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The Fire Modeling Intercomparison Project (FireMIP) for CMIP7

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Abstract. Fire is a global phenomenon and a key Earth system process. Extreme fire events have increased in recent years, and fire frequency and intensity are projected to rise across most regions and biomes, posing substantial challenges for ecosystems, the carbon cycle, and society. The Fire Model Intercomparison Project (FireMIP), launched in 2014, has contributed to advancing global fire modeling in Dynamic Global Vegetation Models (DGVMs) and improving understanding of fire's local drivers and local impacts on vegetation and land carbon budgets through land offline (i.e., uncoupled from the atmosphere) simulations. We now bring FireMIP into Coupled Model Intercomparison Project Phase 7 (CMIP7) to: (1) evaluate fire simulations in state-of-the-art fully coupled Earth system models (ESMs); (2) assess fire regime changes in the past, present, and future, and identify their primary natural and

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anthropogenic forcings and causal pathways within the Earth system, including the associated uncertainties; and (3) quantify the impacts of fires and fire changes on climate, ecosystems, and society across Earth system components, regions, and timescales, and elucidate the underlying mechanisms. FireMIP in CMIP7 will advance the fire and fire-related modeling in fully coupled ESMs, and provide a quantitative, detailed, and process-based understanding of fire's role in the Earth system by using models that incorporate critical climate feedbacks and multi-model, multi-initial-condition, and CMIP7 multi-scenario ensembles. This paper presents the motivation, scientific questions, experimental design and its rationale, model inputs and outputs, and the analysis framework for FireMIP in CMIP7, providing guidance for Earth system modeling teams conducting simulations and informing communities studying fire, climate change, and climate solutions.

1. Introduction

Fire is a critical Earth system process, the primary form of terrestrial ecosystem disturbance on a global scale, and has been present since the emergence of terrestrial plants around 400 million years ago (Scott and Glasspool, 2006; Randerson et al., 2006; Bowman et al., 2009; Li et al., 2013). Each year, fire burns over 400 Mha of vegetated land (Giglio et al., 2018; Chuvieco et al., 2019; Chen et al., 2023), releasing 2–4 Pg of carbon globally along with large amounts of aerosols, greenhouse gases, and tropospheric ozone precursors (van der Werf et al., 2017; Wiedinmyer et al., 2023; Whaley et al., 2024; Kaiser et al., 2025). Fire is regulated by climate, vegetation, and human activities, and feeds back to them in multiple ways, both locally and remotely, across various temporal scales, forming intricate feedback loops (Bond-Lamberty et al., 2007; Jiang et al., 2016; Li and Lawrence, 2017; Li et al., 2017, 2019, 2022; Jones et al., 2022; Lou et al., 2023; Mao, 2024; Park et al., 2024; Harrison et al., 2025; Zhao et al., 2025). These feedbacks may interact with potential tipping elements in vulnerable systems, such as permafrost thaw, Amazon rainforest dieback, boreal forest dieback, and Arctic sea-ice loss (Lenton et al., 2019). Although global burned area has declined over the past two decades (Andela et al., 2017), the frequency and intensity of extreme fire events (Cunningham et al., 2025), as well as forest fire emissions (Zheng et al., 2021), have increased. Importantly, global fire activity is projected to rise across most biomes, especially under the high-emission scenario and in extratropical regions (Li, 2021; Yu et al., 2022; UNEP, 2022; Sayedi et al., 2024; Bhattarai et al., 2025).

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Earth system models (ESMs) simulate the processes and feedbacks within and among the atmosphere, ocean, land, sea ice, and biosphere, and are essential for understanding historical climate, environment, and ecosystems changes and for projecting the Earth's future (Scholze et al., 2013). ESMs have replaced climate models as the primary coupled models since the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Dunne et al., 2025). Due to the critical role of fire in the Earth system, most ESMs now incorporate fire modeling. In CMIP6, 19 models submitted outputs of fire variables (Li et al., 2024a) versus 9 in CMIP5 (Kloster et al., 2017), and this number is expected to grow further in CMIP7. Furthermore, many ESMs have updated their fire schemes (e.g., Li et al., 2024b; Teixeira et al., 2025; Oberhagemann et al., 2025). Assessing the performance of CMIP7 ESMs in simulating fire and related variables is crucial for advancing fire-related process modeling.

Several studies have investigated fire changes across the past, present, and future and their local drivers. Over the past decades, global fire-regime changes are found to be driven mainly by human fire suppression (both direct and indirect, the latter through land-use-induced reduction in fuel continuity), enhanced by rising CO_2 levels that increase fuel load through CO_2 fertilization, and increasingly influenced by climate change (Andela et al., 2017; Li et al., 2018, 2019; Teckentrup et al., 2019; Burton et al., 2024; Scholten et al., 2024; Verjans et al., 2025). For the future, studies project an overall increase in global fire activity under CMIP5 and CMIP6 scenarios, particularly under the high emission scenario, mainly due to climate change including warming and increased lightning in Arctic-boreal regions and drying in the tropics (Kloster et al., 2017; Chen et al., 2021; Li, 2021; Wu et al., 2022; Byrne et al., 2024; Sayedi et al., 2024). Nevertheless, substantial uncertainties remain in the simulation of historical and future fire changes (Kloster et al., 2017; van Marle et al., 2017; Li et al., 2019; Li, 2021; Hamilton et al., 2024). In CMIP7, the Scenario Model Intercomparison Project (ScenarioMIP) provides updated future scenarios that are more plausible than those in CMIP6, along with forcing datasets (van Vuuren et al., 2025). In addition, many studies have used simulations from the Detection and Attribution Model Intercomparison Project (DAMIP) experiments in CMIP6 to attribute the impact of anthropogenic and natural forcings on climate (IPCC, 2021; Gillett et al., 2025), but far fewer have examined the downstream impacts on wildfires, and those that do are focused on the western United States (e.g., Zhuang et al., 2021). How fire regimes will change under the CMIP7 scenarios and how anthropogenic and natural forcings have shaped historical global fire changes through climate and ecosystem processes remain unknown.

