# BorealBlaze: Climate effects and feedbacks of changing high-latitude wildfire


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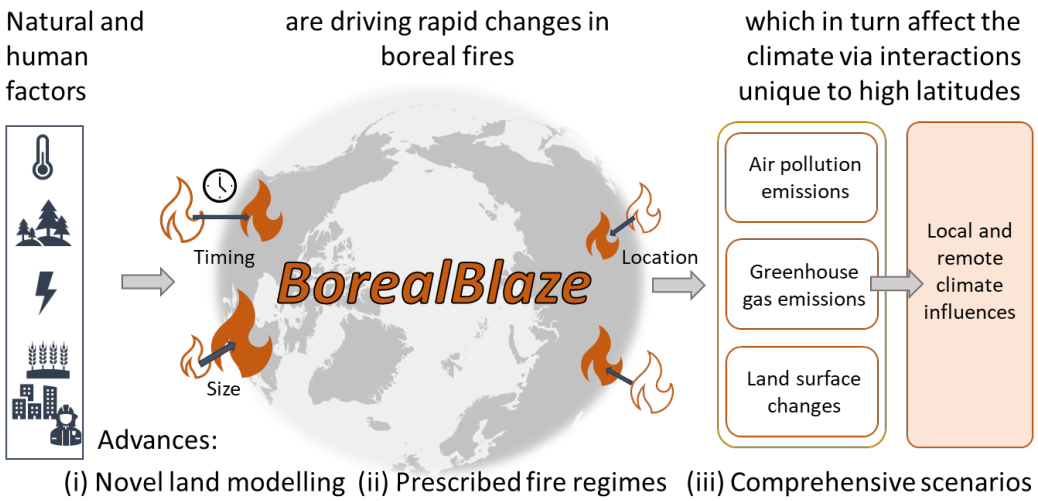
## 1. Excellence

**Fire plays a key role in the Earth system and can affect climate through smoke emissions and changes to the land surface.** Currently, fire regimes, i.e. the frequencies, intensities, timing, and type of vegetation fires, are changing dramatically in many regions. Evidence points to the reasons being a combination of climate and land use changes, and **some of the most marked recent increases in wildfire occurrence are found in boreal forests at high northern latitudes**. The trends are expected to continue with global warming, but projecting future changes in boreal burning remains a major scientific challenge, with limited published estimates and substantial differences between them. **This is a critical shortcoming, as high latitude fires (here; >60°N) have unique characteristics that, combined with their close proximity to the Arctic, are thought to have strong regional climate influences and Earth system feedbacks.**

**BorealBlaze** tackles the time critical challenge of providing a sharper picture of the climate implications of future changes in Northern high latitude wildfires. Our approach is to (i) leverage progress in land surface modeling, (ii) explore future fire regimes through novel constructed fire activity scenarios, combining existing literature and expert knowledge about the role of human factors on fire risk through machine learning techniques, and (iii) perform Earth system model experiments that separate and quantify the influences of a broad set of fire-induced climate driving mechanisms, with a particular focus on aerosols and the carbon cycle. Further research in this area is critical for our understanding of boreal land-climate interactions, and for projections of future climate change and risk.

**BorealBlaze starts at the research frontier,** by gathering world-leading experts on boreal fires, land modelling, aerosols, climate scenarios and the carbon cycle, **and then moves beyond it**, by designing high-latitude specific fire pathways and decoupling them from uncertain global scenarios. This allows us to explore, in a consistent modelling framework, details of the subsequent effects that have so far been inaccessible, including the dependence on location, seasonality, and type of wildfire change. Building on this, we will also design a suite of next-generation, risk driven multi-model community experiments, to provide stakeholder-oriented scientific information and future research directions.

**BorealBlaze addresses a burning question at the forefront of climate science** and will deliver knowledge of high relevance to the scientific community, stakeholders, and local communities.



### 1.1 State of the art, knowledge needs and project objectives

Fire is a natural phenomenon that occurs in terrestrial ecosystems worldwide and can be critical to maintaining healthy ecosystem functioning, shaping landscapes, ecosystem development and composition, and biogeochemical cycles (Bowman et al. 2009, Pausas and Keeley 2019). However, **when vegetation fires burn out of control, they can become wildfires[1] and can have severe impacts on human health, economy, infrastructure and livelihoods, ecosystem services, and climate** (UNEP 2022).

Wildfire occurrence and severity is determined by the complex interplay between meteorological, physical, biological, and social factors. Climate is a key factor in shaping fire regimes[2] from the landscape to the global scale, directly due to its control on fire weather (weather conditions characterized by high temperature, low precipitation, low humidity, and often high winds), indirectly through interactions with vegetation (fuel availability, distribution and flammability) (Archibald et al. 2013), and through changes in ignition (e.g. lightning strikes). Observational and modelling evidence suggest that climate change is now driving changes in fire risk and regimes (Jain et al. 2022, Jones et al. 2022, Richardson et al. 2022), with the signal emerging from natural variability in regions such Canada and Scandinavia (Smith et al. 2020), and even causing fire on landscapes that would not usually burn, such as permafrost and peatland (UNEP 2022).

