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Global patterns and drivers of climate-driven fires in a warming world

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Abstract

Wildfires increasingly threaten human lives, ecosystems, and climate, yet a comprehensive understanding of the factors driving their future dynamics and emissions remains elusive, hampering mitigation efforts. In this study, we assessed how future climate change would influence global burned area (BA) and carbon emissions between 2015 to 2100. Using the Community Land Model (version 5) with active biogeochemistry and fire, we simulated the effects of climate drivers such as temperature, precipitation, and CO_2 levels under two future pathways (low warming, SSP1-2.6, and high warming, SSP3-7.0). Our model reproduces historical BA magnitude and spatial distribution, projecting a global BA increase of +6400 km^2 yr^{-1} under SSP1-2.6 and +7500 km^2 yr^{-1} under SSP3-7.0. While tropical regions remain nearly stable, boreal regions experience the most significant rise, with BA increasing by +5200 km^2 yr^{-1} in SSP1-2.6 and +8500 km^2 yr^{-1} in SSP3-7.0, an overall increase of 200%. This rise is accompanied by increased carbon emissions of +4 Tg yr^{-1} and +7 Tg yr^{-1} under SSP1-2.6 and SSP3-7.0, respectively. The main drivers of these changes are reduced soil moisture and increased fuel supply (i.e., vegetation carbon) under a warming climate, with CO_2 fertilization enhancing biomass growth and further contributing to higher fire risks. These findings underscore the need for integrating climate-driven wildfire dynamics into global management and policy frameworks to mitigate future fire-related threats.

Keywords:

Wildfires, Burned Area (BA), Carbon Emissions, Climate Change, Community land model (CLM5)

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1. Introduction

Wildfires, known for their unplanned and rapid spread, have profound and wide-ranging impacts, from threatening human welfare and infrastructure to altering ecosystems and contributing to global climate dynamics (Li et al., 2017; Bowman et al., 2020). These events cause devastation through combustion and release of vast amounts of chemically and radiatively active gases and aerosols into the atmosphere (Andreae and Merlet, 2001; Bowman et al., 2009; Coen et al., 2013; Liu et al., 2019; Tang et al., 2022; Zhang et al., 2022; Bhattarai et al., 2024). Annually, wildfires consume millions of square kilometers of land, shaping natural forest successions while disrupting ecological equilibria (Wright and Heinselman, 2014). Recent estimates on Global Fire Emissions Database version five (GFED5) shows a declining trend (1.21% yr^{-1}) of global annual burned area (BA) from 2001 to 2020, with a 20-year average BA of 7.74 million km^2 yr^{-1}, which is around 5.9% of ice free land (Chen et al., 2023). Such decline is primarily driven by reduced BA in savannas, mainly due to agricultural expansion and intensification (Andela et al., 2017). However, BA trends largely vary with region, where the boreal region experiences an increasing trend (2.5% yr^{-1}), while most other regions show reductions by up to 2.7% yr^{-1}. BA declines over vast grasslands but increases in small forested areas, resulting in a sharp overall reduction in BA, while carbon emissions remain nearly stable, as forests emit more carbon per unit area than grasslands, offsetting the decline in emissions (Zheng et al., 2021). Long-term analysis indicates that climate change may exacerbate BA trends, substantially increasing carbon emissions from the biosphere and amplifying disruptions to the global carbon cycle (Van Der Werf et al., 2010; Burton et al., 2024; Jones et al., 2024).

The socioeconomic impacts of wildfires are also substantial (Kochi et al., 2010; Tymstra et al., 2020). For instance, the 2019/2020 Australian wildfires resulted in nearly $100 billion of economic losses including firefighting costs and damage to infrastructure, business, and wildlife (Roach, 2020). Similar devastating events in Canada peaked in 2023 due to a combination of hot, dry weather conditions and human activities, including vehicle accidents, recreational uses of forests, and land management practices, causing accidental ignitions (Owens, 2023; Byrne et al., 2024). Lightning is the major igniting source of wildfires in Canada, contributing to 85% of the total burned area every year. Additionally, unprecedented

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wildfires have ravaged the western US (Higuera and Abatzoglou, 2021), Siberia (Bondur et al., 2020), and the Himalayas (Bhattarai et al., 2023), often exacerbated by climate change-associated weather anomalies (Jones et al., 2022).

Wildfire dynamics is governed by the complex interplay of natural and human factors. Meteorological variables, such as temperature, soil moisture, precipitation, wind, and relative humidity (RH) significantly influence fuel availability and combustibility (Aldersley et al., 2011; Kloster et al., 2012; Hantson et al., 2015; Knorr et al., 2016; Jones et al., 2022; Senande-Rivera et al., 2022; Shi and Touge, 2022). Higher temperatures and stronger winds increase wildfire risks, while precipitation and soil moisture mitigate fire spread. Vegetation dynamics also play a critical role, as elevated precipitation and CO_2 levels enhance vegetation growth, which in turn can potentially increase the availability of combustible materials (Allen et al., 2024). In addition, anthropogenic land-use changes, including deforestation and agricultural expansion, have transformed landscapes in ways that either amplify or suppress wildfire risks. For example, agricultural expansion in South America has reduced BA in some regions (Aldersley et al., 2011; Zubkova et al., 2023). These factors collectively drive the spatiotemporal variability of wildfires.

Climate change is a dominant driver of increasing wildfire risks, with rising global temperatures and more frequent El Nino-Southern Oscillation (ENSO) events leading to regional temperature extremes and prolonged dry periods (Fuller and Murphy, 2006; Fasullo et al., 2018). These conditions exacerbate wildfire frequency and intensity, particularly in boreal and tropical forests (IPCC, 2014; Fasullo et al., 2018). For instance, Canadian fire season has extended by around two weeks, starting a week earlier and ending a week later compared to its pattern 50 years before (Owens, 2023). Future projections indicate heightened wildfire risks due to climate-induced shifts in meteorological conditions, such as snow melt timing and extended droughts (Flannigan et al., 2009; Liu et al., 2010; Veira et al., 2016; Di Virgilio et al., 2019; Li et al., 2020; Jones et al., 2022). However, the interplay of socioeconomic factors, including population density and gross domestic product (GDP), may mitigate these risks through improved fire suppression and management measures (Kloster et al., 2012; Val Martin et al., 2015; Veira et al., 2016). Studies based on Representative Concentration Pathways (RCPs) suggest that while climate change amplifies fire risks, human

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intervention could counterbalance these effects to some extent (Dong et al., 2022; Nurrohman et al., 2024).