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Fire impacts on the Earth system remain poorly quantified and understood. First, earlier studies primarily focused on specific components, such as biomass-burning effects on land carbon budgets or the radiative forcing and climate impacts of fire aerosols (Lasslop et al., 2019). Many other important fire impact processes, especially those across multiple Earth system components, are still unknown, for example, the global land-atmosphere-ocean carbon cycle, CH_4 emissions through affecting permafrost and wetland and their evolution in the atmosphere. Second, even for those processes that have been quantified, earlier estimates are likely inaccurate due to neglecting some critical climate feedbacks. Earlier studies quantified the fire impacts on land carbon and vegetation using land models driven by prescribed meteorological forcing, thereby neglecting fire-induced changes in surface climate (e.g., Li et al., 2014; Li and Lawrence, 2017; Ward et al., 2018; Arora and Melton, 2018; Lasslop et al., 2020; Pellegrini et al., 2023; Seo and Kim, 2023). Some coupled simulation studies adopted prescribed sea surface temperatures (SSTs) and/or sea ice coverage (e.g., Jiang et al., 2016; Grandey et al., 2016; Li et al., 2017a, b; Zou et al., 2020; Xu et al., 2021; Tian et al., 2022; Zhong et al., 2024; Blanchard-Wrigglesworth et al., 2025), which likely underestimated fire impacts due to the lack of air-sea interactions and sea-ice-albedo feedbacks (Jiang et al., 2020). Conversely, studies using a slab-ocean model, which lack horizontal heat transport, deep-water exchange, and ocean dynamics, may overestimate fire impacts (e.g., Jiang et al., 2020; Li et al., 2022; Zhao and Suzuki, 2019). Models without aerosol–cloud interactions (ACIs) have produced biased, sometimes even opposite-sign, fire-aerosol effects (e.g., Tosca et al., 2013; Yue and Unger, 2018; Li, 2020; Xu et al., 2021). Third, earlier coupled studies relied on a single model or a single initial-condition simulation, limiting characterization of model uncertainty and internal climate variability. For example, differences in the strength of ACIs or aerosol–radiation interactions can produce large inter-model spread in estimated net fire-aerosol effects, ranging from net cooling to net warming (Landry et al., 2017; Jiang et al., 2020; Zhong et al., 2024; Blanchard- Wrigglesworth et al., 2025). Moreover, small perturbations to initial conditions can influence simulated climate states for decades to even over a century (Kay et al., 2015). Multi-model, multi-initial-condition, fully coupled simulations with critical climate feedbacks from CMIP7 therefore offer a unique opportunity to more robustly quantify fire's local and remote impacts across Earth system components and timescales, reveal the underlying mechanisms, and characterize the associated uncertainties.

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The Fire Model Intercomparison Project (FireMIP), an international initiative launched in 2014, has worked to improve global fire modeling in DGVMs, understand local drivers of fires, and assess the influence of fires on vegetation, land carbon budgets, and, since 2020, on land and socioeconomic sectors as part of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Hantson et al., 2016; Rabin et al., 2017; Frieler et al., 2024). Now integrated into CMIP7, FireMIP advances the study of fire's role in the Earth system using coupled model simulations. It contributes to improving fire and fire-related simulations in ESMs and addresses critical challenges in understanding fire dynamics, drivers, and impacts. CMIP7 FireMIP is also expected to provide useful insights for fire management, carbon accounting, air quality management, public health, land-use planning, and biodiversity protection. These insights link Earth system science to evidence-based policy making for risk management, ecosystem conservation, and sustainable development.

With the motivation and context outlined above, we describe in the following sections the scientific questions (Section 2), experimental design and rationale (Section 3), input and output variables (Section 4), and recommended analyses (Section 5), and conclude with the expected contributions to CMIP7 (Section 6).

2. Scientific Questions

FireMIP in CMIP7 aims to address three fundamental fire-related scientific questions (Fig. 1):

(1) How well do state-of-the-art ESMs simulate global and regional fires?

Li et al. (2024) evaluated fire simulations from CMIP6 ESMs and found that they had addressed three critical issues identified in CMIP5: (1) simulated global burned area being less than half of observations, (2) failure to reproduce the high burned area fraction observed in Africa, and (3) very weak fire seasonal variability. However, CMIP6 ESMs still underestimate the recent decline trend in global burned area, fail to capture the spring fire peak in the Northern mid-latitudes, and perform poorly in the Arctic-boreal zone. Since CMIP6, modeling groups have updated their ESMs (with fire-scheme improvements in some models), and more models will provide fire outputs in CMIP7. The first scientific question is therefore designed to assess how well state-of-the-art ESMs simulate fires, whether CMIP6 issues have been resolved, and what remaining or new issues emerge in CMIP7. It further aims to identify biases in fire and fire-related variables to guide future improvements in modeling fire–carbon–climate feedbacks, and

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to support model selection and bias correction for more reliable assessments of fire changes, drivers, and impacts addressed in Questions 2 and 3.

(2) How have fire regimes changed in the past, how will they change in the future, and what are the dominant drivers of these changes?

This question investigates temporal and spatial changes in fire activity across the past, present, and future, along with the associated uncertainties. It examines the influence of natural and anthropogenic forcings on changes in fire regimes and, for anthropogenic forcings, further isolates the roles of greenhouse gases, aerosols, and land-use change. By comparing these effects, the dominant forcings and their causal pathways within the Earth system can be identified.

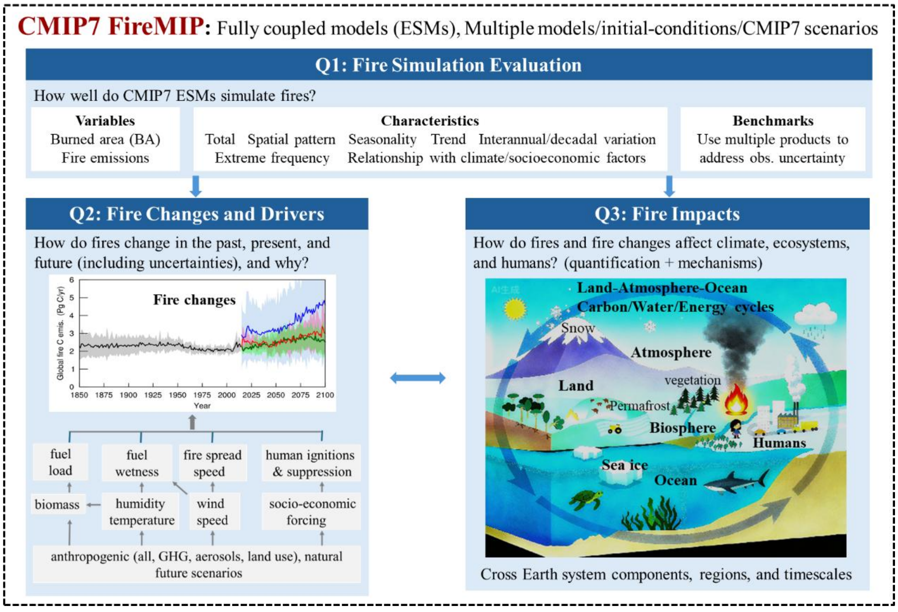

Figure 1. Scientific questions and proposed analyses for FireMIP in CMIP7. The fire-change panel is adapted from Li (2021).

