of which is our focus. We observed a correlation between North Atlantic hurricane and South Amazon fire activities, which we hypothesise is driven by cross-equatorial circulation anomalies, where latent heat released by Caribbean hurricane-related precipitations play a role.

- **Historical wildfires in Guyana.** In our palaeofire work, we are addressing the timing of wildfires in the landscape across the Neotropics and Guyana throughout the last 12,000 years using sedimentary charcoal records. This complements other research that we are carrying out in Guyana.

- **Spatial and temporal trends of wildfires in Ethiopia.** Burned area is reportedly decreasing across much of northern and eastern Africa, but these trends are not always clear, especially in semi-arid, highly variable climates typical of East Africa. Broad-scale studies can miss potentially important social, cultural and political context factors, justifying a more zoomed-in approach. We are working to uncover spatial and temporal trends in burned area across Ethiopia and to model the relative influence of climate and social drivers using remote sensing and GIS. Disentangling these drivers is important to understand how fire regimes are changing and the possible effects on people and the environment.

- **Wildfire trends in Kenya.** We are researching wildfires in protected areas in Kenya, identifying trends in burnt area, frequency of fires and how they differ between savanna and forest ecosystems, to guide development of site action plans and management plans while exploring the incorporation of wildfires in the management of protected areas.

- **Understanding wildfire patterns in India's forests.** Studying the use of fire by agrarian communities in the Uttarakhand Himalayas, we have found that livelihood use of fire by communities happens in winter and not in summer, and that these low-intensity surface fires in the winter season differ from more widespread and higher-intensity summer fires. This finding highlights that blaming local communities for intentionally starting fires in the summer season is mistaken, and other factors need to be looked at in explaining summer fires.

- **Fire activity through the fire season in SE Asia.** An air quality study focused on regions of Northern SE Asia (Laos, Thailand, Vietnam) enabled ground-based data to be collected before, during, and after the spring fire season. Together with satellite detections of active fires, these data help with understanding the progression of activity through a fire season along with comparison to 'normal' conditions, when weather limits the development of fires started for agricultural purposes.

- **Social-ecological interactions East and Southern Africa.** In an affiliated project (funded by the SSCP DTP), we are modelling complex and uncertain social-ecological interactions and feedbacks across contested conservation areas where wildfires are increasing across East and Southern Africa, specifically looking at the impacts of different systems variables on wildfires, savanna health, and local livelihoods.

- **Fire regimes in Ghana.** In another affiliated project (funded by LISS DTP) we are exploring trends in fire regimes in Northern Ghana over the last 22 years and the factors that account for the observed trends. Our findings revealed a declining trend for burned areas and active fires in Northern Ghana, although the decline was not statistically significant. The seasonality of fires aligned with the extended period of dry weather conditions in Northern Ghana. However, institutional interviews revealed that increased sensitization and implementation of land restoration projects coupled with the establishment of fire volunteer groups are changing the ways in which local people use fires on the landscape.

O1: Fire in the North

- **Behaviour of smouldering Arctic fires.** In the northern high-latitudes, peat soils are being exposed to fire, including fires that smoulder underground, due to the melting of permafrost, with both local and transboundary impacts. Through laboratory experiments, we have been examining how such smouldering peat fires behave in the Arctic, using a variety of measuring instruments, such as thermocouples to study thermal phenomena and visual and infrared cameras to qualitatively analyse the propagation patterns. We also aim to understand the impacts produced by the laboratory-scale experiments, in an effort to better understand how the Arctic fire process occurs.

O1: Fire at the Wildland-Urban Interface

- **Relationships between politics, policies and wildfire regimes in Greece**. Current wildfire policies in Greece typically involve active fire exclusion, contributing towards changes in fire activity by disturbing existing fire regimes. Political willingness to adopt proactive prevention has been slow, as politics favour fast, ad-hoc reactionary measures such as suppression due to its immediate

political appeal. A paradigm shift in management is urgently needed with involvement of experts and stakeholders to allow learning via diffusion of knowledge helping create a more co-ordinated response on mitigating wildfire damages. We interviewed stakeholders in Crete to detangle their views around wildfires. Our results suggest there is scope for conflict resolution and potential collaboration for producing holistic wildfire management.

- **The influence of electoral cycles on wildfires occurrences in the United States**. We have been enhancing our understanding of wildfire regimes by examining the influence of electoral cycles on wildfire occurrences in the United States. We identified a consistent change in wildfire frequency in states where incumbent governors seek re-election, revealing a distortion in wildfire management due to political incentives. Findings from an additional investigation on government partisan affiliation and wildfires also suggests disparities between political parties, with Republican governors linked to a reduced incidence of wildfires at the state level from 1992 to 2018.

- **Landscape management and wildfire regimes in the United States.** We have extracted and analysed wildfire protection strategies from community wildfire protection plans in the United States to understand how different strategies impact wildfire regimes through landscape management, specifically wildfire suppression. Additionally, in an affiliated project funded by LEMONTREE, we have been identifying critical drivers for modelling wildfire occurrence in a diverse set of environments across the contiguous U.S.

- **Agricultural burning in China.** It is common for farmers worldwide to burn crop straws and stubble left in their fields after harvest to prepare for new crops, reduce pests, and fertilize soils. However, the burning can easily contribute to air pollution and wildfires and thus many countries introduced burning bans. To understand how burning bans are implemented, we used China as a case and conducted interviews with regional, local, and grassroot agricultural burning regulators and village leaders in different parts of the country. We found implementation and enforcement of the bans are highly heterogeneous and the variations are not only shaped by local climates, but by societal pluralist interests, arrangement of departmental responsibilities and top-down accountability and blame. This project can advance the knowledge about how developing countries control biomass burning and about how the frequency, intensity, timing, and spatial pattern of fire on the landscape are influenced by social and political institutions.

Objective 2 - Predicting Fire

How can we incorporate new biophysical understanding, social learning and realistic human-environment dynamics so as to model fire regimes and associated patterns of land cover change more accurately, credibly, and accountably?

O2: Fire in Global Systems

- **A new global database on fire use.** We conducted an extensive systematic literature review and developed a global database, 'LIFE', on smallholder and subsistence-oriented fire practices. Using this database, we have now analysed seasonal patterns of intentional small-scale human fire use, distinguishing different timings of fire use during the year based on the intended purpose and local climate. We have made recommendations on how this could be used to inform and better represent the seasonal timing of human fire use in global models, and are now looking to extend this analysis with data from the Database of Anthropogenic Fire Impacts (DAFI) and the Global Fire Use Survey, both also compiled by our Centre.

- **Advancing wildfire predictions through Artificial Intelligence (AI).** We have created advanced wildfire prediction models at both regional and global levels through the use of simulations and satellite data, and the JULES-INFERNO fire model from the UK-Met Office. Additionally, we are leading the development of innovative AI-based wildfire predictive models that incorporate human interventions such as fire barriers and fire retardants, an aspect not currently addressed by existing AI fire prediction tools.

- **Improving model reliability.** Models always need improvement and testing. We have therefore tested our past and future fire regimes models on an out-of-sample experiment, showing that it could reproduce spatial patterns in burning under very large changes in conditions. We were also able to reasonably reproduce interannual variability. This makes our projections of how these properties may change under future conditions more reliable and credible.

- **Modelling fire occurrence.** In an affiliated project funded by LEMONTREE, we have developed a model to predict the daily likelihood of fire occurrence, with utility in earth system and regional modelling.

- **Post-fire resprouting**. Also funded by LEMONTREE, we have investigated post-fire resprouting which is a key adaptation promoting ecosystem recovery through rapid regeneration from meristems after fire. Resprouting has a significant impact on the terrestrial carbon cycle by promoting carbon sequestration after fires. We applied optimality theory, which would suggest that there must be a balance between the benefits of rapid recovery of photosynthesis against the costs of carbon storage. We are developing a theoretical basis for including plant adaptations to fire as a function of costs versus benefits in different fire regimes, and the impacts of these adaptations on ecosystem dynamics. This study will ultimately contribute to developing a more realistic model of the interactions between fire and ecosystems by considering the impact of resprouting trait.