Despite these advancements, significant knowledge gaps remain in understanding the divergent fire dynamics over tropics and boreal regions, their seasonal variability, and the roles of vegetation and hydrological changes under future climate conditions. While several studies have projected future wildfire trends and carbon emissions using various climate scenarios (e.g., Scholze et al., 2006; Knorr et al., 2016; Kloster and Lasslop, 2017; Wu et al., 2022), research specifically addressing the effects of recently developed low and high warming climate pathways on BA and wildfire emissions remains limited. Existing studies have primarily focused on fire weather indices (Quilcaille et al., 2023) or specific mitigation strategies such as solar geoengineering (Tang et al., 2023a), leaving the broader influence of climate change on global wildfire patterns, independent of direct socioeconomic drivers, less explored. Investigating future fire dynamics using the latest climate-fire-enabled global terrestrial system model, combined with state-of-the-art climate projections, is essential to improve predictions of wildfire frequency and intensity and their cascading effects on air quality, carbon cycling, and climate feedback.

In this study, we examined how future climate change would impact global wildfires throughout the 21st century, focusing on SSP1-2.6 (low-warming) and SSP3-7.0 (high-warming) (hereafter referred to as SSP1 and SSP3). Using the climate projections from the Community Earth System Model (CESM) database, we analyzed trends in BA and emissions of key carbonaceous species to provide new insights into the spatial distribution and intensity of future wildfire events. By focusing on climate-driven changes while holding land use and population constant, our study isolates the effects of warming on fire dynamics, offering a clearer understanding of how different climate pathways shape future wildfire risks. This research highlights the potential implications for carbon emissions and informs strategies to mitigate the impacts of future wildfires in a changing climate.

2. Methods

2.1 Community Land Model (CLM)

In this study, we used the Community Land Model version 5 (CLM5), the land component within the Community Earth System Model (CESM) (Lawrence et al., 2019; Danabasoglu et

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al., 2020). CLM5 was run with active biogeochemistry and an interactive fire module (Li et al., 2013) to investigate the implications of climate change on wildfires and their resulting effects on BA and emissions of carbonaceous species. This configuration enables vegetation to respond dynamically to changes in climate conditions and elevated CO_2 levels within its carbon and nitrogen cycles. CLM5 operates at the plant functional type (PFT) level, simulating interactions among each PFT, soil organic matter, and atmosphere, thereby capturing the impacts of climate change and fires on terrestrial ecosystems.

We conducted model simulations at a horizontal grid resolution of 0.9° × 1.25° (latitude × longitude). Within each grid cell, subgrid cells defining various land cover types in CLM5 are represented, including urban, glacier, and vegetated areas. Vegetated land is further characterized by 16 distinct PFTs, encompassing diverse vegetation ranging from forest to grasslands and crops, and including bare land.

2.2 Fire module in CLM5

The CLM5 fire module has been rigorously validated through comparisons with fire emission inventories and satellite observations, and has been widely adopted in prior research (Li et al., 2012; Li et al., 2013; Li et al., 2017; Ford et al., 2018; Li et al., 2019; Tang et al., 2023b). The CLM5 fire module represents an advancement in understanding the interplay among fire dynamics, vegetation, and the Earth's climate system (Li et al., 2013). Built on a process-based fire parameterization, the CLM5 fire module accounts for four distinct fire types: (i) agricultural fires in croplands, (ii) deforestation fires in tropical closed forests, (iii) peat fires, and (iv) non-peat fires occurring beyond croplands and tropical closed forests (Li et al., 2012; Li et al., 2013). Fire ignitions include both natural and anthropogenic sources, with lightning datasets from NASA serving as the basis for natural ignitions, while anthropogenic ignitions are influenced by population density and GDP, whereby higher population and GDP effectively suppress fire occurrences. The module estimates the likelihood of fire occurrence by considering the availability of biomass as fuel, combustibility of the fuel depending on its moisture content, and presence of an ignition source, whether human-induced or from lightning. Thus, BA within the CLM5 fire scheme is driven by socioeconomic activities, vegetation composition, and prevailing weather conditions (e.g., temperature, RH, wind, precipitation, and soil moisture). Upon determination of BA, gas and aerosol emissions from fires are obtained at the grid cell level.

In this study, to focus on the impact of future climate change on wildfires, land use and population were held constant at present-day levels, allowing only climate to evolve over time. This approach thus fixes natural and anthropogenic ignition sources while permitting fuel availability and combustibility to change along with future climate. Climate change accounts for changes in CO_2 levels and precipitation, temperature, pressure, RH, wind, and radiation. These changes exert direct influences on fuel availability and combustibility, shaped by evolving climate conditions and vegetation characteristics. We considered two future climate projections: low warming (SSP1-2.6; hereafter referred to as SSP1) and high warming (SSP3-7.0; hereafter referred to as SSP3). SSP1 projects an increase of atmospheric CO_2 of 70 ppm up to 2050, after which it stabilizes, whereas SSP3 projects a 140 ppm increase by 2050 and 467 ppm by 2100, relative to 2015 levels (400 ppm). Global land temperature rises sharply under SSP3, with an increase of 1.6°C during the 2050s (2050–2059 average) and 3.8°C during the 2090s (2090–2099 average) compared to present-day conditions (2015–2024 average of 10.4°C). In contrast, SSP1 shows a temperature increase of only 1.2°C by 2050, with relatively stable conditions in the later part of the century.

2.3 Model experiments

We first spun up CLM5 with the fire module active to steady state in 1850 using an accelerated decomposition procedure and fixed pre-industrial CO_2, land use, and atmospheric nitrogen (N) deposition (Lawrence et al., 2019). The accelerated decomposition spin-up was for about 1200 years as the total soil organic matter carbon in the Arctic regions required a longer time frame to reach equilibrium; we considered the model fully spun up when the land surface had more than 97 % of the total ecosystem carbon in equilibrium. The present-day spin-up was based on a historical simulation for 1850–2014 using historical N and aerosol deposition, atmospheric CO_2 forcing, land use change, and meteorological forcings from the Global Soil Wetness Project (GSWP3v1) (Lawrence et al., 2019).

For future runs, we initialized CLM5 in 2015 with the prescribed climate for the low and high warming scenarios simulated by CESM2 for Coupled Model Intercomparison Project Phase 6 (CMIP6), and conducted transient simulations until 2100. For the first ten years, both scenarios exhibit very similar behavior in terms of BA (SSP1: 5.18±0.37 million km^2, SSP3: 5.15±0.39

million km^2) and emissions (Figure S1), as climate and CO_2 levels at the start of both scenarios are nearly identical and have not yet diverged. Therefore, we considered the period from 2015 to 2024 for SSP1 as representative of present-day conditions (referred to as 'Baseline' and reported average ± standard deviation, SD). Although these are transient simulations, for certain analyses we selected results from 2090 to 2099 (referred to as "2090s" and reported average ± SD) to calculate the differences from the present-day conditions for the respective climate scenario to estimate future changes. These experiments were aimed to assess the isolated impacts of climate change on wildfires and emissions of air pollutants, while holding anthropogenic land management constant.