(3) How do fires and fire changes impact the climate, ecosystems, and humans?

This question explores the impacts of fires and changes in fire regimes on the land-atmosphere-ocean carbon, water, and energy cycles; vegetation distribution and structure; atmospheric composition, chemistry, and circulation; surface climate (e.g., temperature, precipitation, humidity, wind speed); the

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cryosphere (permafrost extent and active-layer depth, sea ice extent and thickness, snow cover and depth); air quality; and human activities. It also investigates the associated uncertainties, and the feedback mechanisms that cascade across Earth-system components. For example, it examines how fires influence climate and the carbon cycle through changes in land ecosystems and emissions of aerosols and trace gases, and how these changes, in turn, affect the spatial and temporal variability of fires. Addressing this question can also help clarify the potential role of fires in triggering or amplifying tipping-point transitions in boreal forests, the Amazon rainforest, permafrost, and Arctic sea ice.

3. Experimental design

CMIP7 FireMIP comprises three experiment groups (Table 1) designed to address the scientific questions outlined above. The design follows the principle of minimizing computational burden while effectively addressing the scientific questions, aiming to encourage broad participation from the modeling community, given that fully coupled ESM runs are very expensive. The tier-1 (required) experiments in Groups 1 and 2 come from CMIP7 Diagnostic, Evaluation and Characterization of Klima (DECK) and Assessment Fast Track (AFT) experiments. To participate in FireMIP, modeling groups must output two fire variables (i.e., burned area fraction and fire carbon emissions) from these simulations. Group 3 (Fire impacts) experiments are specific to FireMIP. Modeling groups are required to provide the hist-no-fire simulation and are encouraged to conduct one to three additional Group 3 experiments based on scientific interest and available resources. Running at least three initial-condition ensemble members for each experiment is strongly recommended to improve the robustness of the assessment, given the role of internal climate variability, and is consistent with DECK and AFT requirements.

Group 1 experiments are used to evaluate fire simulations and identify biases. The experiments include concentration-driven (historical) or emission-driven (esm-historical) coupled model simulations, and historical land model offline simulations (land-hist). Fire simulations in coupled models will be assessed to identify improvements compared to CMIP6 and to highlight issues that will guide further model development. Besides, the possible sources of improvement and bias (from land modeling, atmosphere modeling, or air-land coupling) can be identified by comparing coupled (historical or esm-historical) with land only (land-hist) simulations.

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Table 1. Description of CMIP7 FireMIP experiments.

Group	Experiment ID	Description	Priority
1. Fire Simulation Evaluation	(1.1) historical/esm-historical (DECK)	1850–2021 historical concentration- or emission (esm)-driven coupled simulations	1
	(1.2) land-hist (AFT; LMIP tier-1)	1850–2021offline land-model simulations	3
2. Fire Changes and Drivers	(2.1) scen7-hc/esm-scen7-h scen7-mc/esm-scen7-m scen7-mlc/esm-scen7-ml scen7-lc/esm-scen7-l (AFT; ScenarioMIP tier-1)	2022–2100 concentration-driven or emission- driven coupled simulations under high (h, policy failure), medium (m, current policy), medium-low (ml, delayed mitigation policy), and low (l, Paris Agreement) emission scenarios	1
	(2.2) hist-nat (AFT; DAMIP tier-1)	same as historical/esm-historical, with solar and volcanic forcings time-varying; other forcings fixed in 1850	1
	(2.3) hist-aer & hist-GHG (AFT; DAMIP tier-1) hist-lu (DAMIP tier-1)	same as historical/esm-historical, but with time-varying anthropogenic aerosols (hist-aer), greenhouse gases (hist-GHG), and land use (hist-lu), while other forcings fixed in 1850	2
	(2.4) scen7-vlloc/ esm-scen7-vllo scen7-vlhoc/ esm-scen7-vlho (AFT; ScenarioMIP tier-1)	2022–2100 coupled simulations under very low emissions after limited overshoot (vllo) and high overshoot (vlho) scenarios	3
2 Fire Impacts	(3.1) hist-no-fire	1850–2021 historical coupled simulations with fires set to zero thereafter	1
	(3.2) hist-no-fireaero	branching from historical/esm-historical no later than 1920, with fire aerosols set to zero thereafter	2
	(3.3) scen7-h-no-firechange	2022–2060 simulations as scen7-h, but with fires fixed at the 2001–2020 average	2
	(3.4) scen7-h-no-fireaerochange	2022–2060 simulations as scen7-h, but with fire aerosol emission fixed at the 2001–2020 average	2

Priority: 1 (required); 2 (recommended); 3 (optional)

Group 2 experiments are used to assess fire changes and drivers. These experiments include: (2.1) simulations for 2022–2100 under high (h, policy failure), medium (m, current policy), medium-low (ml,

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delayed mitigation policy), and low (l, aligned with Paris agreement) emission scenarios; and (2.2) a historical sensitivity simulation (hist-nat) similar to historical and esm-historical, driven by time-varying solar and volcanic forcings, with all other forcings fixed at their 1850 levels. In addition, lower-priority simulations in FireMIP include (2.3) 2022–2100 simulations under very low emissions after limited overshoot (vllo) and high overshoot (vlho), and (2.4) 1850–2022 simulations as historical and esm-historical with only anthropogenic aerosols (hist-aer), greenhouse gases (hist-GHG), and land use (hist-lu) varying in time, with other forcings fixed at 1850 levels.

Experiments (2.1) and (2.3), together with the historical and esm-historical simulations in Group 1, are used to assess how fire and fire emissions have changed during the historical period and how they will evolve under current-policy and failed-policy futures, as well as under varying levels of mitigation-policy success. Comparing experiments (2.2) and (2.4) with the historical and esm-historical simulations enables the assessment of how natural and anthropogenic forcings influence fires and isolates the effects of anthropogenic forcings, including aerosols, greenhouse gases, and land use.