O2: Fire in the Tropics

- **Predicting site-level vegetation fire vulnerability using remote sensing.** We are working to demonstrate how remotely-sensed data can be incorporated in wildfire monitoring at the site level, predicting the most fire vulnerable vegetation within the protected areas with the current technology accessible to remote multipurpose African landscapes.

- **El Niño-Southern Oscillation and wildfires in SE Asia.** We have studied the oceanic subsurface heat content of the Pacific basin as a long-range predictor of tropical atmospheric anomalies, particularly Continental and Maritime Southeast Asia fires and regional precipitations throughout the tropics. El Niño-Southern Oscillation (ENSO) is well-known to be one of the main drivers of multiple aspects of tropical meteorology. Our rationale here is to trace the chain further back to the intermediate stage during the ENSO cycle leading up to the maturation of an ENSO event. This study also helps fill an existing research gap on the dependence of Continental Southeast Asia fires on ENSO.

- **Predicting vegetation properties.** We are now able to predict post-fire related vegetation properties (using seasonal Landsat time series data) across different tropical landscapes (open savanna, riparian savanna forest, peatswamp forest, evergreen forest) in South America, Africa and South-east Asia.

- **A model of human-environment dynamics in Kenya.** In an affiliated project funded by SSCP-DTP, a Belief Network has been developed which incorporates different types of data and experience to model human-environment dynamics, including empirical data collected through fieldwork in Kenya (e.g., interview and questionnaire data), published literature, and expert opinion. It is parameterised based on future climate and socio-economic trajectories for this region and includes both implemented and proposed policy and management interventions.

O2: Fire in the North

- **Adding northern high-latitude peat fires into existing models**. Peat fires are some of the largest and most persistent fires on Earth which threaten to release vast amounts of long term stored carbon from the soil to the atmosphere. However, explicit representation of peat fires has been missing from the majority of fire and land surface models, leading to underestimations in burning and carbon emissions, particularly in the northern high latitudes. Therefore, we have developed INFERNO-peat, which adds a novel peat fire parameterisation for the northern high latitudes to the existing INFERNO fire model framework. The inclusion of peat fires, and their specific drivers, allows us to better represent patterns of burnt area across the northern high latitudes. Representing peat fires has also improved how the INFERNO fire model captures the interannual variability in carbon emissions from fires, allowing for more accurate and credible modelling of fires and their associated emissions.

Box 1: Arctic Wildfires Working Group

The Arctic Science WG aims to bring together the growing number of Centre members whose research relate to fires in the Arctic and northern high-latitudes. It aims to catalyse research collaboration and knowledge exchange, and identify and create opportunities to further contribute to the Arctic science community, such as working with the Arctic Council AMAP (Arctic Monitoring and Assessment Programme). It builds on a number of activities we have been involved in relating to Arctic fires, including leading a workshop at Arctic Science Summit Week 2023 (Tromsø, Norway) in collaboration with University of Leeds- ACRoBEAR and Arctic Voices; presenting at the Arctic Circle Assembly 2022 (Reykjavik, Iceland), leading a special session at International Symposium on Arctic Research, ISAR-7 in 2023 (Tokyo, Japan), in collaboration with ACRoBEAR, Arctic Voices and Arctic PASSION, and involvement in the development of Wildfires as a Shared Arctic Variable (with Arctic PASSION and Finnish Meteorological Institute), at a workshop in Inari, Finland (2023).

Photo: Participants at the Wildfires as a Shared Arctic Variable workshop in Inari, Finland in September 2023

O2: Fire at the Wildland-Urban Interface

- **Predicting and responding to fire vulnerability from firebrands at the WUI.** In an affiliated project funded by PyroLIFE (and based at Imperial Hazelab), we have developed practical quantitative tools that can be applied to measure the vulnerability of WUI homes to wildfire ignition and to predict the contact exposure of firebrands, the most challenging wildfire spread modality to mitigate, to simple WUI obstacles. The Wildfire Resistance Index (WRI) we have developed is a practical and effective tool policy makers and emergency services can use to calculate the relative vulnerability of WUI buildings to wildfire damage; this tools assists predicting wildfire damage, and in assisting the most vulnerable buildings in a community during an emergency. We also developed firebrand contact exposure maps, a method to visualise firebrand contact exposure around simple obstacles, modelled in FDS (a computationally fluid dynamics software, widely used in fire safety engineering). This method can be applied by construction and insurance companies to quantify and predict firebrand exposure under varying conditions, thus assisting in designing safer building to more safely live with fire. These tools also contribute to Objective 4, Living with Fire.

Objective 3 - Quantifying Impacts

How are people, the places and properties they value, and the resources and ecosystem services they rely on (including biodiversity, air quality, carbon sources/sinks, and climate), affected by wildfire and by changes in the regimes governing it?

O3: Fire in Global Systems

- **The first global database of human impacts on fire**. We constructed the freely available Database of Anthropogenic Fire Impacts (DAFI) from a meta-analysis of 1,800 worldwide case studies of landscape fire. DAFI represents the most comprehensive meta-analysis of global fire use to date, spanning all key land systems and policy regimes from over 105 countries on all continents (except Antarctica) between 1990-2020 from 523 papers. Analysis of DAFI revealed that seven fire-use types account for >90% of case studies, and we found distinctive quantitative signatures in the different fire uses.

- **Measuring emissions in the laboratory and field.** Work to understand emissions from wildfires has taken place in both laboratory and field settings. By measuring gases and particulates emitted from different fire sources (different fuels such as leaf litter, wood, peat) and different burning conditions (flaming or smouldering) data has been collected to help refine larger scale emissions estimates that are derived from satellite measurements. A range of equipment is used to make these measurements including new sampling techniques using drones. Measurements have been made as part of a number of other projects to cover a range of biomes, including Canada, Indonesia, Laos and China. We have also facilitated real-time, high-resolution measurements of Green House Gases (GHGs), air pollutants, and trace gases, which has enabled a comprehensive understanding of emissions' spatial and temporal dynamics, helping us to quantify impacts on air quality, and climate. By simultaneously measuring gas species, trace gases, and particulates, we can unveil intricate interactions among emissions, and contributes to understanding global climate change drivers.

- **Impacts of future fire emissions.** Working with colleagues from the FireMIP initiative, we are producing a synthesis of projected future fire emissions under different IPCC climate change scenarios, taking into account the feedbacks from climate change using several different fire models. We have also analysed the impact that changing fire emissions in the future themselves could have on atmospheric composition and the rate of climate change. We are now also working with the United Nations Environment Programme TF-HTAP (Task Force on Hemispheric Transport of Air Pollutants) and Arctic Council AMAP (Arctic Monitoring and Assessment Programme) working groups on developing updated future fire emissions scenarios.

- **Wildfire impact on radiation budget.** We are looking at how wildfires in Africa change surface properties and what effect this has, both locally and globally, on the radiation budget (the overall balance between the incoming energy from the sun and the outgoing thermal and reflected energy from the earth). Do to this, in a project co-funded by NERC NCEO, we are analysing satellite data to quantify surface reflectivity changes following landscape fires and calculate the effect of these on the amount of solar radiation absorbed. Locally, we believe this could have significant

implications, affecting the amount of heat available near the surface and therefore influencing atmospheric circulation and precipitation patterns.

- **Hydrological effects of wildfires**. We are attempting the quantification and the intercomparison of short/medium term hydrological effects of wildfires, from a water resources perspective, at a global scale. It quantifies the regional effects based on observational data and further recognizes and analyses the underlying mechanisms and drivers of those changes. We found variability in severity and direction of wildfire impacts on river flows across globe, with indications of anthropogenic water management induced mitigation of the wildfire effects.

- **Forestry, wildfire risk exposure, and investment.** Evaluating forestry investment potential involves analysing global wildfire, carbon sequestration and biodiversity data to understand its impact on investment portfolios. We have conducted research to assist not only financial institutions in gauging direct wildfire risk exposure in forestry investments, but also asset owners in modelling and understanding wildfire risk and vulnerability across asset classes. Consideration of climate risk projections reveals additional opportunities for sustainable, climate-resilient investments. A forward-looking, holistic approach integrating wildfire risk exposure, carbon sequestration potential and biodiversity enhancement is expected to yield long-term economic gains aligning novel investment opportunities with environmental sustainability.