2.4 Validation of global burned area and fire emissions

Our model results capture both the spatial distribution and magnitude of global BA and wildfire emissions (Figure 1), demonstrating good agreement with the Global Fire Emission Database (GFED) (Randerson et al., 2017; Chen et al., 2023). GFED derives estimates of BA and emissions by integrating satellite-derived fire activity data with biogeochemical modeling approaches. We consider both GFED4.1 and GFED5 in this validation as they use different methodologies, with GFED5 accounting for small fires that are often missed by satellite sensors, leading to higher BA estimates compared to GFED4.1 (Chen et al., 2023).

For the present day (2015–2024), CLM5 simulates a global annual BA of 5.18±0.37 million km^2 (mean ± SD), which lies between the estimates of GFED4.1 averaged for the 2007–2016 (4.48±0.36 million km^2) and GFED5 averaged for the 2011–2020 (7.31±0.39 million km^2). The decadal mean is calculated based on the data available in the last ten years. Our results also align with historical estimates for 2001–2018, ranging from 3.9 to 5.2 million km^2 (Lizundia-Loiola et al., 2020). Despite some biases, the model performance is robust, with a normalized mean bias of +15.6% (–29.1%) and a correlation coefficient (R) of 0.64 (0.62) when compared to GFED4.1 (GFED5).

Emissions of key fire-related species such as total carbon (TC), black carbon (BC), organic carbon (OC), and nitrogen oxides (NO_x) were also compared against GFED4.1 as data are not available for GFED5 (Figure 1d). Decadal averaged results show strong agreement for most species, with TC emission of 2017±158 Tg yr^{-1}, closely approximating the GFED4.1 estimates

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of 1997±175 Tg yr^{-1}. However, certain species, such as OC, are slightly overestimated, while NO_x emissions are marginally underestimated.

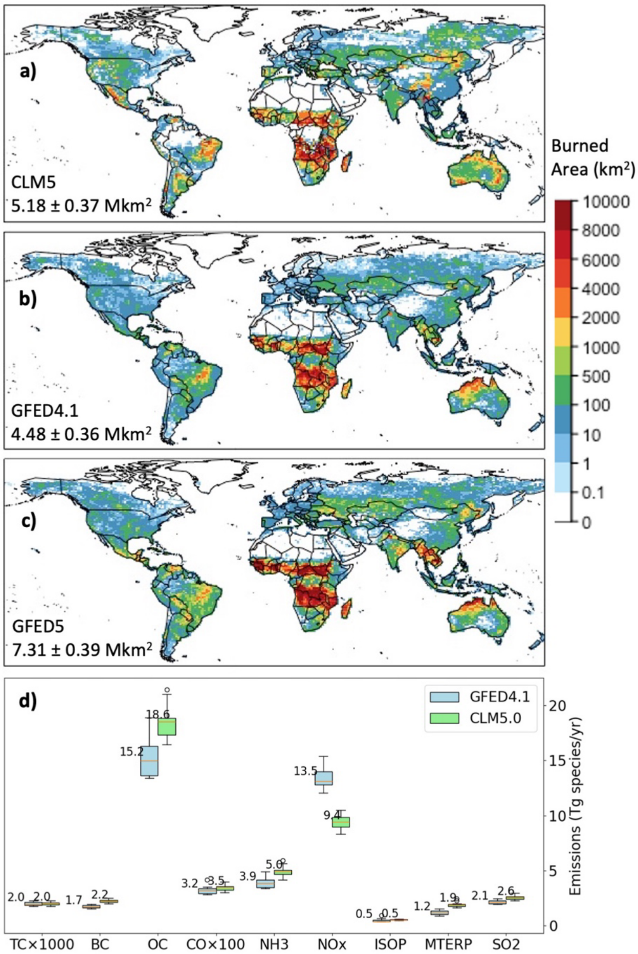

Figure 1. Comparison of CLM5-simulated results (2015–2024, SSP1) with the Global Fire Emissions Database (2007–2016 for GFED4.1; 2011–2020 for GFED5). Spatial distribution of burned area for a) CLM5, b) GFED4.1, and c) GFED5 are averaged for a decade. d) Global annual emissions of main fire-emitted species, including total carbon (TC), black carbon (BC), organic carbon (OC), carbon monoxide (CO), ammonia (NH_3), nitrogen oxide (NO_x), isoprene (ISOP), monoterpene (MTERP), and sulfur dioxide (SO_2) are compared between CLM5 (model) and GFED4.1 for the same time period as that of burned area.

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3. Results

3.1 Trends and spatial variations in burned area and carbon emissions

The projected impact of climate change on BA and carbon emissions shows a marked increase under low and high warming scenarios. Global BA is projected to increase by +6383 km^2 yr^{-1} under SSP1 and +7465 km^2 yr^{-1} under SSP3 between 2015 to 2100 (Figure 2a), resulting in an overall increase of +0.73 million km^2 and +0.68 million km^2, respectively, by the 2090s compared to the present day. These increases are particularly centered toward the higher northern latitudes in both low and high warming scenarios (Figure S2). Sharp BA reductions (~25%) in the tropics in high warming negate BA increases in high northern latitudes, leading to a lower global average under SSP3 as compared to SSP1, which sees sharp increases in tropics (Figure 2b-d). However, the overall rate of increases in BA under SSP3 is approximately +1000 km^2 yr^{-1} higher relative to SSP1, primarily driven by sharp increases in fuel supply, reduced soil moisture, and favorable meteorology, such as elevated surface temperature and reductions in RH (Figure S3) (detailed analysis in section 3.2).