**Climate and land use changes are driving dramatic changes in fire regimes, but the consequent effects of fires on climate and environment are insufficiently quantified.** Wildfire activity is affected by the climate, and in turn also affects the climate, via several pathways. These include direct emissions of greenhouse gases such as carbon dioxide ($CO_2$) and methane ($CH_4$), as well as pollutants such as aerosols and chemically reactive gases. Fire-produced, or biomass burning, aerosols can absorb sunlight and affect the radiative balance of the atmosphere as well as cloud microphysical properties and dynamics. However, the magnitudes and signs of the effects vary with meteorological and cloud properties (Koch and Del Genio 2010). Studies also suggest important feedback processes related to biomass burning aerosols through changes in precipitation, relative humidity at the surface, and photosynthetically active radiation (Zou et al. 2020, Xu et al. 2021, Li et al. 2022), and via deposition onto snow and ice surfaces in the Arctic (Flanner 2013). Fire also interacts with climate through biochemical and biophysical processes associated with surface/vegetation changes. These include changes in the carbon cycle and capacity of vegetation for carbon uptake, in emissions of biogenic volatile organic compounds (BVOCs), and in albedo and moisture fluxes (biophysical feedback) (Jia et al. 2019). Such land-to-climate feedback processes have been difficult to assess, as climate models have lacked connected representation of several relevant processes, including fire itself, vegetation dynamics and its interaction with fire, regrowth following fire disturbance, and the dynamics and effects of short-lived chemical tracers such as biogenic volatile organic compounds (Jia et al. 2019). Where they are included, the feedbacks between components and processes make the analysis of responses to forcing complex. The fire-induced climate effects and feedbacks can be substantial but the sign and strength differ between models and studies (e.g. Arnold et al. 2015, Canadell et al. 2021), and literature remains scarce for some of the pathways. Further studies are thus urgently needed, on individual pathways, and on how they combine and interact.

**Some of the largest and most rapid climatic and environmental changes are happening in the high northern latitudes.** The high northern latitudes (here, >60°N), which include large swathes of boreal forests and tundra, have seen unprecedented fire activity and shifts in fire regimes in recent years (McCarty et al. 2021). Some of the largest percentage increases in fire occurrence are found in this region (UNEP 2022), although the long-term trend is spatially heterogeneous (Xing and Wang 2023). Climatic factors are playing an important role in driving these changes (Masrur et al. 2018, Touma et al. 2021). Attribution studies show that weather conditions associated with some of the recent record-breaking fires and fire seasons in Siberia and Canada have been made much more likely by, or would even be virtually impossible without, anthropogenic climate change (Kirchmeier-Young et al. 2017, Ciavarella et al. 2021). Reduced precipitation and increased temperature during summer has been shown to raise the likelihood of years with high fire activity in tundra and high latitude boreal forests (Hu et al. 2015, Masrur et al. 2018), while surface warming enhances fuel flammability by increasing the growing season length and vegetation productivity, and contribute to permafrost thawing (Swanson et al. 2021). Observed increases in lightning frequency have also contributed to recent increases in area burnt by fire in the Canadian Arctic (Veraverbeke et al. 2017, Hanes et al. 2019).

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*[1] Different terms and definitions relating to fire (e.g. wildfire, forest fire, vegetation fire, wildland fire) exist. Here we talk about wildfire as an unplanned and unpredictable free-burning vegetation fire, with natural or human cause, that can be short or long in duration and small or widespread in extent, largely following the definition by UNEP (2022).*

*[2] Typically defined as the main characteristics (including frequency, size, seasonality, and type, e.g. peat or crown fires) of fire activity for a given location (Hanes et al. 2019).*

**High latitude wildfires have unique characteristics that give rise to distinct Earth system impacts and feedback processes, across time scales from immediate to decadal and centennial.** The high northern latitudes contain nearly half of the world's peatlands, and approximately 80 per cent of the global peatland carbon and nitrogen stocks (Hugelius et al. 2020). Climate change, fire, permafrost thaw and atmospheric $CO_2$ can interact, and amplify regional changes into global impacts (Mack et al. 2011). The emission characteristics of high-latitude fire may differ from fire in other regions, giving rise to distinct aerosol-climate effects. One example is the ratio between organic matter and black carbon from smoldering peat fires (e.g. Akagi et al. 2011). Seasonality is another factor: High latitude fire activity peaks in the summertime, when photochemistry is at its most active and the atmosphere is otherwise cleaner, and hence more susceptible to aerosol-induced cloud changes. The location of high-latitude boreal fires may also facilitate transport and subsequent deposition onto snow and ice. **Few studies to date have explored the regional-to-global scale climate influences specifically of high-latitude fire, in particular when considering a comprehensive set of fire-climate interactions in a state-of-the-art modeling framework.** This poses **a key knowledge gap in Earth system science** with further implications for our ability to project future climate change and risk, and land-climate interactions including the role of terrestrial carbon storage in climate change mitigation strategies.

**A key limiting factor is the capability of current tools to project future burning.** While global warming is expected to expand the areas prone to fire risk (Senande-Rivera et al. 2022), projecting specific future changes in burning remains a challenge. The reasons include uncertainties in the projections of precipitation and humidity changes that fire regimes are sensitive to, as well as in forecasting of fire outbreaks. Human dimensions of fire, such as management, fuel treatment, and economic development, are also understood to be important drivers of changes in burnt area in many regions (Bowman et al. 2011, Sizov et al. 2021). However, there are still no comprehensive future fire scenarios that take into account both human activity and climate change (Paunu and McCarty 2023). As a result, projections of specific future changes in burning can be extremely imprecise, even in regions where modelled climate-fire relationships are strong (UNEP 2022). Moreover, the representation of both vegetation and fire dynamics in Earth System Models is highly heterogenous (Hantson et al. 2016). Many do not include fire (Spafford and MacDougall 2021), and others have optional fire configurations. Several key features of fire systems are currently lacking from many of these models, including the representation of size-related fire impacts on vegetation, tracking of regrowth following disturbance, and tracking of post-fire burnt area properties - and their subsequent influence on the climate system and future fire dynamics. BorealBlaze is designed to address these gaps and limitations.