  We have observed a direct connection between wildfire risk and biodiversity-carbon sequestration potential in forestry, delivering a way to mitigate the risk while capturing the upside potential of the investments. At the same time, we have identified biomes for which wildfire is intrinsically associated with biodiversity. We are integrating these considerations in the optimal design of forestry-backed assets, a particular type of carbon-based assets. Our recommendations are that investors wanting to finance forestry-backed carbon projects should look to diversify their investment across relevant geographies, tree types and vintages. There are natural benefits of risk pooling to be reaped while controlling for wildfire risk exposure and biodiversity targets at the same time. The use of state-of-the-art wildfire risk models is essential in the optimal design of carbon-based assets.

- **Financial risks and wildfires.** We have several further projects relating to financial risks and wildfires. The first relates to the valuation of forestry-based debt instruments and assessing their viability and benefits as a financial instrument in different scenarios. An in-depth analysis explicitly quantifies the adverse monetary impact of wildfires on the valuation of these forestry-based instruments and consequently the funding of forestry-based projects.

  A second project investigates the impact of rising temperatures on the creditworthiness and pricing of the debt of sovereign countries. The impact of increasing temperatures is propagated to a country's macroeconomic indicators via GDP damages. We have successfully modelled and projected the joint evolution of macroeconomic variables, acute physical risks and sovereign ratings of ~80 sovereign states up to year 2050 under different climate policies, and quantifying the impact on the cost of sovereign debt.

  A third project assesses the incentives to abate emissions in the presence of short vs. long-lived gasses and carbon markets. The project goes at the heart of carbon accounting rules and as such

allows us to examine in detail how wildfire risk at different locations (e.g., peatland) can undermine carbon-based projects and financed emissions in different ways.

O3: Fire in the Tropics

- **Measuring air quality in Indonesia.** A study on air quality impacts from Indonesian peatland fires highlighted how damaging air quality could be to vulnerable people. A sensor network set up during the 2019 fire season proved how extreme the concentrations of airborne particulate matter were, along with how these measurements compared with satellite-based estimates. A substantial amount of work was also undertaken to verify how well these small sensors operate in extreme conditions. The data from Indonesia were then used in an additional study quantifying how this exposure affected pregnant women and birth outcomes (such as lower birth weight).

- **Air quality sensor network in SE Asia.** Our air quality work has expanded further to include a network of small sensors across parts of northern South East Asia (Laos, Thailand, Vietnam) – the SE Asia Air Quality Sensor Network– which is the first of its kind. Satellite data from this region suggested that it had some of the worst air quality in the world, but there was very little ground-based data to verify this. The network of around 60 sensors has enabled baseline and fire season data to be collected with the intention of collecting a multi-year dataset.

- **Impact of Indonesian peat fires on weather and climate.** We have developed a fully-coupled atmosphere-ocean climate model to investigate the effect that extensive smoke from Indonesian peat fires during El Niño years has on the weather and seasonal climate, finding a significant feedback on Pacific Ocean temperatures and El Niño progression.

- **Fires and ecosystem services in India.** In the Uttarakhand Himalayas, we examined how summer and winter fires provide different ecosystem services to the local communities. While the winter fires are critical to the local agrarian economy, their role is not recognised in media or policy. The singular framing of 'all fires are bad' forms part of the dominant narrative.

- **Fires and ecosystem services in the Brazilian Amazon.** Our models of fire in the Brazilian Amazon show that fires are more frequent in the portion of indigenous land/protected areas that are close to unprotected lands. The resulting forest degradation of protected forests jeopardizes some important ecosystem services at a regional level, such as conservation of biodiversity, evapotranspiration or carbon storage.

- **Understanding fire impacts through charcoal records in Guyana**. Our analysis of charcoal record in the Neotropics and Guyana are being used to understand the impact of fire on the landscape, specifically on how the vegetation/biodiversity responds to changes in fire.

- **Quantifying the impact of wildfires on the human-wildlife conflict dynamics in Kenya.** Wildfire impacts have not been quantified in the context of human-wildlife conflicts and other human-wildlife interactions. We have recently started a project quantifying the impact of wildfires on the human-wildlife conflict dynamics in multiple use landscapes in Africa, with a focus on Kenya. Additionally, it will also identify how wildfires, large mammals and livestock shape the vegetation in protected areas and non-protected areas. This is aimed to guide an upcoming model, integrating

wildlife and livestock especially in non-protected areas where fires are used regularly to maintain forage.

- **Applying burning emissions areas abatement schemes to African savannas**. In an affiliated project (funded by SSCP DTP), we review the opportunities and challenges for savanna burning emissions abatement schemes developed in Northern Australia to be implemented in East and Southern African savanna-protected areas, explicitly highlighting the trade-offs between greenhouse gas emissions targets with biodiversity, savanna health, and local people in this context.

O3: Fire in the North

- **Improving CO emission estimates at high latitudes. We** are working on improving our Carbon Monoxide emission estimates for high-latitude fires (focusing on Siberia and the Canadian Arctic) from polar-orbiting satellites. By having more accurate emission estimations, there is the potential for improving the data that goes into large-scale global models that forecast future climate scenarios for climate change modelling.

- **Canadian fighter exposure to wildfire smoke.** Data have been collected to form a pilot study to quantify exposure of fire fighter crews to hazardous smoke. The study instrumented members of fire crews whilst on a fire line in Ontario, Canada. Together with ambient measurements of smoke, the personal exposure will help to identify situations where exposure is highest.

- **Future impacts of prescribed burning in Scottish Highlands**. In collaboration with the Game & Wildlife Conservation Trust, we investigated future impacts on biodiversity and carbon stocks, of prescribed fires and woodland restoration in the Cairngorms National Park. Amongst other findings, the results show that restrictions on prescribed fire use will have a mixed impact on open-ground species and a negligible impact on sequestration of carbon in biomass. The impact of prescribed fire restrictions is concentrated in parts of the park dominated by carbon-rich soils and will have a stronger economic impact on sporting estates in these areas, especially if they are unsuitable for mechanical mowing.

O3: Fire at the Wildland-Urban Interface

- **Effectiveness of wildfire mitigation in the United States**. We are analysing a uniquely created dataset combining community wildfire protection plan features and wildfire event characteristics in the United Sates, in order to quantify the effectiveness of wildfire protection strategies in mitigating wildfire impacts on social systems.

- **Costs and preference of wildfire management policies in Crete**. Understanding the costs of wildfire on human wellbeing is complicated through the fact that many damages from wildfires are unquantifiable. We have used economic valuation surveys in Crete to estimate social benefits for shifts in the current suppression-oriented policies by eliciting the change in social welfare that this would produce. The costs related to this were measured in the form of taxation for a new wildfire management policy. Overall, our findings indicate a strong preference amongst the

general public in Crete to shift current policies based on suppression towards more integrated approaches dealing both with prevention and post-fire management.

- **Impact of Greek wildfires on weather and air quality.** We are investigating the impact of the devastating Greek wildfires in August 2021 on weather and air quality. Using an atmospheric model called WRF–Chem and validating the simulations with observations, we found on average 1°C lower temperatures for the smoke plume affected areas compared to the fire free areas. We compared our model's predictions of air pollution levels to observations from NASA's MODIS, finding that including emissions from wildfires improved our results by 50%. Overall, using data from the wildfires made our predictions considerably more accurate.

Objective 4 - Living With Fire

What does wildfire mean to different social groups, and what changes in fire regimes and associated landscapes and management practices would be culturally, politically, environmentally, and economically acceptable to whom – and why?

O4: Fire in the Tropics

- **Indigenous fire management and protected areas in Guyana**. We have conducted research focused on the place-based fire knowledge and practice of the Wapichan and Macushi peoples in South Rupununi, Guyana. We investigated how varying land users perceive and interact with fire, how changes in wider land use affect local burning regimes and impact decisions about governance at a livelihood and communal level. We also examined the tensions that exist between incongruous and disparate intentions in fire management, including looking at fire management within the context of the carbon market. Our research illustrates how land tenure and land use objectives are closely linked to perceptions of 'appropriate' savanna fire management.