Group 3 experiments are designed to quantify the impacts of fires, fire aerosols, future fire changes, and future changes in fire aerosols, respectively, and to explore the underlying mechanisms. Among them, (3.1) hist-no-fire is a 1850–2021 simulation without fires. In this experiment, burned area in the code should be set to zero, and any fire-induced emissions that are not simulated and passed to the atmosphere model need to be set to zero in the input data. CanESM simulations indicate that the global vegetation carbon pool and land surface air temperature require approximately 150–200 years and nearly 50 years, respectively, to reach their new no-fire equilibria after fires are switched off (V. K. Arora, 2025, personal communication). Therefore, starting the experiment from a 1850 no-fire spin-up is strongly recommended, to cleanly isolate present-day fire impacts (i.e., to avoid contamination by artificial trends caused by climate and carbon adjustment before equilibrium is reached). Experiment (3.2) hist-no-fireaero branches from the historical or esm-historical simulation no later than 1920, with fire-aerosol emissions set to zero thereafter. The year 1920 is chosen to provide at least 70 years of no-fire-aerosol spin-up, allowing the isolation of present-day fire-aerosol impacts. The spin-up length is informed by evidence that the global water cycle in CESM2 reaches no-fire-aerosol equilibrium after about 70 years (Li et al., 2022), and that the global vegetation and soil carbon pools require roughly 50 and 80 years, respectively, to equilibrate or show only minor slow changes in the CMIP6 global deforestation experiment (Boysen et al., 2020). Comparing the present-day averages, seasonality, recent

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trends, and decadal/interannual variations of target variables from experiments (3.1) and (3.2) with the historical or esm-historical simulations enables the assessment of fire impacts and fire-aerosol impacts, respectively.

Additionally, Experiments (3.3) scen7-h-nofirechange is a 2022–2060 simulation, the same as scen7-h, but with burned area and fire emissions fixed at their 2001–2020 average; this requires burned area to be prescribed as an input field using each model's own 2001–2020 average derived from its historical simulations, and in models without interactive fire-emission modules, fire emissions in the 2022–2060 input files must likewise be replaced with the 2001–2020 average. Experiment (3.4) scen7-h-no-fireaerochange is a 2022–2060 simulation, the same as scen7-h, but with fire aerosol emissions in the inputs fixed at the 2001–2020 average, which is not applicable to ESMs with interactive fire-emission modules. Comparing Experiments (3.3) and (3.4) with the scen7-h simulations for 2022–2060 facilitates assessing the impacts of future changes in fires and fire aerosols, respectively, under a high-emission scenario.

4. Inputs and outputs

4.1 Inputs

Fire-specific inputs include: (1) population density, for modeling ignitions and human fire suppression; (2) lightning frequency for natural ignitions; (3) GDP for human fire suppression; (4) peatland area fraction, for peat fire modeling; (5) peak month of agricultural fires for timing of agricultural waste burning; and (6) fire-sourced trace gas and aerosol emissions representing part of fire impacts.

Not all ESMs require or use all six inputs. For example, ESMs without modeling direct human effects on fires likely do not need population density, GDP, or peak month of agricultural fires. Similarly, models that do not simulate peat fires do not require peatland area fraction. For ESMs that activate the interactive fire-emission module (i.e., simulate fire emissions and pass to the atmospheric model) and model lightning, prescribed fire emissions and lightning frequency are not needed.

Historical gridded population density data (1850–2025; Paprotny and Hawker, 2025) and fire emission data (1750–2023; van Marle and van der Werf, 2025) are provided by CMIP7 forcing group and available through https://input4mips-cvs--350.org.readthedocs.build/en/350/database-views/input4MIPs_delivery-summary.html. Future population density and fire aerosol emission datasets are under development. Because CMIP7 will not provide forcing data for inputs (2–5), models may use

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their default settings.

4.2 Output variables

The variables requested by CMIP7 FireMIP are classified into two categories: (1) fire variables and (2) fire driver and impact variables. The fire variables, specifically burned area fraction and fire carbon emissions, are the highest priority (Table 2). They are essential for evaluating fire simulations and assessing fire-regime changes.

Table 2. CMIP7 FireMIP outputs: fire variables

Name	Description	Branded name	Unit	#Dims	Frequency
burntFractionAll	Burned Area Fraction	burntFractionAll_tavg-u-hxy-u	% mon^{-1}	3	monthly
fFire	Fire Carbon Emissions	fFire_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly

The fire driver and impact variables include land-atmosphere-ocean carbon cycle variables (Table 3) as well as other land (vegetation structure, vegetation distribution, land nitrogen fluxes and pools, and land hydrothermal, snow characteristics), atmosphere (meteorology, atmospheric circulation, physics, composition, and chemistry), and ocean and sea-ice variables (Table 4). These variables will be used to evaluate model accuracy in capturing fire-ecosystems and fire-climate relationships, and to investigate the drivers of fire-regime changes and fire impacts.

These fire driver and impact variables are selected because previous studies show that they (1) respond to natural and anthropogenic forcings, and can also influence fuel load, fuel flammability, and/or fire spread (IPCC, 2021; Gillett et al., 2025); (2) are significantly affected by fires at global or regional scales, e.g., land carbon budgets and vegetation (e.g., Bond-Lamberty et al., 2007; Li et al., 2014; Yue and Unger, 2018; Lasslop et al., 2020; Zou et.al., 2020; Seo and Kim, 2023), land nitrogen fluxes and pools (Beaudor et al., 2025), surface climate (e.g., Jiang et al., 2016; Li and Lawrence 2017; Li et al., 2017), land–atmosphere energy exchange (e.g., Li et al., 2017), water cycle (Li et al., 2022), CH_4 cycle (Tian et al., 2016), dust emissions (Yu and Ginoux, 2022), atmospheric composition and chemistry (e.g., Ward et al., 2012; Li et al., 2019; Jiang et al., 2020), large-scale atmospheric circulation (Li et al., 2022; Scholten et al., 2022), sea ice and snow (e.g., Li et al., 2022; Zhong et al., 2024), permafrost (Talucci et al., 2025), sea-surface temperature (Li et al., 2022), and marine ecosystems (Liu et al., 2022; Riera and Pausas, 2023); (3) are likely affected by the fire-induced changes listed in (2)

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(i.e., downstream variables), such as atmosphere and ocean carbon and energy; and (4) are needed to diagnose the response and influence mechanisms (i.e., intermediate variables), such as ocean currents.