The **primary objective of BorealBlaze is to quantify the climate influences of changing Northern high latitude wildfire, through direct emissions and land surface processes.** We will adopt a novel approach to managing model complexity in climate-fire interactions and future burning scenarios and to delineating fire-induced climate effects. We will leverage the recent progress in dynamic vegetation modeling to improve understanding of the complex dynamics of fire-vegetation-climate interactions. By constructing pathways for future high-latitude burnt area that include state-of-the-art understanding of the role of human factors**, we broadly explore the space of potential future wildfire changes, and associated effects on climate.** Secondary objectives include: (i) quantifying the sensitivity and non-linearity of fire-induced climate effects to features of high-latitude such as location, timing, and type, (ii) delivering new capabilities in modeling high latitude fire and dealing with model complexity, (iii) delivering recommendations for a future multi-model intercomparison study to further constrain uncertainties in high-latitude fire-climate interaction, and (iv) quantify fire-related physical hazards for impact-oriented research and climate and emissions scenario development.

### 1.2 Research questions and hypotheses, theoretical approach and methodology

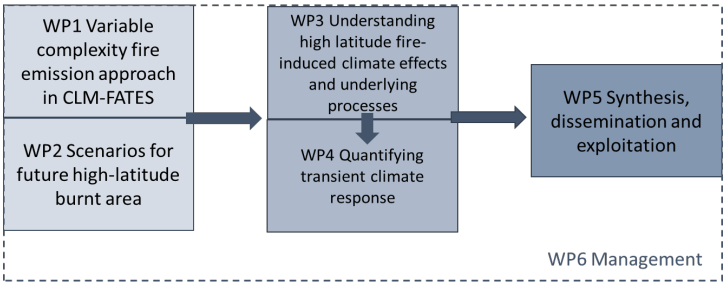
**Our central hypothesis** is that changing high-latitude wildfire regimes will give rise to unique regional-to-global-scale climate effects and Earth system feedbacks. Our **research questions** are:

RQ1: What is the possible range, including extremes, in future high latitude burning given both natural and anthropogenic drivers of fire risk?

RQ2: What is the climate response to the different fire-induced emissions and effects, including sensitivity and non-linearity to features specific for high latitude burning?

RQ3: How do fire-related physical climate and environmental hazards translate to impacts of concern and consequences for society, adaptation, and management?

BorealBlaze explores this through five scientific work packages (WPs), with an additional WP covering management. See Sect. 3.2 and application forms for further details on implementation.




**Concept and tools**

The approach in BorealBlaze is centered around managing one critical part of the complexity in simulating vegetation-fire-climate interaction: **Our key starting point lies in decoupling the Earth system response to changing wildfire from uncertainties in the underlying fire activity change, hence delineating the fire-induced climate implications**. Attempts to diagnose effects and feedback processes by running components in isolation are already applied in Earth System Model (ESM) studies, e.g., by running given model components in 'offline' mode or e.g. using observed vegetation distribution in lieu of dynamical prediction. Such reduced complexity modes can provide substantial insight into the function of individual parts of the full system (Fisher and Koven 2020). Here we propose a novel extension of this functionality to the case of fire, by introducing the capacity to prescribe burnt area[3] to a land model (WP1). Burnt area prediction depends on many highly uncertain elements including ignition rates, fire duration (and thus suppression activities), landscape and weather impacts on fire spread and other biophysical factors. To efficiently explore sensitivity to such factors and derive the burnt area to drive the land model, a machine learning (ML) based tool will be developed, integrating natural and human drivers of fire risk, the latter of which are typically lacking in scenarios (WP2). Deriving burnt area independently from dynamical predictions will allow us to diagnose coupled system impacts of fires (in terms of emissions, climate effects and vegetation change) in isolation from the substantial biases that can be introduced by burnt area prediction algorithms (Hantson et al. 2020) (WP3/4).

Our primary tool is the Norwegian Earth System Model (NorESM, Seland et al. (2020)), which is built and used by the Norwegian climate modeling community. To study fire-vegetation interactions, we will use a leading demographic vegetation model, CLM-FATES, which is embedded in NorESM and links the Community Land Model (Lawrence et al. (2019) and the Functionally Assembled Terrestrial Ecosystem Simulator, (Fisher et al. (2015) Koven et al. (2020)). Demographic models, that track both time-since-disturbance of patches of land and size distributions of plants, have recently been incorporated into ESMs (Fisher et al. 2018), and are useful tools for understanding the complex dynamics of fire vegetation climate interactions (Shuman et al. 2017, Shuman et al. 2023). FATES incorporates a version of the SPITFIRE (SPread and InTensity of FIRE) model, modified to integrate with multiple plant size classes (Shuman et al. 2023). We will also use the United Kingdom Earth System Model (UKESM), which couples key components of the Earth system including: the atmosphere, ocean, ocean biogeochemistry, terrestrial carbon and nitrogen cycles, dynamic vegetation and a stratosphere-troposphere chemistry and aerosol scheme (Sellar et al. 2019, Sellar et al. 2020). The first version of UKESM was used extensively in CMIP6 in several different configurations including atmosphere-only (with prescribed values for sea surface temperatures and sea ice concentrations) and fully coupled, which will also be used in this project as part of WP3 and WP4 respectively.

**WP1 Variable complexity fire emission approach in CLM-FATES**

**Goal:** Perform the key developments to CLM-FATES to enable the prescribed burning capability, plus updates to improve simulation of high latitude fire.