- **Connecting palaeofire records with current fire patterns and traditional knowledge.** Through our palaeofire work in Guyana analysing long-term charcoal records, it is hoped that a natural baseline of fire can be seen within the landscape and be used to understand if current fire patterns are suitable. We are also investigating if this new environmental data complements the traditional knowledge on fire changes in the region.

- **Traditional fire use and practice in Mozambique.** Ethnographic research that we have undertaken with indigenous communities around Gile National Park in Mozambique demonstrates that as anticipated, fire continues to support a range of subsidence activities as it remains the most accessible and effective tool for land conversion. However, contrary to common misrepresentations, burning is conducted judiciously with the careful consideration of a variety of ambient conditions. In addition to which, a range of precautionary behaviours are undertaken to mitigate the risk of wildfires. These preventive measures include the creation of fire breaks, the

use of back-burning as well as constant fire-tending and vigilance during burning events. Taken together, these practices reposition local people from 'wanton burners' to adept fire-users in possession of traditional fire knowledge. As part of this project, we have produced and presented the participatory seasonal calendar to conservation managers which will help the Park authorities make important decisions regarding fire management as well as assisting the development of community-based projects more broadly.

- **Conflicts in fire governance in Ethiopia.** In our work exploring the drivers and trends of fires in southern Ethiopia, we have focused on a case study in a Community Conservation Area (CCA) where fire is widely used, for example by local pastoralists. The study aims to address questions around traditional fire management and conflicting views between community, government, and non-government actors on how fire should be governed and managed from a wildlife or livelihoods perspective, comparing these different opinions and to uncover competing or complementary worldviews. To date, we have conducted focus groups and participatory mapping with communities covering three different stakeholder ethnic groups.

- **Fire use and management in India and the impact of rural depopulation.** In our research in the Uttarakhand Himalayas, we conducted an extensive survey covering over 100 villages and 600 participants in the study area to test the findings from ethnographic fieldwork. We looked at how past forestry practices have shaped the flammability and fuel continuity in the landscape. It looked at how local agrarian practices keep the fuel load low in these landscapes and prevent bigger, more catastrophic fires in summer. The findings caution that rural depopulation can put these landscapes at greater risk of more extensive catastrophic fires in future, similar to what happened in Mediterranean Europe in the 20th century.

- **Legacies of colonial regimes on land governance and fire regimes in East and Southern African savanna-protected areas**. In an affiliated project (funded by SSCP DTP) we reviewed the current framing, nature, and extent of community-based fire management across East and Southern African savanna-protected areas. This review centralises the legacies of different colonial regimes on inter- and intra-group relations across this region and their impacts on land governance systems, highlighting the challenges these processes have embedded in decentralising decision-making rights over natural resource management and fire use.

- **Equitability of Ghana's fire policies.** In another affiliated project (funded by LISS-DTP), we employed a critical discourse analysis to understand the key discourses that have dominated debates about traditional fire practices and rendered it governable in Ghana. Additionally, we employed the social equity framework to assess how equitable are Ghana's fire policies. Preliminary findings revealed that both farmers and shea nut pickers (who are predominantly women) are often affected by late fires which has implications for household food security and local livelihoods. In contrast, the declining burned areas are modifying livelihoods of hunters who are being discouraged from burning to drive out rodents from the bushes for hunting for game as well as herders who use fire to resprout grasses for grazing.

Box 2: Fire Governance Working Group

Fire is governed by governments, non-governmental organisations, and communities. It can be influenced by regulations, economic policies, development projects, community agreements and customary norms. Most often, state governance has suppressed, rather than supported, controlled human fire use, with implications for livelihoods, culture, and biodiversity.

The Fire Governance Working Group aims to stimulate discussion about how fire is managed and governed across the world. It provides a space for Centre students and staff to present their ideas and work, to explore commonalities and differences, and to challenge current thinking and paradigms of governance.

Themes we have been exploring and developing for a joint publication include: the legacies of colonialism in anti-fire regulations and narratives; the indirect effects of economic policies, land tenure reforms, and infrastructural development on fire; and the interactions between different types of fire governance.

The WG is has held several events including a virtual workshop on pastoralism and fire in Africa (2022), a session on governing fire across spatial boundaries, at the Royal Geographical Society Conference (2023), and recently a webinar with international experts on trade-offs and synergies in multi-level fire governance (2023).

O4: Fire in the North

- **Implications of changing fire use in Scotland**. Scotland is revising its legislation governing fire use. These reforms are targeted at grouse estate managers, and the implications for crofters' (smallholder farmers) fire use are poorly understood. We sought to fill this knowledge gap by exploring how fire use is important in crofting, and how fire use has changed in living memory in response to changing social, economic, and ecological conditions. We carried fieldwork in the Highlands & Islands of Scotland, conducting semi-structured interviews with crofters about changing fire use, and participating in meetings held by the Scottish Crofting Federation. Our research points to the loss of controlled fire use as a driver of wildfires in Scotland, and to the enduring importance of fire use within marginal agricultural livelihoods in the UK, despite poor public understanding of these issues. The partnership we built with the Scottish Crofting Federation means that our research findings are helping to inform the Federation's response to ongoing legislative change regarding fire use in Scotland.

O4: Fire at the Wildland-Urban Interface

- **Towards improved wildfire policies in Sicily.** In Italy, we have been exploring the significance of wildfires to diverse social groups, through organizing a stakeholder workshop in Monreale in Sicily. Through discussions and Q-Methodology, we unveiled complexities, conflicts, and tensions associated with wildfires, and formalized diverse perspectives among stakeholders, exposing socio-economic and political dimensions. By recognizing inherent conflicts in the policy-making process and identifying areas of consensus, the project contributes to culturally, politically, environmentally, and economically acceptable wildfire policies, enhancing the acceptability of wildfire management practices in the Monreale region.

- **Perceptions and enforcement of agricultural burning bans in China.** Farmers worldwide tend to burn crop straws and stubble left in their fields after harvest to prepare for new crops, reduce pests, and fertilize soils. However, to control urban air pollution, many countries introduced burning bans. In determine how the bans are implemented, we used China as a case and conducted 64 interviews with burning regulators and village leaders in different parts of the country. We found that regulators in many localities had to be soft in implementation as farmers had multiple ways to game with inspectors. Through those methods, farmers in many localities had successfully reduced the stringency of enforcement to an acceptable level. This finding reveals agricultural wildfires have different meanings for rural and urban residents, and practical interactions between farmers and regulators can mitigate the adverse impacts of absolute burning bans.

- **Wildfire risk perception and management in South Africa.** We are exploring how risk perception, government coordination, and social capital in divided post-apartheid South African society influences different functional dimensions of managing wildfires in the wildland-urban interface areas. These functions include: (1) tensions between preventative land-use planning to reduce risk and housing growth to satisfy housing need and respond to demands for land, (2) vegetation management, conservation, and controlled burning to reduce fire risk, and (3) fire suppression emergency operations.

- **Wildfire evacuation planning.** In an affiliated project, funded by EPSRC (based in Imperial Hazelab), we used simulations to inform and aid in evacuation planning. Understanding how wildfire behaves in the landscape around a community, how people choose to evacuate when faced with a hazard, and how the two processes interact is critical in accurately quantifying the impact of wildfires on communities. Providing communities with tools to decide when to start the evacuation and avoid dire conditions, develop relevant policies and assess the effectiveness of wildfire preparedness plans plays a critical part in ensuring resident safety. Having such plans is an important step in living with fire, and being prepared for the extreme cases of fire threatening human settlements.