Table 3. CMIP7 FireMIP outputs: land-atmosphere-ocean carbon cycle variables

Name	Description	Branded name	Unit	#Dims	Frequency
gpp	Gross Primary Productivity	gpp_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly
ra	Autotrophic Respiration	ra_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly
rh	Heterotrophic Respiration	rh_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly
fLuc	Land-Use Change carbon emissions	fLuc_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly
npp	Net Primary Productivity	npp_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly
nep	Net Ecosystem Productivity	nep_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly
nbp	Net Biospheric Productivity	nbp_tavg-u-hxy-lnd	kg C m^{-2} s^{-1}	3	monthly
cLeaf	Carbon mass in leaves	cLeaf_tavg-u-hxy-lnd	kg C m^{-2}	3	monthly
cStem	Carbon Mass in stems	cStem_tavg-u-hxy-lnd	kg C m^{-2}	3	monthly
cRoot	Carbon Mass in Roots	cRoot_tavg-u-hxy-lnd	kg C m^{-2}	3	monthly
cProduct	Carbon Mass in Products of Land-Use Change	cProduct_tavg-u-hxy-lnd	kg C m^{-2}	3	monthly
cVeg	Carbon Mass in Vegetation	cVeg_tavg-u-hxy-lnd	kg C m^{-2}	3	monthly
cLitter	Carbon Mass in Litter	cLitter_tavg-u-hxy-lnd	kg C m^{-2}	3	monthly
cSoil	Carbon Mass in Soil	cSoil_tavg-u-hxy-lnd	kg C m^{-2}	3	monthly
co2	Mole Fraction of CO2 in air	co2_tavg-p19-hxy-air	mol mol^{-1}	3	monthly
fgco2	Surface Downward Mass Flux of Carbon as CO2	fgco2_tavg-u-hxy-sea	kg C m^{-2} s^{-1}	3	monthly
spco2	Surface Aqueous Partial Pressure of CO2	spco2_tavg-u-hxy-sea	Pa	3	monthly
dissic	Dissolved Inorganic Carbon Concentration	dissic_tavg-ol-hxy-sea	mol m^{-3}	3	monthly
dissoc	Dissolved Organic Carbon Concentration	dissoc_tavg-ol-hxy-sea	mol m–3	3	monthly
intnpp	NPP by Phytoplankton	intpp_tavg-u-hxy-sea	Kg C m^{-2}	3	monthly

The variables required for CMIP7 FireMIP are in the variable list of CMIP7 DECK and AFS experiments, with no additional requests specifically for FireMIP. It is acceptable for some variables to be absent if the model does not include the corresponding component or process, such as the ocean ecosystem, terrestrial nitrogen cycle, CH_4 cycle, groundwater, or air-quality (e.g., surface $PM_{2.5}$ and O_3 concentrations).

Some variables in Table 4 are listed with daily or hourly frequencies because corresponding

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monthly variables are unavailable in the CMIP7 variable list. If modeling teams provide monthly outputs for these variables, that is acceptable. CMIP7 FireMIP does not have specific requirements for spatial resolution.

Table 4. CMIP7 FireMIP outputs: other land, atmosphere, ocean, and sea ice variables

Name	Description	Branded name	Unit	#Dims	frequency
		Land			
lai	Leaf Area Index	lai_tavg-u-hxy-lnd	unitless	3	monthly
vegHeight	Height of Canopy	vegHeight_tavg-u-hxy-veg	m	3	monthly
treeFrac	Tree Cover Percentage	treeFrac_tavg-u-hxy-u	%	3	monthly
grassFrac	Grass Area Percentage	grassFrac_tavg-u-hxy-u	%	3	monthly
shrubFrac	Shrub Area Percentage	shrubFrac_tavg-u-hxy-u	%	3	monthly
cropFrac	Crop Area Percentage	cropFrac_tavg-u-hxy-u	%	3	monthly
baresoilFrac	Bare Soil Area Percentage	baresoilFrac_tavg-u-hxy-u	%	3	monthly
fNgasFire	Nitrogen Lost to the Atmosphere from Fire	fNgasFire_tavg-u-hxy-lnd	kg N m^{-2} s^{-1}	3	monthly
fNdep	Nitrogen deposition	fNdep_tavg-u-hxy-lnd	kg N m^{-2} s^{-1}	3	monthly
Fbnf	Biological Nitrogen Fixation	fBNF_tavg-u-hxy-lnd	kg N m^{-2} s^{-1}	3	monthly
fNleach	Nitrogen Loss to Leaching or Runoff	fNleach_tavg-u-hxy-lnd	kg N m^{-2} s^{-1}	3	monthly
fNup	Total Plant Nitrogen Uptake	fNup_tavg-u-hxy-lnd	kg N m^{-2} s^{-1}	3	monthly
nVeg	Vegetation Nitrogen Mass	nVeg_tavg-u-hxy-lnd	kg N m^{-2}	3	monthly
nLitter	Nitrogen Mass in Litter	nLitter_tavg-u-hxy-lnd	kg N m^{-2}	3	monthly
nSoil	Nitrogen Mass in Soil	nSoil_tavg-u-hxy-lnd	kg N m^{-2}	3	monthly
nMineral	Soil Mineral Nitrogen	nMineral_tavg-u-hxy-lnd	kg N m^{-2}	3	monthly
tsl	Soil temperature	tsl_tavg-sl-hxy-lnd	K	4	monthly
mrsol	Water Content of Soil Layer	mrsol_tavg-sl-hxy-lnd	kg m^{-2}	4	monthly
mrso	Total Soil Moisture Content	mrso_tavg-u-hxy-lnd	kg m^{-2}	3	monthly
evspsblveg	Canopy Evaporation	evspsblveg_tavg-u-hxy-lnd	kg m^{-2} s^{-1}	3	monthly
evspsblsoi	Soil Evaporation	evspsblsoi_tavg-u-hxy-lnd	kg m^{-2} s^{-1}	3	monthly
tran	Transpiration	tran_tavg-u-hxy-lnd	kg m^{-2} s^{-1}	3	monthly
evspsbl	Evapotranspiration	evspsbl_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
mrro	Total Runoff	mrro_tavg-u-hxy-lnd	kg m^{-2} s^{-1}	3	monthly
mrros	Surface Runoff	mrros_tavg-u-hxy-lnd	kg m^{-2} s^{-1}	3	monthly
rivo	River Discharge	rivo_tavg-u-hxy-lnd	m^{3} s^{-1}	3	daily
friver	Water Flux into Sea Water from Rivers	friver_tavg-u-hxy-sea	kg m^{-2} s^{-1}	3	monthly
dgw	Change in Groundwater	dgw_tavg-u-hxy-lnd	kg m^{-2}	3	daily