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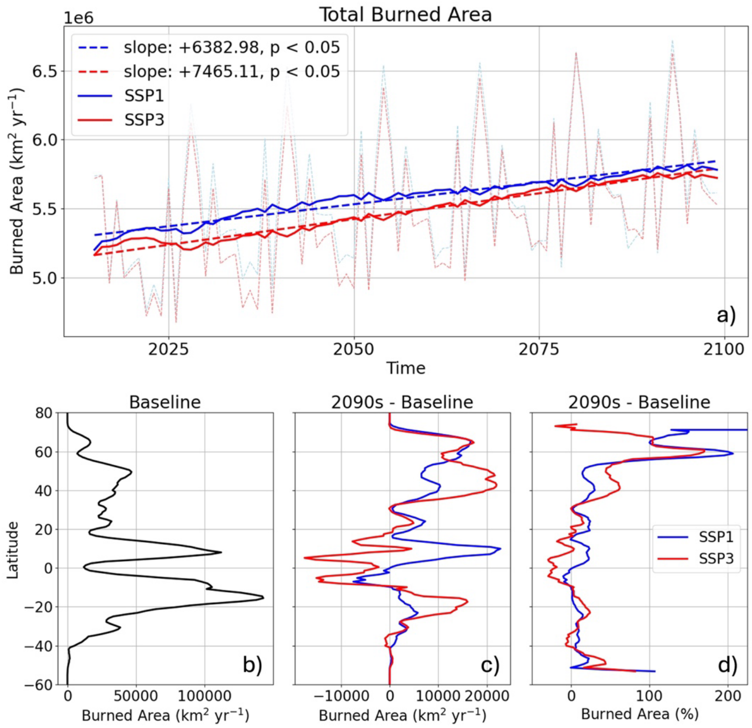

Figure 2. Trend analysis of global burned area (BA) during the 21st century (2015-2100) under SSP1 and SSP3 climate scenarios. In panel a), dotted lines indicate the annual variations and their trends, while the solid lines indicate the 25-year moving average. The latitudinal variations of BA during b) baseline (averaged 2015-2024; SSP1) and its c) absolute and d) percentage future differences are shown at 5-degree moving average.

We found important differences at a regional scale. In high northern latitudes, near 60°N, where tundra dominates alongside alpine forests, shrubs, and grasses, our simulations project substantial BA and TC increase of over 150% in both scenarios (Figure 3a-d and Figure S4). In contrast, a large regional discrepancy is observed for both BA and TC emissions over the tropics (20°S–20°N) and boreal (30°N–70°N) regions (Figure 3e-h). For instance, BA regional trend over boreal region shows a significant positive trend at the rate of +5237 $km^2\ yr^{-1}$ under SSP1 and +8515 $km^2\ yr^{-1}$ under SSP3. Conversely, tropical regions show a sharp decline in BA under SSP3 (–2429 $km^2\ yr^{-1}$) and a more moderate decline under SSP1 (–64 $km^2\ yr^{-1}$), which remains statistically insignificant at 95% level. In any case, tropical fires dominate the global landscape for both BA and carbon emissions, compared to boreal fires.

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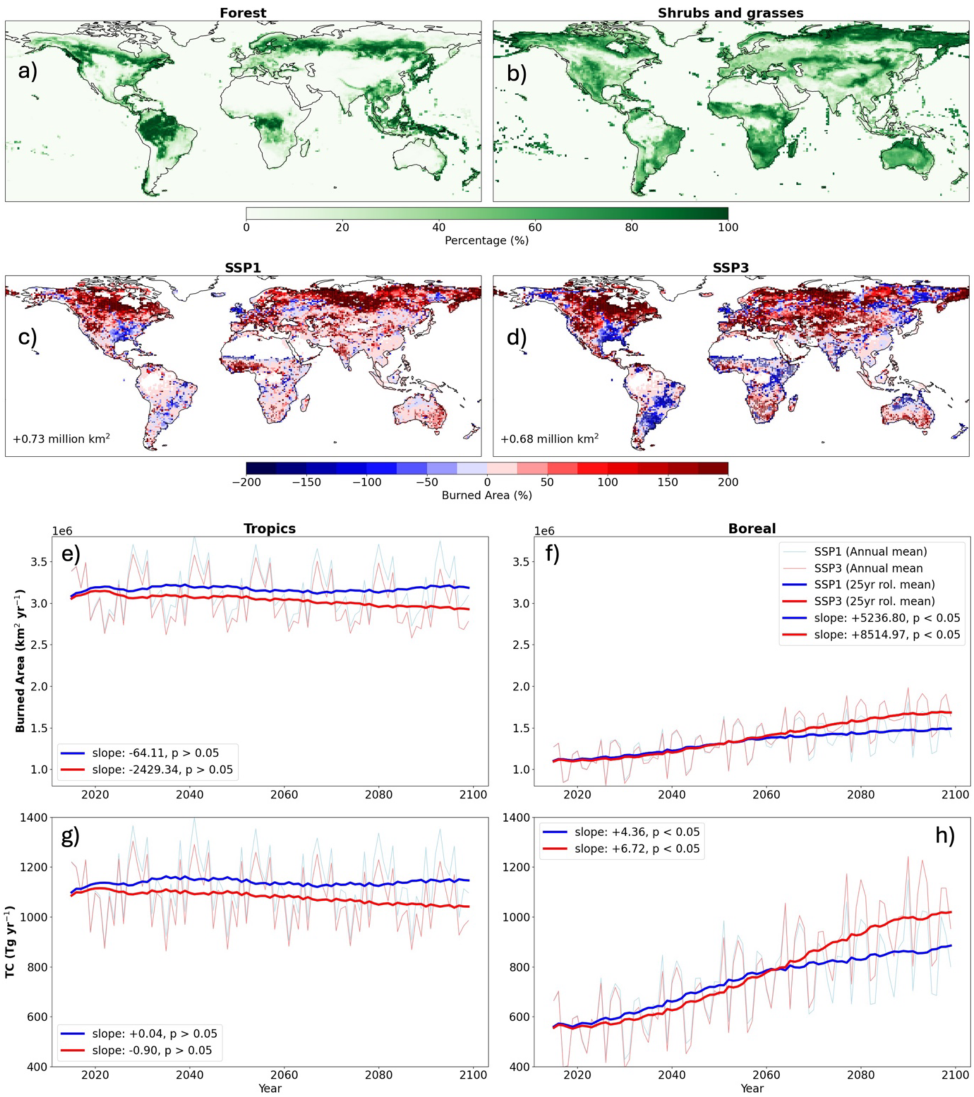

Figure 3. Spatial variations of present-day land cover: (a) forest and (b) shrubs and grasses, derived from the product of natural plant functional types (PCT_NAT_PFT) and natural vegetation (PCT_NATVEG) fractions, summed over the relevant natural PFTs (forest: 1-8, shrubs and grasses: 9-15). Percentage difference in BA [future (2090 to 2099) – baseline (2015 to 2024)] under (c) SSP1 and (d) SSP3 scenarios. Trend lines for (e, f) BA and (g, h) TC emissions are shown for tropics and boreal regions throughout the 21st century. Dots in panels c and d indicate regions with significant difference at 95% confidence interval. Lighter colors of trend lines represent annual variations, while bold lines indicate a 25-year moving average.