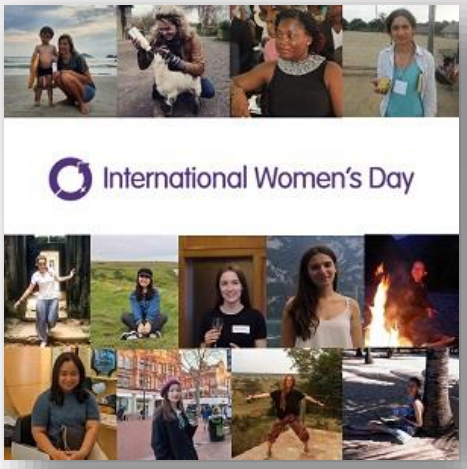
Box 3: Equality, Diversity and Inclusion Working Group

The Equality, Diversity and Inclusion Working Group (EDI WG) was set up with the aim of embedding EDI and social justice into the culture of the Centre, and to be an integral part of the way we do things at all levels. Our motive is to help contribute to making a fairer, more just and equitable society, starting with the way we operate as a Centre and as individuals. The WG focus includes how we work with each other on a day-to-day basis (such as meetings and workshops, and providing support to our members), how we do our research (e.g. exploring decolonising environmental science), and our outreach and communications (including recruitment).

Some actions we have taken, to date, include:

- an ongoing series of decolonising fire science workshops and associated reports
- building on-going collaborations in the places where we work
- utilising international fee waivers to recruit students from low-middle income economy countries and to have students from the countries we are working in
- offering full travel bursaries for our summer conference to ECRs from low-middle-income economy countries
- offering paid summer placement programmes for undergraduates, encouraging applications from underrepresented groups
- connecting with our art-science initiative to help share diverse and overlooked voices
- advertising PhD and post-doctoral positions with BBSTEM
- partnering with charity Generating Genius to engage students from African and Caribbean backgrounds in a virtual wildfire challenge
- celebrating International Women's Day through a special feature on women in our Centre.

Many of our Early Career Research activities (page 32) also aim to increase the feeling of community and inclusion, and to provide professional development opportunities to all our members.



Images: Top – celebrating International Women's Day

Bottom: Bursary recipients, Aline Naawa from Ghana and Naftal Kariuki, from Kenya, attending the Leverhulme Wildfires Summer Conference 2023

Partnerships and Collaborations

Through our pre-existing partnerships, and new networks that we have developed over the last four years, we have built an impressive array of organisations, communities and individuals with which we work and support, both nationally and internationally.

Formalised partnerships have been made with several Affiliated Organisations and Groups, which undertake substantial work on wildfires and bring their own resources to work with the Centre for a specific period of time on a particular topic or activity, including:

- **Technical University of Crete:** specifically, climate.tuc - *The Laboratory of Atmospheric Environment and Climate Change* – who are constructively building a deeper understanding of fires, their impacts, and best ways of managing them, particularly (but not limited) to the Mediterranean. Climate.tuc is home to several members of our Centre, including an Associate Director.
- **FURNACES**: *Fire in the Future- Interaction with Ecosystems and Society,* a three-year German-Austrian collaborative project, which aims to bring together expertise in fire ecology, social ecology, remote sensing, data science and vegetation modelling to better understand the local to global relationships between human, climate, vegetation and fire.
- **ACRoBEAR and Arctic Voices:** These are closely linked projects, both led by the University of Leeds, are focused on improved understanding of societal impacts of high-latitude fire.
- **LEMONTREE**: *Land Ecosystem Models based On New Theory, Observations and Experiments,* a five-year project involving an international consortium led by the University of Reading, aiming to develop a next-generation model of the terrestrial biosphere and its interactions with the carbon cycle, water cycle and climate.

Beyond these Affiliated organisation and groups, in the UK we work closely with both the **Met Office** and **NERC National Centre for Earth Observation** as well as the **British Antarctic Survey**. We are a member of the **England and Wales Wildfire Forum** and the **UK Wildfires Research Group** (UK WRG), and have hosted in-person meetings for these two networks, as well as the **National Fire Chiefs Council,** at Imperial. We have built good connections with individuals within these networks, including members of the Fire and Rescue Service and the Forestry Commission. We have also collaborated with NGOs, including the **Cobra Collective**, the **Game and Wildlife Conservation Trust,** and are beginning a collaboration with **RSPB.** We also work with many UK universities, including (but not limited to), the **University of Exeter** and **University of Oxford.** For our engagement work, we have collaborated with **Arts Cabinet** and **Science Gallery London**, and the **United Nations Association Climate and Oceans** and **Space4Climate**. We have also worked with industry for example, **Optect**, as part of an Innovate UK project**, AXA XL** insurance, and through **The Lighthill Risk Network.**

We also have extensive partnerships and collaborations across the world. Some of our connections arise through being involved in newly funded projects, others are developed through our research or our engagement and dissemination activities. In addition to many additional collaborations made locally in our study sites, partnerships with international organisations, projects and formal networks include (but are not limited to):

- European Space Agency (ESA)
- The National Aeronautics and Space Administration (NASA)
- European Centre for Medium Range Weather Forecasting
- Canadian Forest Service (Canada)
- Ontario's Ministry of Natural Resources (Canada)
- Upper ASEAN Wildland Fire Special Research Unit (Thailand)
- National Centre for Hydro-Meteorological Forecasting (Vietnam)
- Commonwealth Scientific and Industrial Research Organisation CSIRO (Australia)
- AirTank (USA)
- Cool Ground (Ethiopia)
- Arba Minch University (Ethiopia)
- The National University of Colombia (Colombia)
- The University of Alcalá (Spain)
- The University of Melbourne (Australia)
- University of California, Davis (Jin Lab) (USA)
- National University of Laos (Laos)
- Strathmore University (Kenya)
- Kasetsart University (Thailand)
- United Nations Environment Programme TF-HTAP (Task Force on Hemispheric Transport of Air Pollutants)
- Arctic PASSION
- iFireNet
- TREEADS
- FirEURisk
- FireAdapt
- PyroLIFE
- FireMIP

Photo: Members of our KCL team conducted a five-week campaign in Ontario in collaboration with Ontario's Ministry of Natural Resources and the Canadian Forest Service in 2023, with funding from ESA. Staff from CFS assisted with the overall planning and operating instruments on science flights and MNR facilitated a 10-day ground campaign, sending out a fire response crew with staff from both CFS and our Centre, to conduct research at the fireline of a wildfire. Credit: Mark Grosvenor, King's College London

Engagement and Impact

Engagement with the public, practitioners and science community

We strongly believe in the importance and value of engaging with people beyond our Centre, to share our research as well as to learn from others. We have been doing this in a variety of ways, which include:

- **Fire in Practice webinar series:** *'Fire in Practice – Conversations with Wildfire Practitioners'* is an ongoing programme in which we invite practitioners from across the world to talk about their area of wildfire practice. The aim is to explore the developments and challenges 'in the real world' of wildfire, reflecting on the role and opportunities of research in addressing these issues, and to bring this to both our Centre members, the science community, and the public.
- **Public workshops and webinar:** in addition to Fire in Practice, we hold ad-hoc public webinars and events on specific topics of interest.
- **Fire science community meetings:** we have organised focused workshops with key experts, for example on UK Wildfire Modelling (2023), Fire Ecology (2021) and the Reading Palaeofire Database (2021).
- **Leverhulme Conferences –** in July 2023, we held our first open conference (since our launch event), which was a great success, bringing together wildfire scientists and practitioners, and sharing our research as well that of others. Going forward, we plan to hold a summer conference every two years, with the years in-between focusing on an internal spring symposium for Centre members and affiliates. We held our first internal symposium in spring 2022.
- **UN Climate Change Conferences** – we have engaged with the UN Climate Change COPs in several ways, including a side event at COP26 in Glasgow (in collaboration with Space4Climate), hosting the United Nations Association Climate and Sustainability Youth Summit fringe event for COP28 at Imperial, and holding an exhibition at the KCL 'Time for Action not Words' COP28 fringe event.
- **Media** – we have regular engagement with the media, including TV and radio interviews, news, and feature pieces, often in response to major wildfire incidents. This includes major networks such as BBC, Sky News, The Sun, Channel 5 News, Times Radio, The Independent etc, as well as smaller outlets and podcasts (e.g. the Good Fire Podcast).
- **Great Exhibition Road Festival 2022:** some of our research on the social and physical modelling of wildfire through AI, was presented to the wider public in this annual festival.
- **Wildfires and Art –** we have an on-going initiative, Wildfires at the Art-Science interface, described further in Box 4 below, which engages scientists, artists, the public and practitioners with wildfires in creative ways.