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wtd	Water Table Depth	wtd_tavg-u-hxy-lnd	m	3	daily
prveg	Canopy Interception	prveg_tavg-u-hxy-lnd	kg m^{-2} s^{-1}	3	monthly
rlds	Surface Downwelling Longwave Radiation	rlds_tavg-u-hxy-u	W m^{-2}	3	monthly
rsus	Surface Upwelling Shortwave Radiation	rsus_tavg-u-hxy-u	W m^{-2}	3	monthly
rlus	Surface Upwelling Longwave Radiation	rlus_tavg-u-hxy-u	W m^{-2}	3	monthly
hfls	Surface Upward Latent Heat Flux	hfls_tavg-u-hxy-u	W m^{-2}	3	monthly
hfss	Surface Upward Sensible Heat Flux	hfss_tavg-u-hxy-u	W m^{-2}	3	monthly
hfds	Downward Heat Flux at Sea Water Surface	hfds_tavg-u-hxy-sea	W m^{-2}	3	monthly
hfdsl	Ground heat flux	hfdsl_tavg-u-hxy-lnd	W m^{-2}	3	3-hourly
rsdsdiff	Surface Diffuse Downwelling Shortwave Radiation	rsdsdiff_tavg-u-hxy-u	W m^{-2}	3	daily
snm	Surface Snow Melt	snm_tavg-u-hxy-lnd	kg m^{-2} s^{-1}	3	monthly
snd	Snow Depth	snd_tavg-u-hxy-lnd	m	3	monthly
snc	Snow Area Percentage	snc_tavg-u-hxy-lnd	%	3	monthly
snw	Surface Snow Amount	snw tavg-u-hxy-lnd	kg m^{-2}	3	monthly
Atmosphere					
pr	Precipitation	pr_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
tas	Near-surface air temperature	tas_tavg-h2m-hxy-u	K	3	monthly
tasmax	Daily Maximum Near-Surface Air Temperature	tas_tmax-h2m-hxy-u	K	3	monthly
tasmin	Daily Minimum Near-Surface Air Temperature	tas_tmin-h2m-hxy-u	K	3	monthly
sfcWind	Near-Surface Wind Speed	sfcWind_tavg-h10m-hxy-u	m s^{-1}	3	monthly
hurs	Near-Surface Relative Humidity	hurs_tavg-h2m-hxy-u	%	3	monthly
psl	Sea Level Pressure	psl_tavg-u-hxy-u	Pa	3	monthly
zg	Geopotential Height	zg_tavg-p19-hxy-air	m	4	monthly
ua	Eastward Wind	ua_tavg-p19-hxy-air	m s^{-1}	4	monthly
va	Northward Wind	va_tavg-p19-hxy-air	m s^{-1}	4	monthly
ta	Air Temperature	ta_tavg-p19-hxy-air	K	4	monthly
hus	Specific Humidity	hus_tavg-p19-hxy-u	1	4	monthly
cldnvi	Column Integrated Cloud Droplet Number	cldnvi_tavg-u-hxy-u	m^{-2}	3	monthly
clt	Total Cloud Cover Percentage	clt_tavg-u-hxy-u	%	3	monthly

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rsdt	TOA Incident Shortwave Radiation	rsdt_tavg-u-hxy-u	W m^{-2}	3	monthly
rsdcs	Downwelling Clear-Sky Shortwave Radiation at the surface and TOA	rsdcs_tavg-alh-hxy-u	W m^{-2}	4	monthly
loadbc	Load of BC	loadbc_tavg-u-hxy-u	kg m-2	3	daily
loadpoa	Load of Dry Aerosol Primary Organic Matter	loadpoa_tavg-u-hxy-u	kg m^{-2}	3	daily
loadso4	Load of SO4	loadso4_tavg-u-hxy-u	kg m^{-2}	3	monthly
od550bb	Aerosol Optical Depth at 550nm Due to Biomass Burning	od550bb_tavg-u-hxy-u	1	3	monthly
od550bc	Black Carbon Optical Thickness at 550nm	od550bc_tavg-u-hxy-u	1	3	monthly
od550oa	Total Organic Aerosol Optical Depth at 550nm	od550oa_tavg-u-hxy-u	1	3	monthly
lwp	Liquid Water Path	lwp_tavg-u-hxy-u	kg m^{-2}	3	monthly
sfo3	O3 Volume Mixing Ratio in Lowest Model Layer	o3_tavg-h2m-hxy-u	mol mol^{-1}	3	hourly
sfpm25	PM2.5 Mass Mixing Ratio in Lowest Model Layer	sfpm25_tavg-h2m-hxy-u	kg kg^{-1}	3	daily
emico	Total Emission Rate of CO	emico_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
emibbch4	total emission of CH4 from all biomass burning	emibbch4_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
emich4	Total Emission Rate of CH_4	emich4_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
ch4global	Global Mean Mole Fraction of CH4	ch4_tavg-u-hm-u	1E-09	1	monthly
eminox	Total Emission Rate of NO_X	eminox_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
emibvoc	Total Emission Rate of Biogenic NMVOC	emibvoc_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
emidust	Total Emission Rate of Dust	emidust_tavg-u-hxy-u	kg m^{-2} s^{-1}	3	monthly
Ocean and sea ice					
no3	Dissolved Nitrate Concentration	no3_tavg-ol-hxy-sea	mol m^{-3}	3	monthly
po4	Total Dissolved Inorganic Phosphorus Concentration	po4_tavg-ol-hxy-sea	mol m^{-3}	3	monthly
chl	Mass Concentration of Phytoplankton Expressed as Chlorophyll in Sea Water	chl_tavg-ol-hxy-sea	kg m^{-3}	3	monthly