WP1 is responsible for **developing and setting up CLM-FATES with two new capabilities to disentangle the processes driving climate/fire/vegetation interactions**. We will integrate the capacity to run with the prescribed burnt area. We will override the burnt area algorithm in SPITFIRE (including ignition, fire spread and duration calculations), and instead read in transient burnt area estimates from the input ('surface') datasets of the CLM. Initially, these will be extracted from satellite derived burnt area (e.g. GFED5), and added to the transient historical model driver data sets. Once burnt area is known, the model forced with burnt area will estimate fire intensity, subsequent fuel combustion (across six fuel size categories), as well as flame height and vegetation mortality, and emissions. Fire effects on vegetation will operate independently of the emissions sent to the atmosphere, to allow the direct prescription of atmospheric effects. The CLM5 model (unlike most fire schemes) contains a representation of peat fire that simulates carbon emissions, but not aerosols and trace gases. We will link this depiction to FATES and extend it to include a parameterization of aerosol and trace

[3] *Here, "prescribed" is used to signify a climate model simulation with predefined conditions, e.g. burnt area or emissions. Note that this is distinct from "prescribed burning" as a fire and land management and suppression measure.*

gas emissions, using emission factors available in the literature (e.g. Akagi et al. 2011, Hu et al. 2018). More recent literature will also be reviewed (for both peat and other biomass) to refine emission factors where possible. The emissions simulated by CLM-FATES with prescribed burnt area for present-day conditions, will be evaluated against biomass burning emission inventories, such as GFED5, GFAS and FINN. We will also benchmark offline CLM-FATES fire and fire vegetation interactions (e.g. fire intensity, impacts, and recovery) using available observational products (including field campaign data that will also inform process level studies in later WPs). We will conduct low dimensional emulator-assisted calibration (Dagon et al. 2020) targeted parameters related to fire behavior and impacts. Calibration of CLM-FATES gas exchange and biogeochemistry, and implementation of crown fire capabilities is ongoing (with collaborator A. Foster, NCAR) and within the NorESM consortium.
**Key outcome(s):** Newly flexible configurations for investigating the role of separate processes in determining fire mediated earth system feedbacks. Calibrated fire predictions for CLM-FATES.

**WP2 Scenarios for future high-latitude burnt area**
**Goal:** Quantify an envelope of likely high latitude burnt area under a range of external (natural and anthropogenic) conditions

In WP2 we will **derive projected burnt area information to drive** the newly created capability **in CLM-FATES** (WP1), for simulations conducted in WP3 and 4. This will be done through *i)* compilation and review of existing literature (including studies more recent than AMAP (2021) report), model experiment output (e.g. CMIP6, FireMIP/ISIMIP3), and observational data (e.g. remote sensing, national burnt area statistics) to assess the status of knowledge about recent past and projected changes in fire activity across the region, *ii)* elicitation of expert judgement about how human factors can influence wildfire risk in the region, *iii)* use of machine learning techniques. Improved integration of human dimensions of fire risk, where these elements are missing, will be based on three Arctic specific pathways recently developed by Paunu and McCarty (2023). The pathways provide qualitative descriptions, separated by Arctic country and for three scenarios (high – "let it burn", low – "we got this", and "best guess"), of demographics (e.g. population, urbanization), human development (e.g. tourism, technology), fire suppression and management, and policies and incentives. Through WP2, these storylines will be further spatialized, which involves producing expert estimates for how and where the various factors will unfold, for some factors (e.g. population, urban development) supported by existing scenarios such as the Shared Socioeconomic Pathways (SSPs). The concrete work will be centered around a dedicated, hybrid workshop, inviting participation from the broader fire research community and key stakeholders from the Arctic regions (see Sect. 3.2). An ML-based tool will be developed to derive spatially distributed projections of burnt area through the 21$^{st}$ century, building from recent applications to present-day fire (Son et al. 2024) and other vegetation-climate-human interactions (Shi et al. 2020, Lindgren et al. 2021), and leveraging related ongoing work at the University of Leeds (Conibear et al. 2022). Trained on available present-day data, the goal is a tool that, given known drivers of fire relating to weather, land surface characteristics, and human activity, produces estimates of burnt area on spatiotemporal resolution required for the CLM-FATES modeling for the high latitudes. We will review existing ML approaches in climate science literature and their strengths and weaknesses for our application to high latitude fire, as well as state-of-knowledge about predictors that are important determinants for high latitude burning. Possible sources of data for training and evaluation include, but are not limited to, satellite-derived (MODIS, VIIRS, FireCCI51, GFEDv5), reanalysis, land use datasets, data bases of socioeconomic factors.
**Key outcome(s):** projections for future high latitude burnt area spanning a broad range of possible outcomes, a community available tool for further applications, input to WP5 on the role of human factors of fire risk.

**WP3 Understanding high latitude fire-induced climate effects and underlying processes**
**Goal:** Quantify the sensitivities of fire-climate interactions to variations in size, location, timing, and frequency of high latitude fire.

In parallel with recent development of realistic fire representation in climate models, several communities have successfully utilized idealized simulations of aerosol emissions (Samset et al. 2016, Persad 2023), land cover change (Lund et al. 2021) and similar. In WP3, we extend this approach to simulations of idealized high latitude fire. By prescribing burnt area or the resulting emissions, in a multi-decadal, repeating-fire setup, we can **isolate the local and remote, and individual and joint, influences of direct fire emissions and land surface processes, respectively, on the climate system.** Simulations will be performed with the NorESM/CLM-FATES (including developments in WP1) and be informed by the outcomes of WP2 and observational datasets. Moreover, while a comprehensive multi-model study is beyond the scope of this project, a first order investigation of model differences in response to direct fire emissions will be performed by running a selection

of the sensitivity experiments also with UKESM, with fire emissions from CLM-FATES as input. Previous studies have highlighted large inter-model diversity in high latitude distributions of fire-emitted trace gas and aerosol (e.g. Arnold et al., 2015). This stems from different model treatments of transport, aerosol processing, wet removal, and aerosol-cloud interactions. The complexity of these processes leads to high diversity in model-diagnosed radiative impacts from fire-emitted aerosol compared with e.g. $CO_2$ forcing. The use of two models will allow us to carefully assess where both models agree on robust responses and in which regions and processes there are major differences. This information will be used to inform the design of experiments and recommendations in WP4, allowing us increased confidence in the diagnosed responses, and highlighting areas where more constraint is needed to adequately quantify potential important effects.