Box 4: Wildfires at the Art-Science Interface

Wildfires at the Art-Science Interface is a multi-layered initiative launched in 2020, delivered through a partnership with the Arts Cabinet, along with other collaborators including Strathmore University in Nairobi, the University of Melbourne, and the Science Gallery London. The initiative brings together artists with researchers from our Centre – as well as practitioners, external researchers, students and members of the public – to engage creatively and critically with an exploration of wildfires through art. It is a fluid, dynamic and ongoing initiative, involving multiple phases and activities, and was recently presented as plenary 'AFEx' talk at the Association for Fire Ecology 10th International Fire Ecology and Management Congress, in California. Phases to date include:

- **Seeing Fire: Perspectives Through Art and Science** (2020)– an online gallery which showcased works by artists whose practices connect with fire, alongside texts and images by scientists from our Centre. We sought to bring these different perspectives together presented side-by-side with no-hierarchy of knowledge.
- **Wildfires (Working Title)** (2020) - online collaborations between selected artists and scientists, for approximately three months, where pairs or teams were asked to produce three submissions for the online editorial. The aim was to facilitate thought exchange and generate new understandings and thinking around wildfire.
- **Stolen Climate** (2021-2023) - a commission by Torres Strait Islander artist Clinton Naina, which culminated in an exhibition at Science Gallery London. The exhibition presented Australia's First Nations Peoples' perspectives on fire and climate, whilst the launch event brought together the public, scientists, and artists to share global perspectives of fire. The exhibition also included the film 'The Fire Keepers' by Tim Georgeson, exploring cultural fire practices, alongside satellite imagery showing Australian wildfires through the lens of technology.
- **Fire, Climate, Landscapes and Decolonising Fire Science – collaborations in Kenya** (2022-2023). In collaboration with Strathmore University in Nairobi, we organised a workshop involving stakeholders from across Kenya to discuss fire management. The workshop also involved a local artist, Shadrack Musyoki, who led a participatory mural with workshop attendees, and created two further paintings. Leading on from this, we held an art-science workshop simultaneously in London and Nairobi, where participants again engaged in painting a mural. As part of the workshop, we also ran a competition with Strathmore, where students and staff submitted written or visual creative entries responding to the question – *"What does Climate Justice Mean to you?"*
- **Wildfire Research Through the Lens** (2023). In association with our summer conference, we ran a competition to find photographs and accompanying narratives that best communicate the impressive work of PhD students studying wildfires from across the world. The entries were exhibited at the conference and at further outreach events.

Photos: Left, Clinton Naina with "Stolen Climate", and Right: "Mazingira yetu wajibu wetu" (Our Environment, Our Responsibility) by Shadrack Musyoki and workshop participants

Impact of our work

Real-world impact of research is an essential component of modern science, contributing to enhancement of society. We already have demonstratable impact from our research and collaborations, beyond our contribution to scientific understanding through our publications and databases. This will continue to grow substantially in Phase II, as Phase I projects complete, and our new projects begin. Examples to date include:

- **Indigenous fire use in South Rupununi savannas of Guyana.** Our research exploring changing practices of Indigenous fire use and the implications for fire governance in the South Rupununi savannas of Guyana, has begun, through collaborative processes, to input into local management plans to be used for making decisions about fire governance. The research has used a combination of archival, ethnographic, and ecological methods and includes the production of a community map identifying areas where gaps in local fire management occur, why the gaps exist, and how local communities can use their participation in the research to lobby for local and appropriate fire policies. This case study will also be providing a report highlighting key recommendations to the overarching Indigenous District representative body. Generally, fire policies are developed top-down with no proper comprehension of the local social-ecological context, in Guyana there has been no such national policy. This research highlights how local communities can self-organise to create local and appropriate policies and how fire research can be used to facilitate this movement in lobbying for appropriate support.

- **Air quality in SE Asia.** Our research led by our KCL team looking at impacts of air pollution from peat fires in Indonesia has led to technology and knowledge exchange with local government. This research project involved measuring levels of PM2.5 (fine particulate matter) in the atmosphere during an Indonesian fire episode by installing a series of air quality sensors around a city located in Kalimantan both during and after an El-Nino driven fire season. The measurements, combined with data on citizen movements logged

by personal GPS devices, were used by health scientists to better understand the exposure of citizens - in particular pregnant woman - to PM2.5 during and also outside of the fire season. The project has led to UNICEF deploying the same technology through a charity project in the city where they were trying to make 'haze free' classrooms that protected children from the poor air quality outdoors. The project also led to knowledge exchange with government representatives, including how much peat was affected and the air quality impact. There is a large peatland restoration peatland in Kalimantan now aiming to reset some areas to try to reduce its flammability. Leading on from this, we have now also led the installation of the first air quality network within rural regions of SE Asia (in Vietnam, Thailand and Laos) (photo above).

- **Fire detection.** We collaborated with a commercial start-up Optect (formally Tethir) to help develop a novel thermal infrared fire detector. Measurements made of fires in our Rothamsted KCL Combustion Chamber from an advanced thermal camera owned by KCL were fundamental to its development. This new device has potential commercial applications for many companies, including fire detections in large warehouses and from electricity pylons owned by energy companies.

- **Satellite products.** Our group at KCL are responsible for designing algorithms underlying a series of operational geostationary active fire products as well as those used by space agencies to deliver information from polar-orbiting satellites. Through this work, we have contributed to the capability of the Sentinel-3 Fire satellite product now working in the day. This will ultimately be used by tens of thousands of people as it will take over from MODIS when that soon retires. We have also contributed to the Himawari fire product being used for real time early warning of fire and smoke throughout SE Asia.

- **European Space Agency.** We are helping to design a new generation of Earth Observation missions with fire measurement capability for ESA. ESA is also using our social wildfires model for nowcasting wildfires in real time.

- **Scottish Crofting Federation.** We are conducting research into fire use by crofters in the Highlands and Islands of Scotland, in partnership with the Scottish Crofting Federation (SCF), which is informing their policy position and consultation response to the draft Wildlife Management and Muirburn (Scotland) Bill. We will be running meetings in crofting communities together with representatives from SCF and the Scottish Wildfire Forum to gather local perspectives on the proposed legislation, and findings from the meetings will be supplemented by detailed research interviews with crofters. The Bill has mostly been designed with fire use by grouse shooting estates in mind, and this research fills an important gap in knowledge about the fire knowledge and needs of smallholder farmers who will also be affected by the new burning regulations.

Further potential impacts in the near-future include:

- **Predictive models for firefighting.** We have established a connection with Airtank, a company specializing in the development of aircraft equipped for fire retardant operations. Airtank has shown a strong interest in leveraging our advanced predictive model to strategically deploy firefighting resources for optimal effectiveness. This collaboration highlights the potential synergy between our predictive capabilities and their cutting-edge technology, which could significantly enhance wildfire management strategies.

- **Wildfire forecasting for insurance sector.** We are in active communication with AXA XL Insurance to assess our developed model for wildfires forecasting on a global scale, with a particular focus on evaluating wildfire hazard risks worldwide.

- **Fire policies in Brazil.** The results of our research on fire regimes in the Brazilian Amazon were presented in meeting on the Sustainability of Agriculture in Brazil, organized by Imperial College London and the Brazilian Embassy, in the presence of key stakeholders, including National Secretary of Bioeconomy, representatives from the Ministry of Agriculture, and the head of agribusiness in a large investment bank. This was an important meeting to potentially influence future fire policy and practice in the region.

- **Fire policies in Sicily**. We held two stakeholder consultation workshops in Sicily, in the Municipality of Monreale in June 2023, fostering discussions across diverse sectors and revealing intricacies linked to wildfires. In the second workshop, national-level experts convened, underscoring the crucial significance of landscape-level silviculture for wildlife conservation, wildfire prevention, and human protection in direct response to the pressing needs identified through our research. Again, these were important meetings for potentially impacting on future policy and practice.