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Differences in carbon emissions closely align with the pattern of BA (Figure 3, Figure S5). Boreal regions emerge as the primary contributors to the overall increase in TC emissions, where it increases at the rate of 4.36 Tg yr^{-1} and 6.72 Tg yr^{-1} under SSP1 and SSP3 scenarios, respectively. In contrast, the tropical region experiences a marginal difference in TC emissions in both scenarios. Similar trends are observed for other carbonaceous species, including BC, OC, and carbon monoxide (CO). By 2090s, fire-related carbon emissions are expected to rise by 22–32% compared to the present-day levels. Notably, emissions from regions above 50°N are projected to surge by more than two folds, underscoring the substantial influence of high-latitude fires in shaping future global carbon budgets. In addition, the carbon emitted from boreal fires may become as important as tropical fires, in terms of magnitude (~1000 Tg C yr^{-1}) by the end of the century in a high warming world.

Figure 4 highlights a significant shift in global fire regimes and their carbon emissions across SSP1 and SSP3 scenarios. Under both scenarios, global BA shows a slight increase during 2050s and 2090s compared to the baseline (2020s), but regional trends differ markedly. While tropical BA remains nearly stable or declines slightly, boreal BA increases significantly in both cases, rising from 1.09 million km^2 yr^{-1} during baseline to 1.50 million km^2 yr^{-1} under SSP1 and 1.70 million km^2 yr^{-1} under SSP3. Consequently, the boreal-to-tropics BA ratio increases from 0.35 at baseline to 0.46 under SSP1 and 0.57 under SSP3, indicating the growing contribution of boreal fires relative to the tropics. Similarly, TC emissions exhibit a marked redistribution, with global emissions increasing from 2017 Tg yr^{-1} at baseline to 2535 Tg yr^{-1} under SSP1 and 2552 Tg yr^{-1} under SSP3. While tropical carbon emissions decline slightly, boreal emissions surge from 547 Tg yr^{-1} at baseline to 894 Tg yr^{-1} under SSP1 and 1032 Tg yr^{-1} under SSP3. This shift is also evident in the boreal-to-tropic TC emission ratio, which increases from 0.50 at baseline to 0.76 under SSP1 and 0.97 under SSP3, as well as the boreal-to-global ratio, rising from 27% to 35% under SSP1 and 40% under SSP3. These trends underscore the growing dominance of boreal fires in driving global carbon emissions under future climate scenarios, with more pronounced increases under SSP3. The results highlight the critical role of boreal fire regimes in amplifying climate feedbacks and the need for region-specific fire management strategies to mitigate their disproportionate impact on the global carbon cycle. The interrelationships among BA, carbon emissions, and meteorological factors are further discussed in subsequent sections.

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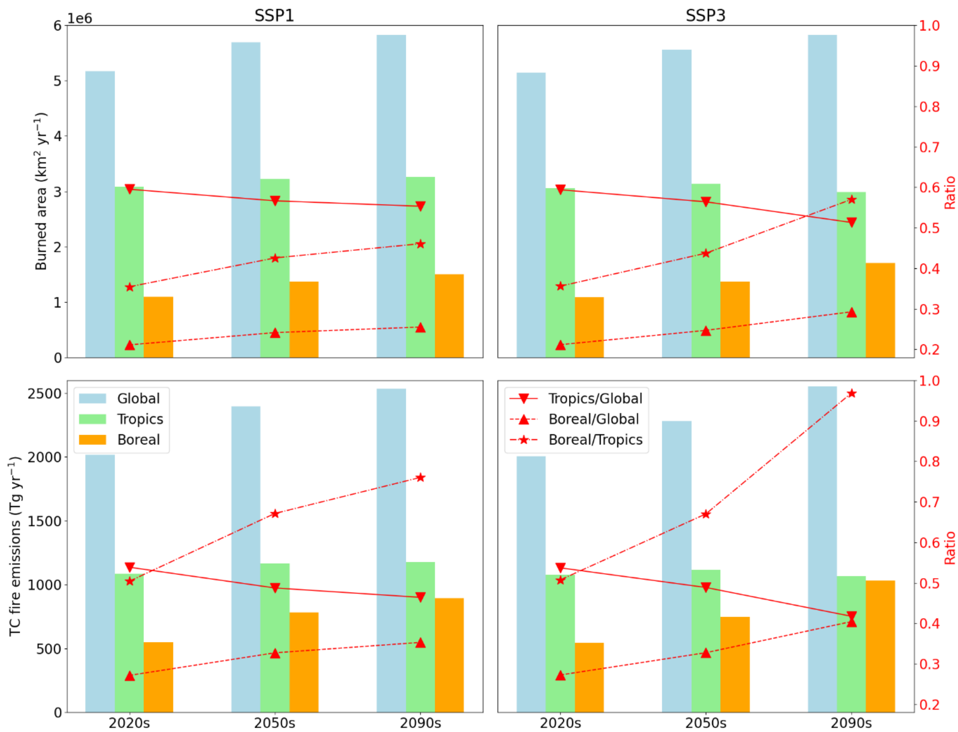

Figure 4. Present day (2020s: 2015-2024) and future (2050s: 2050-2059; 2090s: 2090-2099) decadal mean of burned area (BA) and total carbon (TC) emissions across global, tropics (20°S-20°N), and boreal (30°N-70°N) regions (bar-plot) under low (SSP1) and high (SSP3) warming scenarios. The ratio of BA and TC emissions against tropics/global, boreal/global, and boreal/tropics is presented as line plots, which show the increasing contribution of boreal region on BA and TC emissions.

3.2 Key drivers of burned area in future climates

To identify the main factors influencing climate-driven wildfires, we analyzed the correlations between BA and meteorological factors, vegetation dynamics, and carbon emissions. We found strong correlations of BA with meteorological variables, total vegetation carbon (TOTVEGC), and TC emissions for both SSP1 (Figure 5) and SSP3 (Figure S6) scenarios. The Pearson correlation coefficient analysis was performed on detrained data using monthly data from 2015 to 2100 for each grid. This analysis shows a significant positive correlation between BA and

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surface temperature (R > 0.6), emphasizing the role of rising temperatures in driving BA increases globally. A positive correlation is also observed between BA and total vegetation carbon, particularly in boreal regions where vegetation growth is constrained by temperature and water availability.