Conditions that can be prescribed include: burnt area size and location (e.g. strong fire increase in Alaska, Canada, or regions of Siberia), fire intensity, aerosol vertical profile and composition (e.g. ratio of BC to OC), seasonality and frequency, and background climate conditions. The latter is relevant because ambient weather and fire-climate feedback processes will depend critically on the underlying climate state, including winds, moisture/humidity, vegetation cover, and snow/ice extent. Technically, we will select a sample of parameters and run 50-year prescribed SST (AMIP type) simulations for each combination, to allow sufficient time to derive a robust signal in response to the perturbation. Prescribed burnt area (or associated emissions) will be guided by WP2, with simulations covering max, min, and "best guess" conditions. For "best guess", we will also simulate doubled fire intensity (increased emissions, same area), fires prescribed at two different times a year (spring, summer), and with annual, triannual and 5-yearly frequency. Selected combinations will also be moved to a higher latitude, and be repeated with background climate conditions representative of a +3 °C world (taken from CMIP6 scenario simulations).

Simulating all combinations is not feasible. We will start by simulating some extreme cases (high frequency, intense fires two locations), and from there, draw from Perturbed Parameter Ensemble (PPE) literature (Lee et al. 2011) and ongoing CLM and FATES PPE activities/tools to select the most relevant combinations for further study. The total number of idealized simulations will be around 60, which is feasible to perform within about 1 year of project time. The resulting analysis will focus on atmospheric responses (e.g. temperature, precipitation, cloud changes, teleconnections via circulation), land responses (carbon, nitrogen and methane emissions), and individual and joint physical changes that link to boreal region climate risk (diurnal cycles, air quality, changes in seasonality).

**Key outcome(s):** Mapping of fire conditions to responses and hazards will be input to WPs 4 and 5, as basis for understanding transient, multi-component simulations targeting the net influence of future boreal fires.

**WP4 Quantifying transient climate response**

**Goal:** Perform and compare coupled, transient simulations of extreme and best-case changes in high latitude wildfire.

In realistic situations, fires will evolve in multiple locations, in parallel with other emissions and aspects of climate change, and interact through potentially non-linear processes. In WP4, we **investigate the transient climate influence of future boreal fires**, building on the model developments of WP1, the scenarios of WP2 and the process understanding of WP3. Using NorESM (including CLM-FATES developments), and UKESM (driven by FATES-derived fire emissions), we run fully coupled simulations, except that future high latitude fire conditions will be prescribed as detailed in WP2. We run with both SSPs 126 and 370 as background conditions, to investigate the influence of global warming and other non-fire emissions. This gives a total of six signal cases ("let it burn" under SSP126, etc.). A baseline without the influence of fire will also be run for each SSP. All simulations will run from 2015 to 2100. To reduce the confounding influence of internal variability, as many combinations as feasible will have 10 ensemble members. Based on these simulations, we can directly quantify the boreal fire influence on the climate in these climate models. By tracking the processes listed under WP3 (atmospheric, land, etc.), and comparing to individual-change simulations, we can also quantify non-linearities and interactions with modes of atmospheric and oceanic variability. We also quantify the influence on physical hazards (or Climate Impact Drivers (CIDs), i.e. changes in temperature, precipitation, extreme events) for use in WP5. Finally, WP4 aims to develop recommendations for a future multi-model intercomparison (MIP) study to further constrain uncertainties in high-latitude fire-climate interaction. The simulations of WPs 3 and 4 will be used to identify combinations of high sensitivity/low scientific confidence, ideal for targeting with additional models and future effort. Results will be communicated to existing relevant MIPs (e.g. FireMIP, AerChemMIP, RAMIP), and to the boreal fire community with the aim of instigating a discussion on the need for a dedicated process MIP timed between CMIPs 7 and 8.

**Key outcome(s):** Peer-reviewed publication, recommendation for further multi-model experiments, input for WP5 synthesis.

**WP5 Synthesis, dissemination, exploitation**
**Goal:** Synthesize findings to ensure effective and accessible dissemination and exploitation of results within the scientific community and to decision-makers.

BorealBlaze will deliver knowledge about physical climate and environmental change and hazards (CIDs) resulting from changing high latitude wildfire. These in turn pose risks for human and natural systems. Climate risk is a function of the given CID, and how that hazard translates to impacts, i.e., realized consequences, via the exposure and vulnerability to the hazard (e.g. Ruane et al. 2022). While comprehensive quantification of the impacts of increased high latitude wildfire is a demanding task and beyond the scope and resources available in this project, we aim to deliver impact relevant knowledge by **synthesizing the knowledge produced in the project in a risk framework**. We will build on the concept of systemic, or cascading, climate risk, which is "the probability of a sequence of cascading impacts initially triggered by a climate hazard: from direct impact to first-order indirect impact, to second-order indirect impact, and so on." (Quiggin et al. 2021). Cascading events originating from an increased wildfire risk include enhanced snow melt and permafrost thaw due to black carbon deposition, health effects on local communities, and ecological disturbances in a fragile nature affecting ecosystem service provision. The work will roughly follow three steps: *i)* use existing knowledge and project outcomes to produce a preliminary cascade; *ii)* review and refine through a workshop (one target option is a working meeting at the Arctic Science Summit Week, where project partners have previously organized successful workshops) with invited experts from the fire research community and related relevant fields, as well as key stakeholders; *iii)* produce revised cascade, including second round of review/input from workshop participants. The outcomes of this risk mapping will be disseminated through a policy brief targeting national decision-makers and international stakeholders, e.g. AMAP and Arctic Council, and a peer-reviewed paper. We also aim to produce a web-based portal where users can explore storylines for high-latitude regions/countries (e.g. Alaska, East Siberia). WP5 will also be responsible for the continuous dissemination throughout the project duration. A detailed dissemination plan will be developed at the beginning of the project. See also Sect. 2 for measures for dissemination and exploitation.
**Key outcome(s):** A web-based portal, hosted on CICERO web pages, oriented towards stakeholders and the broader public, updatable and extendable through later projects, and associated documentation.