- **Fire governance network in Kenya.** In collaboration with Strathmore University in Nairobi, we delivered a two-day workshop bringing together stakeholders from across Kenya, including land managers, village chiefs, scientists and NGO representatives, to discuss fire management, forming a new network, and together developed a Joint Declaration on the needs for fire management in Kenya, including what they would initially agree to, to progress the issue of fire management in the country.

- **Firefighter health.** We provided sensors to monitor the smoke exposure of wildfire fighters responding to a fire in Ontario, Canada. The results from this may have potential impacts on Ministry of Natural Resource's policies for their fire crews.

The Next Generation: Education and Training

Developing our Early Career Researchers (ECRs) into skilled, interdisciplinary, confident and considerate fire scientists is a core aim for our long-term impact. Many of these ECRs are likely to go on to further, and eventually permanent, positions in wildfire research or practice, or a related discipline. A new international and cross-disciplinary network of fire and environmental scientists will form as a result. Actions and support that we provide to develop the next generation of fire scientists include:

Photo: Early Career Researchers attending the Vegetation Fire Operators Course run by the Forestry Commission, in 2022. Credit: Rob Gazzard

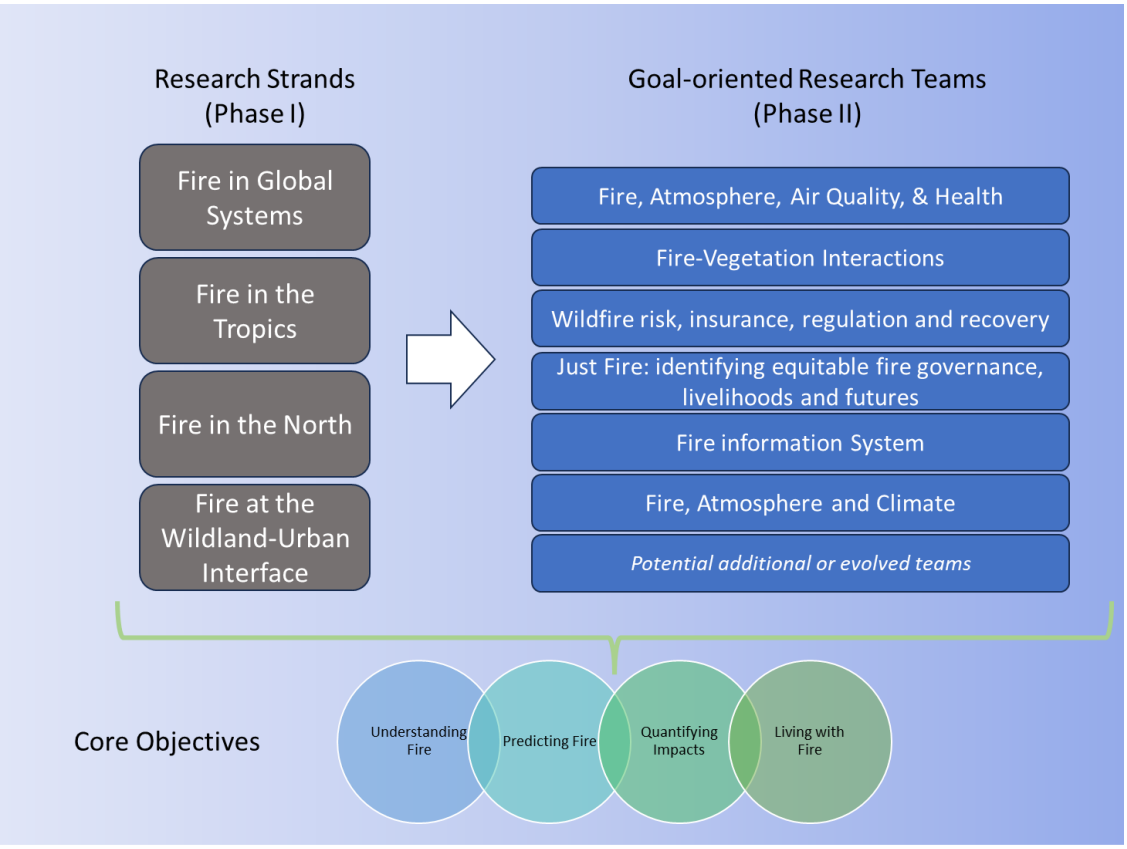
- **Research Workshops –** we hold regular, themed research workshops to which all Centre members are encouraged to attend. These workshops encourage interdisciplinary learning and collaborative research.
- **Student-led ECR meetings**– our ECRs meet regularly to discuss their research, and gain peer support.
- **Leverhulme Wildfires Symposiums and Conferences** – allowing our ECRs to share their work with their peers and scientific community, through oral and poster presentations.
- **Specialist training** – we organise and fund specialist training, such as science communication, and practical fire operators courses.
- **Conference support** – we support students in presenting and leading sessions at national and international conferences, to disseminate their research, gain public speaking experience, and grow their networks.
- **Working Groups** – our working groups provide an opportunity for ECRs to work collaboratively and to take leadership on joint publications and activities.
- **Visiting PhD students** – we have hosted students from oversees, which benefits the Centre and our ECRs through their research activities and engagement.
- **Paid internships –** with external organisations, to broaden skillsets and experience.
- **Secondments** – we encourage and support our students to undertake secondments (examples of secondments taken include to Defra and ESA).
- **Paid summer placements** – we have held several paid summer placements for undergraduates from across the UK. These are supervised by our PDRAs, providing leadership experience and helping advance their research.

Next Steps

Transition to Phase II

During Phase I (years 1-5), we have been making excellent headway in answering the questions posed in our four key objectives. We have investigated many aspects of wildfires across different temporal and spatial scales and across multiple disciplines, providing a considerable contribution to the collective understanding of fire.

Our research has also further revealed future research needs and where our expertise and experience best align with those needs. Therefore, building on the extensive work carried out in Phase I, we are planning for a new research organisation for Phase II. Our core objectives and research questions will remain the same, but our research will be conducted under (initially) six new goal-orientated teams, with clear milestones and desired outputs. As we move through the next six years, these teams may evolve or indeed new ones may be created. This coordinated, goal-orientated approach will help ensure that, as we reach the end of our tenth year, we will have achieved game-changing and tangible outcomes for a better future with wildfires.



The six goal-orientated teams are summarised below. Each team has an academic lead and co-lead who will be responsible for overseeing progress. Our teams are cross-partner and interdisciplinary. They will meet regularly as a team, but will also come together with the other teams to promote further collaboration across the Centre.

1. **Fire, Atmosphere, Air Quality, & Health**

   Wildfire smoke presents a significant and multifaceted public health challenge, demanding a comprehensive approach that encompasses increased knowledge, improved fire management, accurate air quality information, enhanced education, and robust healthcare readiness.

   This team aims to address these complexities by exploring the effects of fires on atmospheric composition, surface-level air quality, and population health. Our focus includes refining the quantification and characterisation of gaseous and particulate emissions in smoke, linking them to human exposure and long-term health impacts, such as carcinogenic elements. Additionally, we examine broader health aspects, including the mental health of those regularly exposed to excessive smoke and the specific risks faced by practitioners directly involved in landscape fire management.

   Organised into three work packages, the team aims to: (1) enhance and exploit top-down (or 'direct') methods developed within the Centre to improve fire emissions estimates; (2) understand the constituents of landscape fire smoke, both gases and particulates, and their controls through investigations involving real-world fires and laboratory experiments; (3) explore the connections between fires and public health, regionally and globally, with a focus on populations residing or working in severely fire smoke-polluted air**.**

Photo: Laos, in January and May 2023, by Martin Wooster, King's College London

2. **Fire-Vegetation Interactions: incorporating a realistic treatment of fire-vegetation interactions in the next generation of fire and earth system models.**

   Current approaches to modelling fire do not take account of the fact that most vegetation types are fire-adapted, but this varies with the nature of the fire regime. Similarly, current models also do not take account the flammability of the vegetation, even though it can be important for the type of fire.