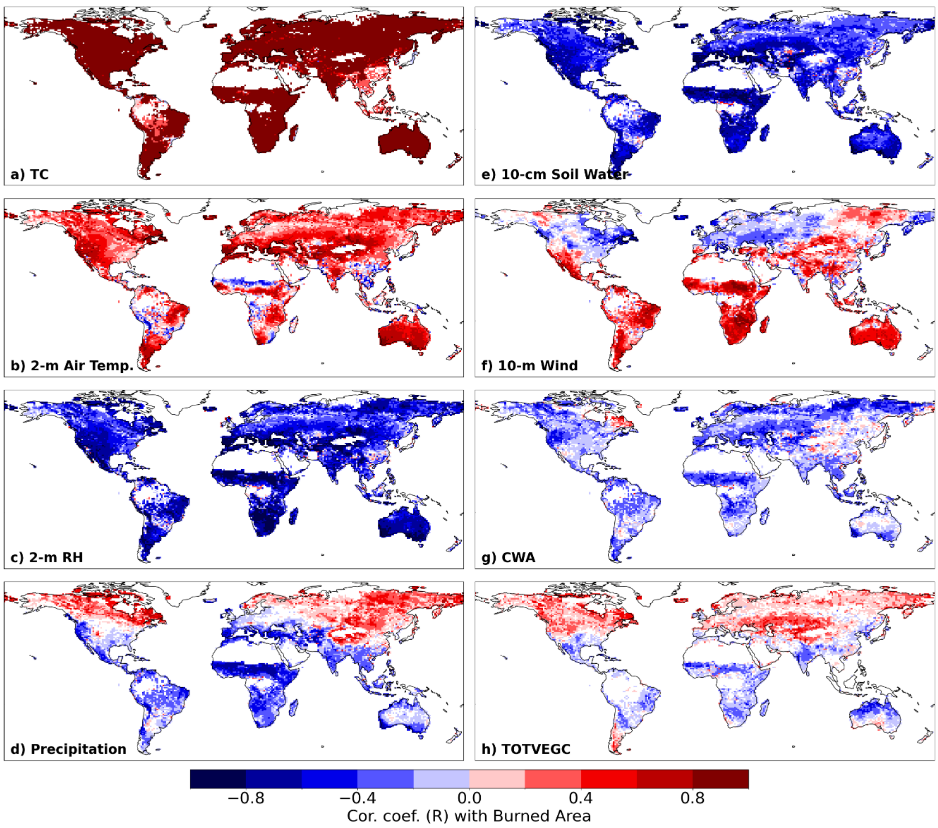

Figure 5. Pearson correlation (R) on monthly time series data (2015 to 2100) between burned area (BA) and (a) TC, (b-g) meteorological variables (2-m surface temperature, 2-m relative humidity (RH), precipitation, 10-cm soil water, 10-m wild velocity, and climate water availability (CWA = precipitation – evapotranspiration)), and (h) total vegetation carbon (TOTVEGC) under SSP1 scenario. Only regions with a 95% significance level are shown.

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Conversely, BA shows a negative correlation with surface RH, 10-cm soil moisture, and climate water availability (CWA = precipitation – evapotranspiration). In tropical regions, elevated precipitation and soil moisture reduce fire risks by decreasing fuel combustibility through higher soil moisture content. Interestingly, in boreal regions, precipitation exhibits a positive correlation with BA, as it enhances vegetation growth, increasing the availability of fuel. However, in tropical regions, where fuel is already abundant, increased precipitation primarily raises soil moisture, further suppressing fire activity rather than promoting it. These contrasting effects of precipitation on fuel availability (in boreal regions) and combustibility (in tropical regions) are crucial in shaping BA and carbon emissions. Wind speed has mixed effects, with higher winds enhancing fire spread in some areas, while in northern latitudes, cold, moist winds act to suppress BA.

The spatial distribution of BA and meteorological variables confirms these trends (Figure S3). Boreal regions experience the largest BA increases due to rising temperatures, reduced RH, and declining soil moisture. In contrast, tropical regions show a decrease in BA as increased precipitation dampens fire activity. These patterns highlight the complex, region-specific interactions between climate, vegetation, and fire dynamics.

Our analysis shows a significant correlation of TC with BA at each grid point, with $R > 0.80$ across most regions (Figure 5). Further analysis of the differences in carbonaceous species also corroborates the robust correlation with differences in BA ($0.56 < R < 0.71$, $p < 0.05$; Figure S7), underscoring the synergetic effect of BA on carbon emissions.

3.3. Seasonality of wildfires

Distinct seasonal variations in BA and wildfire emissions are observed for both present-day conditions and future climate forcings (Figure 6, Figure S8). The most substantial increase in BA and carbon emissions occur during the boreal summer (June to August), particularly in the Northern Hemisphere, including regions such as the western United States, Canada, and Russia (Figure S9). In the Southern Hemisphere, BA increases are predominant during its warmer periods (September to February), most notably in southern Africa and Australia. Conversely, tropical regions experience a sharp decline in BA primarily from December to March under SSP3, while SSP1 shows an increase during the same period, highlighting the varied regional response to climate change. Among these seasonal variations, boreal regions exhibit a pronounced rise in both BA and carbon emissions during the summer months, and the fire

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season may potentially be extended by an additional month by 2100 in temperate latitudes (30-50°N) under high-warming conditions (SSP3).

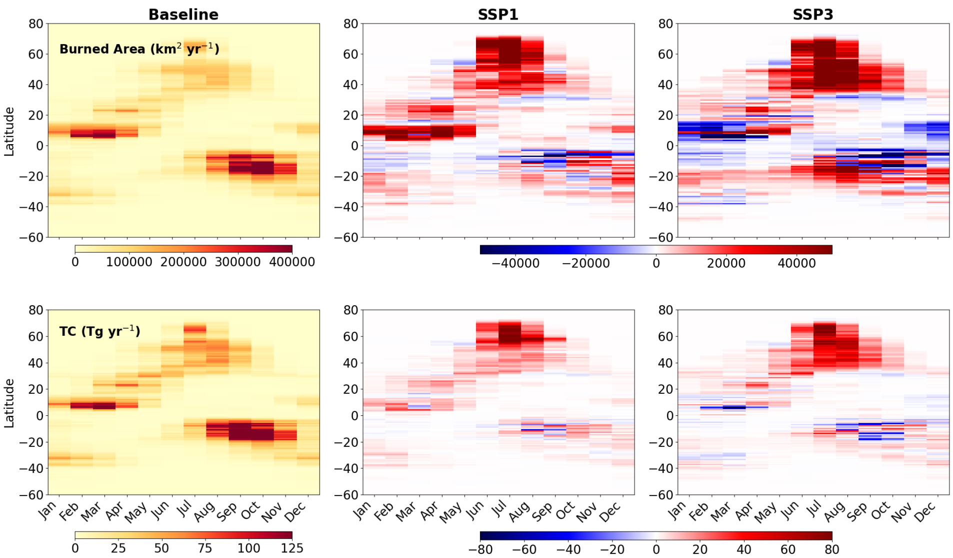

Figure 6. Latitudinal monthly variations in burned area and total carbon emissions at baseline (2015-2024 average) and their future (2090-2099 average) differences in SSP1 and SSP3.