**Potential risks to the project** (technical, research or consortium-related): The likelihood of severe technical risks is considered to be small, as the team and the CICERO staff are highly experienced with HPC computing, data analyses, event organization, and project management, and tools in use are part of well-organized national and international research infrastructures. Due to the significant number of model simulations required, temporary technical problems with developments or computing infrastructure may delay deliverables (medium likelihood). WPs 1 and 2 have tasks that can be started in parallel, reducing risks of significant delays that propagate to later tasks. Built-in contingency time in the project timeline, a detailed task structure and regular communication to monitor progress will further minimize risks. Failure in some element of the research is a higher impact, but low likelihood risk. Members of the project team might leave their current position for other employment (medium likelihood). Consolidation of the collaboration through regular communication from the project start (several team members already have ongoing collaboration in other projects and network) and the broad expertise of team members minimize the risk of losing contact and ensures continuation.
Direct **environmental impacts** are mainly related to air travel and computing power. We will minimize the climate footprint by planning project meetings in connection with larger international conferences and make significant use of virtual meetings and land-based travel. Where air travel is unavoidable, CICERO purchases carbon offsets. The national data storage facility, NIRD, is in an old coastal mine which offers benefits in terms of energy consumption as water from the fjord is used for cooling and then recycled.
**Ethical and gender issues:** There are no ethical or gender issues related to the research. CICERO has a gender-balanced workforce and proactive approach to gender and minorities. The project has good gender balance, with both female and male WP leaders, including an Early Career Scientist, female advisors, and a female PI.

### 1.3 Novelty and ambition

BorealBlaze will advance the research frontier by combining state-of-the-art fire modelling with a novel systematic prescribed fire regime approach. The project will substantially advance our understanding of the regional heterogeneity in climate response to fire, as well as delineating the contributions from fire emissions and those from physical burnt area, both of which are key steps towards constraining the overall role of wildfire in the changing climate system and to further improve climate projections. The track-record of the team demonstrates the high likelihood of publications in leading international journals. While the models are well

used and tested, their application to the problem of delineating the various influences of boreal fires in the present and future climate system goes beyond the state-of-the-art. Specifically, BorealBlaze moves beyond the state-of-the-art by:

i) Adding variable complexity fire emission capability to a state-of-the-art land model (WP1).
ii) Better integration of human factors of fire risk, such as ignition sources, in addition to natural drivers in projections of future burning (WP2).
iii) Delineation of smoke and land surface effects, dependence on region, season, intensity (WP3).
iv) Quantification of the holistic climate effects of boreal fires (WP4)

## 2. Impact

### 2.1 Potential for academic impact of the research project

**Impact 1 Advance the research frontier:** We will conduct excellence-driven research and analyses to reach academics and professionals in the fields of climate science via publications in highly ranked international peer-reviewed journals.

**Impact 2 Shape research agenda and foster interdisciplinary research:** The project will provide insights into further research and model development needs. A key project legacy will be recommendations for multi-model experiments. Furthermore, the ML based tool and output of fire emissions will be made publicly available to the community for further application. The team participates in activities and networks (e.g. PACES, AMAP, International Land Modelling Forum), and we will seek to establish contact with other networks and relevant projects (e.g. through the EU PolarCluster, IGAC initiatives, WCRP activites).

**Impact 3 Improve community Earth system modeling tools**: All the code related to the NorESM, CLM and FATES models is open and specifically intended to be a community wide scientific resource. The capabilities we introduce into FATES will be available across (at least) three ESMs in which it is embedded, and the improved understanding of the model system will benefit all researchers using these tools in future work.

**Impact 4 Inform scientific assessments:** BorealBlaze research has relevance for understanding land-atmosphere interactions and projecting future climate and will thus be of relevance for several scientific communities and assessments, including the 7$^{th}$ IPCC cycle, regional climate assessments, upcoming AMAP assessments.

### 2.2 Potential for societal impact of the research project

**Impact 5 Enhanced knowledge base relevant for climate-policy advisors, Arctic nation stakeholders, and the Paris Agreement process:** The capacity of land ecosystems to take up and store carbon in vegetation and soils is a fundamental component of climate change mitigation strategies but these carbon pools are vulnerable to disturbances such as fire. Moreover, fire-climate effects and feedbacks may hamper achievement of temperature goals and introduce uncertainties in climate projections. These are implications that BorealBlaze will provide needed insights into.

**Impact 6 Better informed policy decisions on managing and adapting to changing wildfire:** Surges in large, uncontrollable fires have high socioeconomic cost and implications for fire-fighting capacity, management tactics, society and human health. Land-use and fire management and suppression strategies can also strongly influence fire severity and human activities are a key source of ignition and thus fire risk. BorealBlaze will deliver information relevant for how political decisions, resource development and human activities may affect fire risk, and the potential benefits of mitigating and adapting to changing wildfire.