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talk	Total Alkalinity	talk_tavg-ol-hxy-sea	mol m^{-3}	3	monthly
fsfe	Surface Downward Net Flux of Iron	fsfe_tavg-u-hxy-sea	mol $m^{-2}s^{-1}$	3	monthly
dfe	Dissolved Iron Concentration	dfe_tavg-ol-hxy-sea	mol m^{-3}	3	monthly
uo	Sea Water X Velocity	uo_tavg-ol-hxy-sea	m s^{-1}	4	monthly
vo	Sea Water Y Velocity	vo_tavg-ol-hxy-sea	m s^{-1}	4	monthly
thetao	Sea Water Potential Temperature	thetao_tavg-ol-hxy-sea	degC	4	monthly
so	Sea Water Salinity	so_tavg-ol-hxy-sea	$1E^{-03}$	4	monthly
tos	Sea Surface Temperature	tos_tavg-u-hxy-sea	ºC	3	monthly
zos	Sea Surface Height Above Geoid	zos_tavg-u-hxy-sea	m	3	monthly
mlotst	Ocean Mixed Layer Thickness	mlotst_tavg-u-hxy-sea	m	3	monthly
msftyz	Ocean Meridional Overturning Mass Stream Function	msftm_tavg-ol-hys-sea	kg s^{-1} or S_v	4	monthly
siconc	Sea-Ice Area Fraction	siconc_tavg-u-hxy-u	1	3	monthly
sithick	Sea-Ice Thickness	sithick_tavg-u-hxy-si	m	3	monthly

5. Recommended analysis

5.1 Fire simulation evaluation

The ability of CMIP7 ESMs to simulate global and regional total burned area and fire carbon emissions will be evaluated, as well as their spatial and temporal variability (including spatial pattern, recent and long-term historical trends, and phases of seasonal variability, magnitude of interannual and decadal variability), extreme fire frequency, and relationships between fires with climatic and socioeconomic factors (Fig. 1). Unlike offline simulations of land surface models and DGVMs, which are driven by observed climate data, coupled models in CMIP are free-running and driven solely by anthropogenic forcing. As a result, they are not designed to synchronize with the actual climate state of specific years or decades. Consequently, expecting a one-to-one match between CMIP-simulated and observed fires for any given year or decade is unrealistic. Instead, we recommend evaluating how fires respond to large-scale climate oscillations, such as ENSO and PDO for tropical fires, and AO/NAO for Arctic-boreal fires (Ward et al., 2016; Chen et al., 2017; Kim et al., 2020; Zhao et al., 2022; Li et al., 2024a).

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Given the large uncertainties in global fire observations (Table 5; Li et al., 2024a; Kaiser et al., 2025), we recommend evaluating fire simulations against multiple benchmarks. For present-day burned area, benchmarks could include GFED5 (van der Werf et al., 2025), FireCCI5.1 (Chuvieco et al., 2019), FireCCI60 (Pettinari et al., 2025), and MODIS Collection 6.1 (Giglio et al., 2018). For present-day fire emissions, options include GFED5 (van der Werf et al., 2025), CAMS-GFAS1.2 (Kaiser et al., 2012), GFAS4HTAP (Kaiser et al., 2024; 2025), FINN2.5 (Wiedinmyer et al., 2023), FEER1 (Ichoku and Ellison, 2014), and QFED2.5 (Darmenov and da Silva, 2015).

Table 5. Summary description of satellite-based products as benchmarks for fire simulations

Name	Methods	Resolution	Period	Global total	reference
		Burned Area			
GFED5	MODIS BA & MODIS、ATSR、VIIRS active fire counts	0.25° monthly	1997–2022	802 Mha yr^{-1} [a]	Chen et al. (2023)
FireCCI5.1	MODIS reflectance &active fire counts	0.25° monthly	2001–2020	473 Mha yr^{-1} [a]	Chuvieco et al. (2019)
FireCCI6	MODIS & Sentinel-3 reflectance; MODIS & VIIRS active fire counts	0.25° monthly	2003–2024	634 Mha yr^{-1} [b]	Pettinari et al. (2025)
MODIS C6.1	MODIS reflectance &active fire counts	0.25° monthly	2001–present	430 Mha yr^{-1} [a]	Giglio et al. (2018)
		Fire emissions			
GFED5	fuel consumption, GFED5 burned area	0.25° monthly	1997–2022	3.4 Pg C yr^{-1} [c] 0.53 Pg CO yr^{-1} [c]	van der Werf et al. (2025)
CAMS-GFAS1.2	(GFED), MODIS FRP (GFAS), MODIS active	0.1° daily	2003–present	2.1 Pg C yr^{-1} [a] 0.36 Pg CO yr^{-1} [a]	Kaiser et al. (2012)
GFAS4HTAP1.2	fire counts (FINN), emis. Factor	0.1° daily	2003–2023	0.36 Pg CO yr^{-1} [d]	Kaiser et al. (2024)
FINN2.5		1km daily	2002–2023	0.58 Pg CO yr^{-1} [d]	Wiedinmyer et al. (2023)
FEER1	GFAS1.2 FRP & MODIS AOD	0.1° monthly	2003-2013	3.9 Pg C yr^{-1} [a] 0.56 Pg CO yr^{-1} [e]	Ichoku and Ellison (2014)
QFED2.5	MODIS & VIIRS FRP &MODIS AOD emis. factor	0.1° daily	2000-present	0.32 Pg CO yr^{-1} [e]	Darmenov and da Silva (2015)

[a] 2003−2014 average from Li et al. (2024); [b] 2003−2018 average from Pettinari et al. (2025); [c] 2003−2014 average from https://www.globalfiredata.org/; [d] 2003−2014 average from Kaiser et al. (2025); [e] 2012−2019 average from Wiedinmyer et al. (2023)

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For long-term historical trend, we suggest using charcoal-based regional data from the Reading Palaeofire Database (RPD), which is based on records from 1480 sites (Harrison et al., 2022). Also, multi-source merged global gridded fire emission products, such as BB4CMIP5 (Lamarque et al., 2010), BB4CMIP6 (van Marle et al., 2017), and BB4CMIP7 (van Marle and van der Werf, 2025), as well as reconstructed global historical gridded burned area products from Guo et al. (2025) and FireCCILT11 (Otón et al., 2021) can be used for comparison with simulations, but they may include larger uncertainties than present-day satellite-based products and RPD.

In addition, regional fire field observations may also serve as valuable benchmarks, e.g., National Interagency Fire Center (NIFC) historical wildfire statistics and Fire Program Analysis Fire-Occurrence Database (FPA FOD) for USA, Canadian National Fire Database (CNFDB), National Forestry and Grassland Administration (NFGA) / Ministry of Emergency Management (MEM) annual wildfire statistics and bulletins for China. The above products are recommended but not limited to these.