To further investigate the drivers behind the sharp rise in BA and carbon emissions in boreal regions, we conducted a detailed analysis focusing on both summer (Figure 7) and winter seasons (Figure S10). Our results show a pronounced seasonal contrast, with the largest BA increases occurring during the boreal summer months. During this period, several climatic factors converge to create optimal wildfire conditions: higher temperatures, increased vegetation productivity, reduced RH, and lower soil moisture. These factors, especially in boreal forests, amplify fire outbreak risks. Increased vegetation, while potentially serving as a carbon sink, paradoxically fuels more intense fires under drier, warmer conditions.

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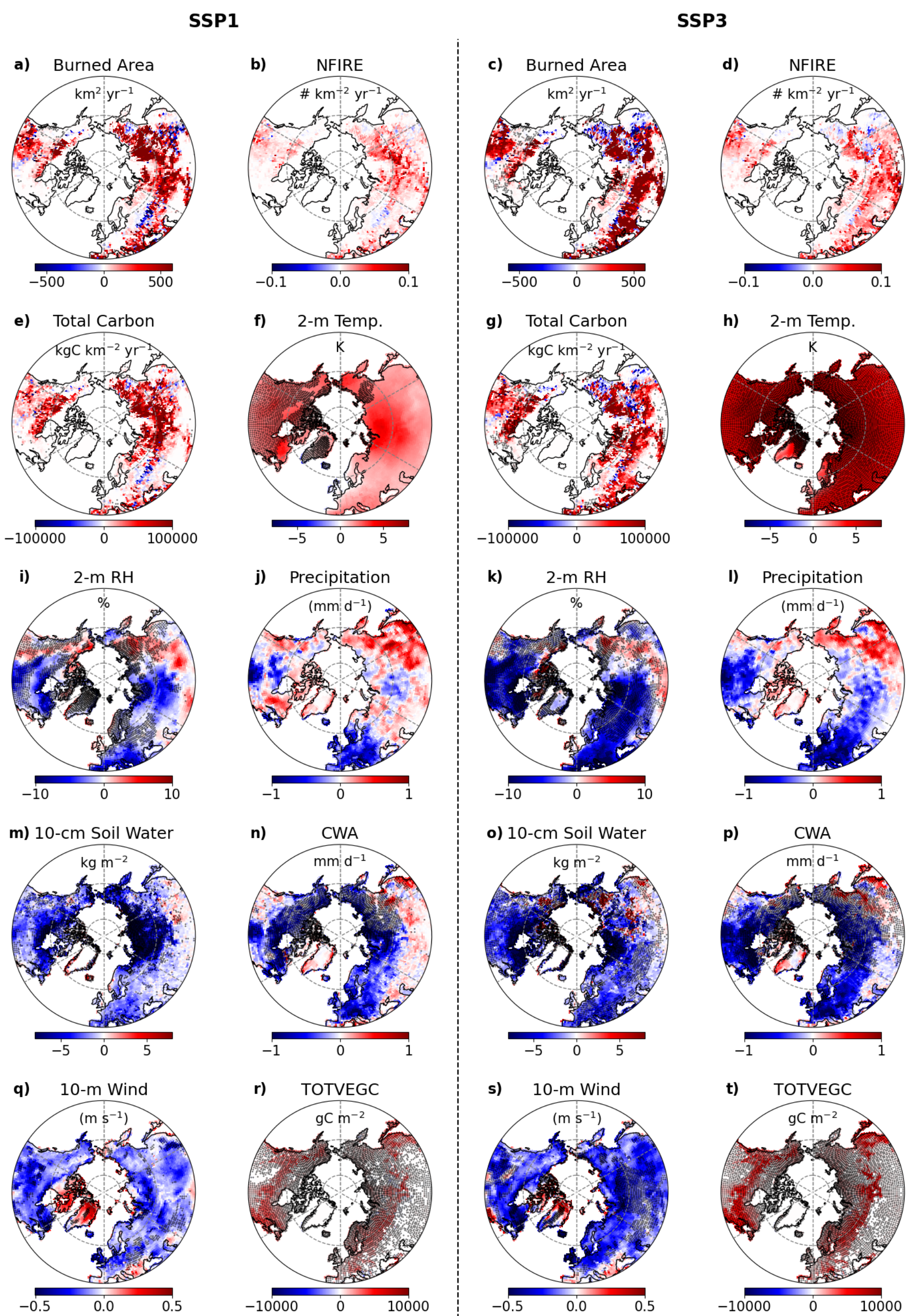

Figure 7. The 2090s fire season (JJA) anomaly (relative to the present day) for modeled burned area, number of fires (NFIRE), BC emissions, meteorology, and total vegetation carbon

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(TOTVEGC) in the boreal region (>40°N) for SSP1 and SSP3. Dots indicate regions with a 95% significance level.

Both SSP1 and SSP3 scenarios predict a significant rise in boreal wildfires, with the increase notably more severe under SSP3, where heightened temperatures result in steeper declines in RH and CWA. Elevated temperatures exacerbate evapotranspiration, leading to drier vegetation and surface conditions that further amplify fire risks. In contrast, the winter season exhibits minimal differences in BA, despite rising temperatures and reduced RH. Extreme winter cold effectively suppresses wildfire ignition, regardless of potential climatic shifts. Elevated soil moisture and CWA during winter, combined with frozen ground and snow cover, limit fire activity, as projected warming remains insufficient to reach the threshold required to sustain fire during winter.

Spatial analysis reveals that the most significant increases in BA and fire emissions occur in boreal Eurasia, where temperature anomalies are especially pronounced. This region shows large areas of intensified fire activity, with isolated pockets of reduced BA under SSP3, possibly due to increased winter precipitation or soil moisture that offsets fire risk.

The importance of various environmental factors driving boreal summer wildfires across northern latitudes (30°N to 70°N) was analyzed using three machine learning models – XGBoost, LightGBM, and Random Forest (Figure 8) – under SSP1 and SSP3. All models consistently identify 10-cm soil water content (which influences fuel availability and dryness) and vegetation carbon (which affects both canopy and surface fuel loads) as primary predictors of wildfire activity. While CLM5 does not explicitly simulate dead fuel moisture, lower soil moisture is often associated with drier fuels, increasing fire susceptibility. However, the relative importance of these variables varies: XGBoost and LightGBM attribute similar weights to soil water and vegetation carbon, whereas Random Forest assigns significantly higher importance to these factors, especially vegetation carbon in SSP1 and soil water in SSP3. Other factors such as RH and 2-m air temperature, show moderate important across models, while wind speed, precipitation, and CWA play a smaller role. These findings highlight the critical role of vegetation and soil moisture in determining wildfire susceptibility in boreal summer, although the influence of secondary factors varies with the model used.