**Impact 7 Increased awareness about the climate-wildfire risks among stakeholders and the broader public:** Wildfire affects people and people affect wildfire. BorealBlaze will increase the knowledge about the role of high latitude fire in the climate system, thus highlighting the importance of behavioural change to avoid fire in high-risk environments. Here BorealBlaze complemens the agenda of the Arctic Council, where the Norwegian Chairship recently launched the Wildland Fires Initiative, aiming to make information on wildland fires in the Arctic more readily accessible.

BorealBlaze is primarily **relevant for the UN's Sustainable Development Goal** (SDG) 13 (climate action) because of its aim to advance the understanding climate-land-atmosphere interlinkages and improve climate projections. We expect project output to be relevant for further studies of wildfire impacts on ecosystems and human health, forming links to SDG 14/15 (healthy ecosystems) and SDG3 (health).

### 2.3 Measures for communication and exploitation

The main **target audiences** for BorealBlaze are the **scientific community** (e.g. scenario developers, IPCC, International Arctic Science Committee (IASC)), **stakeholders** (e.g. local to national scale planners and policy advisors, national civil protection agencies and fire authorities, Environmental Protection Agencies, other

agencies such as the UNEP, Arctic Monitoring and Assessment Programme (AMAP), Arctic Mayors Forum and the Arctic Council) and the **broader public** (in particular in Northern countries). Broad and active dissemination is planned to interact with these groups and to realize the potential impacts of the project. A detailed dissemination plan, including a mapping of relevant policy processes and events, e.g. related to changing wildfire risk in Northern countries, will be developed by month 4 of the project (see section 3.2). Measures and Key Performance Indicators are summarized below, with further details provided in the application form:

BorealBlaze will produce high-quality peer-reviewed publications in scientific journals with open access options. Interaction with the **scientific community** will also take place through presentations and sessions at international conferences and targeted workshops/meetings, dissemination of results to networks, open and accessible release of project outcomes, popular science pieces (e.g. in CarbonBrief). *KPI(s): no. of BorealBlaze publications and citations (tracked through database counts), including in international assessments; presentations at conferences; participation of members in new, related research initiatives; download of data/tools.*

A dedicated website with information on boreal wildfires and impacts tailored to **the three target audiences** will be set up under the CICERO website, updated when project results become available, and broadly communicated utilizing existing media connections, social media accounts, and the networks of project participants. *KPI(s): no. of visits to project website, viewings of social media.*

BorealBlaze will reach both **stakeholders and the broader public** through popular science talks, fact sheets, op-eds**,** videos and articles in CICERO's Klima magazine and social media accounts, and tailored synthesis. Specifically, project results will be synthesized into easily understandable narratives about future fire, and an interactive map on the CICERO site where stakeholders and interested parties may explore scenarios in their region and a policy brief will be produced. We also aim to attend and co-organize events and/or webinars with stakeholder participation jointly with other organizations and projects. BorealBlaze will actively seek to contribute with relevant information from the project to target audiences, e.g. when extreme events occur, and seek to contribute to ongoing relevant discussions connecting wildfires and climate change. *KPIs: no. of media contributions and references to project in other literature/reports/media outlets, visits to the project website, viewings of targeted dissemination products, participation at seminars.*

The track records, connections, and communication experience of the project team is expected to ensure high visibility of project results (in Norway and outside), as well as access to key stakeholders at the science/policy interface. The team and is also well-versed in policy-level synthesis through the production of commissioned reports. The project will benefit from support by CICERO's communication department, which has strong expertise in communication and dissemination of climate research, high visibility in social media (> 11,000 followers on both Twitter and Facebook), and a large network in Norwegian media.

## 3. Implementation

### 3.1 Project manager and project group

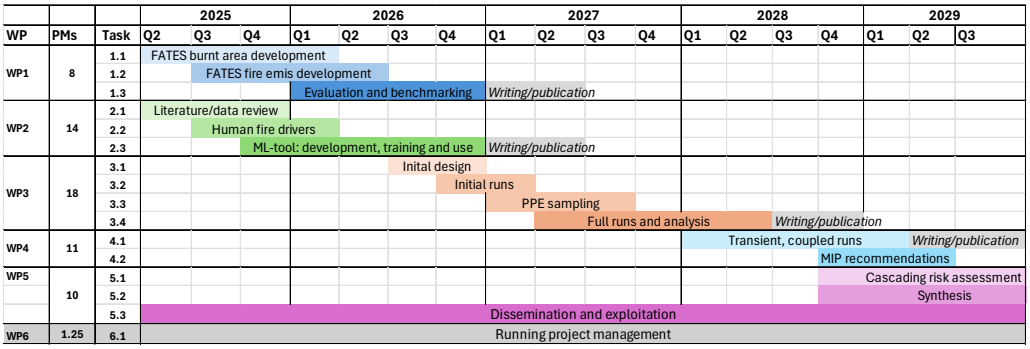
BorealBlaze gathers a team of internationally recognized experts on high-latitude fire, global atmospheric chemistry and Earth system modeling, land surface modeling, and climate impact assessment. The PI has broad expertise within atmospheric modelling, aerosols, chemistry, emission inventories and forest-climate interactions. She is also an experienced project leader. Many of the team members have ongoing collaborations within related topics and the complementarity of skills makes the team highly suited to achieve the aims of BorealBlaze. All partners have committed to providing both expertise and time to work on the project, funded and/or in conjunction with related efforts. BorealBlaze will also benefit from synergies with numerous ongoing projects (e.g. EU CleanCloud, CRiceS) and initiatives (e.g. IASC, AMAP) where participants contribute.