5.2 Fire changes and drivers

We recommend quantifying past, present, and future fire changes using burned area (burntFractionAll) and fire carbon emissions (fFire) from historical/esm-historical and ScenarioMIP experiments (Table 1). These changes include, but are not limited to, changes in annual totals, seasonality (timing of fire-season onset and end, fire-season length, peak activity), frequency of extremes, and interannual variation. Because CMIP7 FireMIP will provide multi-model and multi-initial-condition ensembles, uncertainties in fire changes can be explicitly assessed.

Fires are directly regulated by local ecosystem and climate factors, including aboveground biomass that sets the fuel load, air humidity and/or soil moisture that determines fuel wetness, wind speed that affects the fire spread rate and indirectly influences fuel wetness, and socio-economic factors (e.g., population density; GDP, land use; forcing data of ESMs) that affect human ignitions and suppressions. By comparing hist-nat, hist-aer, hist-GHG, and hist-lu with historical/esm-historical, the effects of natural forcing, anthropogenic forcing, as well as anthropogenic aerosols, greenhouse gases, and land-use changes on local variables and fires can be quantified, and the pathways across Earth system components can be analyzed (Fig. 1). For example, in the Arctic–boreal zone, increasing anthropogenic GHG lead to warming, which can accelerate permafrost thaw and soil drying, thereby drying fuels and increasing fire risks, inferred from mechanisms described in Kim et al. (2024) and Cai (2024). Comparing the influences of different forcings helps identify the dominant one and pathway.

5.3 Fire impacts

The influence of fire and fire aerosol emissions could be quantified by comparing outputs from the historical/esm-historical simulations with those from hist-no-fire and hist-no-fireaero, respectively. Specifically, analyses will focus on variables for land–atmosphere–ocean carbon, water, and energy cycles; vegetation composition and structure; fire-induced trace gas and aerosol emissions; atmospheric circulation, composition, and chemistry; surface climate (e.g., temperature, humidity, precipitation, and wind speed); cryosphere conditions (e.g., permafrost extent and active-layer thickness, snow and sea-ice extent and depth); ocean physics (currents, temperature, salinity) and marine ecosystems; and human health (based on simulated surface $PM_{2.5}$ or O_3 concentrations in ESMs, or calculated outside ESMs using fire carbon emission simulations and atmospheric (chemistry) models). The influence of future fire and fire aerosol emission changes could be quantified using scen7-h compared against scen7-h-no-firechange and scen7-h-no-fireaerochange, respectively, with analyses of a similar variable set. Related uncertainties can also be assessed using multi-model and multi-initial-condition ensemble members.

In addition, by quantifying changes in key variables along different pathways and comparing them, the dominant pathway through which fire exerts a statistically significant influence on the target variables can be identified. For example, CESM-based estimates show that fire aerosol emissions can affect global precipitation through two pathways: (1) increasing cloud droplet number concentration and thus increasing cloud water path, which tends to reduce precipitation; and (2) fire-aerosol-induced cooling that lowers evaporation and reduces atmospheric water vapor, which also tends to reduce precipitation. Our results show that the reduction in atmospheric water vapor is much stronger than the increase in cloud water, indicating that the second pathway is dominant (Fig. 8a in Li et al., 2022).

The full output dataset will support building the first comprehensive picture of global fire's role in the land–atmosphere–ocean carbon cycle. It will also allow for more accurate and reliable quantification of fire impacts on global and regional climate, benefiting from CMIP7 coupling simulations that incorporate aerosol-cloud interaction modeling, fully coupled ocean models rather than prescribed SSTs or slab ocean models, and multi-model, multi-initial-condition ensembles.

6 Summary

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This paper outlines the protocol for CMIP7 FireMIP, detailing its motivation, experimental design, model inputs and outputs, and recommended analyses.

Previous FireMIP studies provided valuable insights into fire's local drivers and local impacts on vegetation and land carbon dynamics using DGVMs but were limited by offline approaches that could not capture fire-climate and ecosystem-climate interactions. Earlier coupled-model studies lacked either critical climate feedback and processes necessary for accurately quantifying fire impacts or an ensemble framework to support comprehensive uncertainty assessment.

FireMIP's integration into CMIP7 aims to address these limitations by using fully coupled ESMs and a multi-model, multi-initial-condition, and multi-scenario ensemble framework. This allows for a systematic assessment of fire regime changes and fire's interactions with the biosphere, land, atmosphere, hydrosphere, cryosphere, and human systems. By capturing fire response and feedbacks across Earth system components, both local and remote, contemporary and legacy, FireMIP in CMIP7 will provide a more comprehensive understanding of fire's role in the Earth system and improve the scientific basis for fire and environmental management and climate-change mitigation.

CMIP7 aims to answer four science questions: (1) patterns of sea surface change; (2) changing dangerous weather; (3) the water-carbon-climate nexus; and (4) tipping points (Dunne et al., 2025). As the only fire-focused MIP in CMIP7, FireMIP relates to questions (1) and (2) and will help address questions (3) and (4). First, FireMIP can assess how fire-driven aerosol forcing and land–atmosphere flux changes influence large-scale atmospheric circulation and subsequently SST patterns. Second, because fires are closely linked to drought and heatwaves, FireMIP's analysis of fire-regime changes can inform how the associated hazards of changing dangerous weather may evolve. Third, because fire is an integral process linking water, carbon, and climate, FireMIP's assessment of fire drivers and impacts can help clarify interactions among them and inform how the water–carbon–climate nexus may respond to anthropogenic forcings. In addition, fires interact with systems that exhibit tipping-point behavior, such as the Amazon rainforests, boreal forests, permafrost, and Arctic sea ice, so FireMIP can help identify fire-related pathways that may increase the likelihood of abrupt or irreversible transitions.

Updated details on the project and its progress will be available at https://wcrp-cmip.org/mips/firemip/ (last access: 1 Oct 2025)

Code and Data availability.

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The protocol paper does not include any code or datasets. The model output from the CMIP7 FireMIP simulations will be distributed through the Earth System Grid Federation (ESGF) and will be freely accessible through ESGF data portals after registration, following standard CMIP7 formats, consistent with other MIPs within CMIP7.

Author contribution.

FL wrote the paper. FL, DL, VKA, BR, HH, MK, RL, ZL, DW, and VA designed the experiments, and FL, YJ, AW, and YL selected the output variables. CL assisted FL in preparing the tables and formatting the reference list. All authors reviewed and edited the paper.

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Competing interests.

One author (David M. Lawrence) is a member of the editorial board of GMD.

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