   The goal of this team is therefore to develop a better understanding of vegetation-fire interactions and the implications of these interactions for fire modelling at a global scale. We will use these insights to develop a new fire-enabled vegetation model, suitable for coupling in a land-surface modelling scheme. It will allow us to explore how changing climate will affect fire regimes, and how this in turn will affect vegetation properties, biodiversity, and ecosystem post-fire recovery. It will also provide a platform for investigating management strategies for mitigating the effects of future changes on fire regimes.

Photo: 'The Hope of Life', by Yicheng Shen

3. **Wildfire risk, insurance, regulation and recovery**
   Insurance is a mechanism not just for financing recovery from wildfires, but also for incentivising risk reduction. However, those insurance mechanisms of risk management are struggling to cope with wildfires, whose frequency and severity are increasing in ways that are poorly understood, not least because of their dependence on loosely coupled and endogenous feedbacks with insurance and property markets, public expectations and behaviour, and with the political and regulatory systems for governing land use, insurance provision, and disaster financing.

This team will therefore answer questions on the role of insurance markets and other mechanisms prevention, protection, and recovery and sustainability from wildfires. For example: what influence do insurance incentives and government regulations for 'hardening' buildings and 'fire-proofing' the immediate landscape around houses have on wildfire risk, public attitudes and behaviour, insurance availability and cost?; how are insurance markets, and other mechanisms for protecting against losses and financing recovery from wildfire, responding to the changing risk, and what are the implications of this?; and how well does insurance serve the aims of covering losses, financing recovery, and providing the loss protection essential for functioning property markets and community sustainability?

Answering those research questions will involve an interdisciplinary programme of research integrating engineering science and statistical modelling combined with qualitative and survey research with insurance market actors, regulators and publics to understand the dynamics of insurance and wildfire risk.

4. **Just Fire: identifying equitable fire governance, livelihoods and futures.** The aim of this team is to promote ecologically sound and socially just approaches to fire management and governance that combine scientific and traditional knowledge systems and support the livelihoods and rights of Indigenous and local communities. To date, we have collected information on different forms of fire use, both at the global and local scales, and analysed it to understand general patterns, including recent human fire use at the regional and global scales, and the changing interactions between fire and the livelihoods and rights of Indigenous and local communities.

   This team will build on this work, focusing on three themes, each of which will benefit from deep-dive research in one or more case study area: (1) Fire governance **-** analysing whether and how fire is represented in international agreements and national laws, and how these constrain and/or enable local level fire governance; (2) Fires, livelihoods and biodiversity - explores the role of fire in mediating the relationship between cultural diversity and biodiversity; and (3) Future fire – asking how fire use is likely to change into the future, taking into account both climatic changes and potential governance responses to those changes.

Photo: 'Keeping Watch- Traditional Savanna Burning' by Kayla de Freitas

5. **Fire information System: A multi-decadal & NRT (Near Real Time) Fire Information System supporting the study of fire regimes, drivers, model representation and model development evaluation.**

   Modern Earth Observation (EO) datasets now span over two decades, and in some cases almost four decades, providing particularly extensive information on burned areas and hotspots. However, there are many uncertainties. For example, our longest record from AVHRR Global Area Coverage (GAC) EO data reveals fire regimes behaving inconsistently with climate-driven indices of increasing landscape flammability. The intricate patterns emphasise the urgency of developing a detailed understanding of the multifaceted nature of fire, grounded in independent and well-understood datasets.

   The primary focus of this team is therefore analysis of multivariate EO data to investigate local to global scale fire behaviour, trends and anomalies, and to provide data and approaches to support the enhancement, further development and testing of fire representation in models. We aim to provide a holistic understanding of the nature of fire activity on Earth and where and how this is changing, supporting examination of its impacts and feedbacks and its potential evolution into the future. The team will help us understand and document fire activity on Earth over past decades, examine current trends, and identify future anomalies. Ultimately, we aim to enhance fire modelling by (i) enabling the rigorous testing of models against this observational dataset, and (ii), help develop process scale models by learning from EO data, thereby helping to construct robust, data-aligned models.

6. **Fire, Atmosphere and Climate**

   Wildfires lead to enormous quantities of pollutants emitted into the atmosphere, and the influence of this on atmospheric composition has been sporadically investigated for a variety of regions, using different approaches. However, a) there remains large uncertainty in those effects, b) there have not been any systematic assessments of fire impacts on atmospheric composition in a holistic way, from a global perspective, going beyond the fragmented single-region, single-constituent, or single-dataset approaches that have been taken so far.

   This team will therefore advance the current understanding of the role of fire in the Earth system via atmospheric composition changes by thoroughly investigating uncertain processes and impacts of fire for the first time, through a novel approach that involves the synergistic use of atmospheric composition modelling, global climate modelling, and a range of targeted observational datasets. The focus will be on important short-lived constituents such as aerosols (black carbon and organic carbon), tropospheric ozone (O3) and its precursors (NOx, CO, CH4, VOCs) whose levels and distributions are challenging to model, and exert inhomogeneous radiative forcing.

Long-term sustainability

The Centre has two main avenues which we will pursue in Phase II for sustaining beyond the initial ten years of funding from the Leverhulme Trust, namely: (a) securing large-scale research grants, and (b) developing educational programmes.

We have already been successful in winning numerous grants to complement and expand our research beyond our original scope. Through these grants, we have hired Early Career Researchers who have become affiliated members, and are contributing to the goals and culture of our Centre. In Phase II, we will horizon scan for large-scale research grants or philanthropy that might allow the Centre to extend beyond 2029. Concurrently, we will also explore the feasibility to launch educational programmes, which may include a new interdisciplinary wildfires MSc programme – few of which exist worldwide - and/or specialist courses, for example targeted at practitioners.

In our first four years, we have established an international reputation for excellent interdisciplinary wildfire research, and developed an extensive network both in the UK and in many regions across the world. As we progress into Phase II, we will further strengthen our partnerships and international standing, and leverage our position to help secure a long-term future for our Centre.

Additional Key Information

Publications

Since launching, our Centre members has produced over 60 publications related to wildfires. A full list of our publications, which is regularly updated, can be viewed at www.centreforwildfires.org/publications/

These publications will provide more information on the research described in this report.

Research grants

In addition to the core projects directly funded by our Leverhulme Trust grant, the following wildfire-related projects awarded to Centre members include (but are not limited to):

- Assessing the impact of recurrent agricultural burning on surface level air quality and health across SE Asian nations, funded by UKRI GCRF ODA (KCL)

- SEMEDFIRE (South Eastern Mediterranean Excellence Development in Fire Research), funded by Horizon 2020 (ICL)
- FIRE-ADAPT funded by Horizon 2020 Marie Sklodowska-Curie Actions Staff Exchange (Reading and ICL)
- TREEADS – A Holistic Fire Management Ecosystem for Prevention, Detection and Restoration of Environmental Disasters, funded by EU GreenDeal (TUC)
- AXA Chair in Wildfires and Climate (PI), funded by the AXA Research Fund (TUC)
- First study of machine learning to detect wildfires in new European satellite data (KCL)
- Fire-emitted Pollution and Climate change: linkages in the past, present, and future (FirePC) funded by the Hellenic Foundation for Research and Innovation (HFRI)(TUC)
- FirEURisk – funded by EU Horizon 2020 (KCL)
- WILDFIRE: Enhanced PIR sensors for remote wildfire detection and prevention – funded by Innovate UK (KCL and ICL)
- LEMONTREE (The Land Ecosystem Models based On New Theory, Observations and Experiments), funded through the generosity of Eric and Wendy Schmidt by recommendation of the Schmidt Futures programme (Reading, ICL)
- Resilience and Adaptation to Climatic Extreme Wildfires (RACE Wildfires) (ICL)
- Wildfire Vulnerability Assessment in North America (ICL)
- GeoStationary Fire data for Developing Countries (KCL)
- Pollution and Climate Smart Agriculture in China (KCL)
- Wildfires at the Arts-Science Interface (KCL)
- Assessment of open crop straw burning and its impact on air quality using satellites and in-situ observations in eastern China (KCL)

LEVERHULME

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