| Participant | Main relevant expertise | Main contribution |
|---|---|---|
| ***Marianne T. Lund*** | Boreal fires, aerosols/short-lived climate forcers (SLCFs), atmospheric modeling, land-atm interactions | PI (all WPs) |
| *Rosie A. M. Fisher* | Land surface/fire modelling, FATES-CLM, carbon cycle | WP1, WP3 |
| *Bjørn H. Samset* | Global modelling, aerosols, variability, scenario design | WP2, WP3, WP4 |
| *Zosia Staniaszek* | Global modeling, atmospheric chemistry | WP1, WP4 |
| *Lin Ma* | Climate risk, economic impacts | WP5 |
| *Heidi Bang* | Communications expert and advisor | WP5 |
| *Stephen Arnold* | Boreal fires, SLCFs, atmospheric modeling | WP3, WP4 |

| | | |
|---|---|---|
| *Ben Silver* | Machine learning, boreal fire, air pollution/quality | WP2 |
| *Steven Turnock* | UKESM modeling, atmospheric chemistry, SLCFs | WP3, WP4 |
| *Jessica McCarty* | Wildland fires, fire regimes, fire emissions | Advisor |
| *Kristina Pistone* | Biomass burning aerosols/SLCFs, Arctic radiative balance, aerosol-cloud-climate interactions | WP2, WP3 |
| *Ville-Veikko Paunu* | Fire emissions, air pollution, emission inventories | WP2 |
| *Stefan Fronzek* | Climate impacts, cascading effects, boreal hazards | WP5 |
| *Adrianna Forster* | Land surface and fire modeling, FATES-CLM | Advisor |

### 3.2 Project organisation and management

BorealBlaze is a 4.5-year project starting April 1st 2025. The Gantt chart summarizes the tasks, timeline and PMs (all partners) of the project, with details given below (see also application form). The contributions of project partners to individual tasks are specified in section 3.1 and below. The experience of the PI and participants is expected to ensure the timely completion of all tasks. In terms of project management structure, the overall responsibility sits with PI, who, together with the WP leaders, will oversee the day-to-day administration and monitor progress and timely completion of deliverables. Management is organized through a separate WP. The PI has extensive experience with project management and event organization, and CICERO has hosted a wide range of similar projects.




**WP1 (M1-M21) (Lead: Fisher, participants: Staniaszek, Lund, Foster)**

*Task 1.1* Required parameterization developments to enable prescribed burnt area functionality.

*Task 1.2* Update fire emission parametrization in FATES: A) include peat fire emissions, B) update emission factors where possible relevant, C) other updates.

*Task 1.3* Benchmarking and calibration: A) compile data for validation, B) offline CLM-FATES runs for benchmarking, C) revise and rerun.

**Milestones:** 1.1) Initial validation/benchmarking (M10), 1.2) CLM-FATES output to WP3 for testing (M16)

**WP2 (M1-M21) (Lead: Lund, participants: Silver, McCarty, Paunu, Samset, Pistone)**

*Task 2.1* Literature/data review, including recent observational campaigns

*Task 2.2* Integrating dimensions of human drivers of fire risk: A) workshop, B) synthesis and input to 2.3.

*Task 2.3* ML burnt area tool: A) data compilation, B) development and training, C) projecting burnt area.

**Milestones:** 2.1) Workshop conducted (M9), 2.2) First set of burnt area projections (M15)

**WP3 (M16-M39) (Lead: Samset, participants: Lund, Arnold, Turnock, Fisher, Pistone)**

*Task 3.1* Setup identification of initial combinations and extraction of burnt area and emission characteristics.

*Task 3.*2 Initial simulations and analysis

*Task 3.3* PPE-derived sampling of further combinations; further simulations

*Task 3.4* Analysis of full idealized dataset; input to WP4 (on understanding the response in realistic cases)

**Milestones:** 3.1) First test runs using emissions from WP1 (M20), 3.2) Decision on experiments (M28)

**WP4 (M34-M48) (Lead: Staniaszek, participants: Samset, Lund, Arnold, Turnock)**

*Task 4.1* Run and analyse coupled, transient simulations with NorESM/CLM-FATES and UKESM

*Task 4.2* Develop recommendations for multi-model experiments.

**Milestones:** 4.1) Setup of first coupled ESM experiments (M35), 4.2) Emissions from FATES-CLM to UKESM (M39).

**WP5 Synthesis, dissemination, exploitation (M1-M54) (Lead: Bang. Participants: Lund, Fronzek, Ma, all)**

*Task 5.1* Cascading risk: A) produce first version of cascade, B) conduct workshop, C) review and revise.

*Task 5.2* Synthesis: A) develop web-based map/portal, B) produce policy brief, C) other synthesis
*Task 5.3* Dissemination/exploitation: A) coordination of dissemination activities, B) production of communication material, e.g. fact sheets, popular science piece and social media material (see section 2 and application form for details)
**Milestones:** 5.1) written communication strategy (M4), 5.2) first version of risk cascade for review (M47)

**WP6 Management (M1-M54) (Lead: Lund, participants: all)**

Running administration and coordination of the project, including data management. Meetings/workshops/visits: Official kick-off meeting, annual meetings with the whole team, and frequent WP-meetings w/ remote attendance options for international collaborators. Additional project meetings arranged in connection with relevant conferences if convenient. Continuous internal project communication will be ensured through regular physical and hybrid meetings, and broad use of collaborative tools (teams, zoom).

**Resource infrastructure:** The required high performance computing resources and data storage will be sought from the Norwegian HPC clusters through Sigma2/NRIS, and using the HPC and data storage facilities at the UK Met Office. Model output, code and key data sets produced in the project will be made openly available, e.g. through GitHub. WP6 will be responsible for ensuring that Fair, Accessible, Interoperable and Re-usable (FAIR) data management practices throughout the project, including preparation of a data management plan.

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*"Anyone can see a forest fire. Skill lies in sniffing the first smoke." – Robert A Heinlein*