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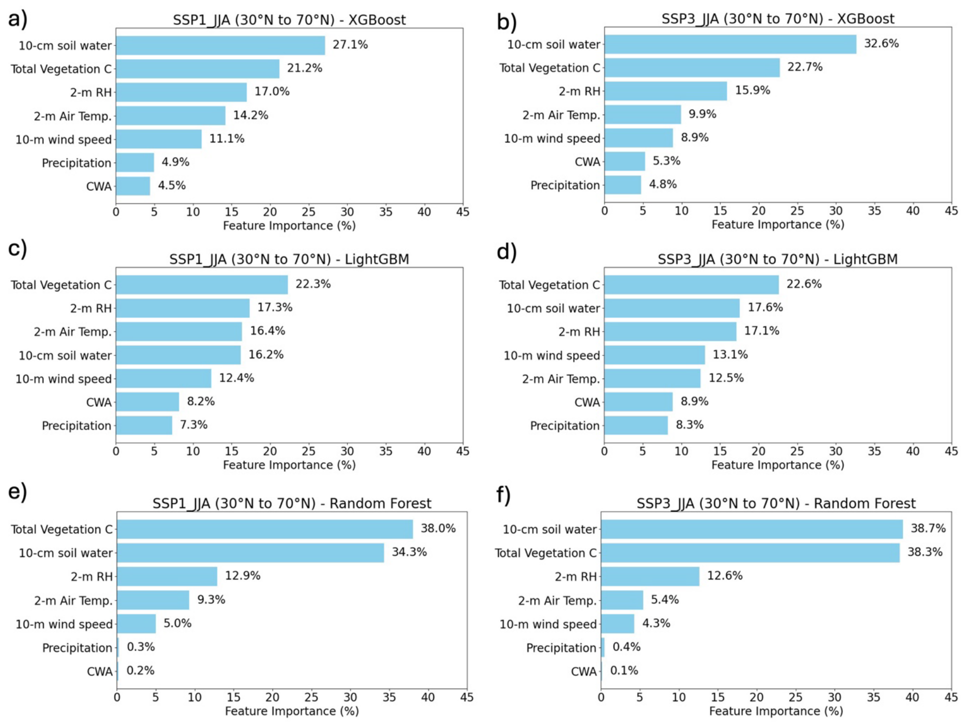

Figure 8. Feature importance analysis of environmental drivers of wildfire activity during boreal summer (JJA) over northern latitudes (30°N to 70°N) using (a, b) XGBoost, (c, d) LightGBM, and (e, f) Random Forest machine learning model under SSP1 and SSP3 scenarios.

This analysis underscores the need for a deeper understanding of the interplay between climatic drivers, vegetation dynamics, and fire behaviors to mitigate boreal wildfire risks under future climate scenarios. While machine learning models identify soil water content and vegetation carbon as the most critical predictors of wildfire activity, rising surface temperatures play an indirect yet pivotal role. Elevated temperatures exacerbate evapotranspiration, reduce RH, and lower soil moisture, thereby intensifying fire risk. These cascading effects highlight the importance of considering temperature as a key enabling factor that interacts with vegetation and hydrological conditions to drive wildfire dynamics. Additionally, the positive correlation between BA and vegetation carbon suggests that future fire management strategies should consider shifts in vegetation growth patterns driven by changing climatic conditions, particularly in boreal ecosystems where temperature and water availability are limiting factors.

Under low and high warming climates, the projected sharp rise in boreal wildfires emphasizes the necessity of comprehensive fire management strategies that address the complex links between climate and vegetation, as well as the seasonality of these interactions. The expected increase in high-latitude fire activity and associated carbon emissions will significantly contribute to the global carbon budget. Targeted mitigation efforts, such as prescribed burns or enhanced fire suppression during critical periods, will be crucial. Furthermore, the cascading impacts of wildfires on carbon cycling and atmospheric composition – including increased emissions of BC and OC – highlight the urgency of adaptive strategies. These strategies must account for the feedbacks between climate change, vegetation growth, and fire behaviors to effectively manage future wildfire risks.

4. Conclusions and discussion

This study highlights a significant shift in wildfire dynamics, particularly in boreal regions under future climate scenarios using a state-of-the-art fire-enabled global terrestrial system model that explicitly simulates interactive fire with active biogeochemistry. Our findings indicate that boreal regions, especially around 60°N, could experience a staggering increase in BA by up to 200% under high-warming scenarios (SSP3-7.0). This increase is primarily driven by reduced soil moisture and an abundance of vegetation carbon, creating dryer and more combustible conditions. These results align with previous studies predicting an intensification of Arctic fires due to climate-induced extreme fire weather, increased lightning activity, and drier fuel conditions (Mccarty et al., 2021). Furthermore, Abatzoglou et al. (2019) explored that regions experiencing heightened fire weather could double at 3°C warming compared to 2°C above preindustrial levels, emphasizing the significant influence of anthropogenic climate change (Turco et al., 2023).

Our results also emphasize the role of other meteorological variables in modulating fire activity. While rising temperatures and CO_2-driven vegetation growth contribute to heightened fire risks, wind speed and precipitation exert secondary influences. Stronger wind speed at high latitudes can suppress fire spread by transporting colder, moist air, whereas increased precipitation can paradoxically increase fire risk by stimulating vegetation growth in water-stressed areas, thereby increasing fuel loads. These results are consistent with historical wildfire studies (Zheng et al., 2023), which documented that warmer and drier conditions in boreal forests contributed to the rapid wildfire expansion from 2000 to 2020. Our findings further extend these insights into the future, demonstrating how climate and vegetation changes will continue shaping wildfire trends.

The projected intensifications of wildfires in boreal regions has significant ecological and climatic implications. Increased fires in sub-alpine regions reduce species diversity, leading to greater forest homogeneity and disrupting entire ecosystems (Cassell et al., 2019; Halofsky et al., 2020). The transition of boreal forests from carbon sinks to net carbon sources due to increased fire emissions could further amplify warming trends through enhanced greenhouse gas concentrations and BC deposition on Arctic ice, accelerating ice melt (e.g., Liu et al., 2014; Mccarty et al., 2021; Virkkala et al., 2025). Furthermore, the degradation of boreal ecosystems threatens biodiversity, disrupts regional hydrological cycles, and deteriorates air quality due to increases in particulate and ozone precursors. These findings underscore the necessity for integrating wildfire dynamics into climate policy frameworks to effectively mitigate future risks.

While boreal wildfires exhibit a strong upward trend, tropical regions exhibit a contrasting response, with either stable or decreasing trend in BA under future climate scenarios. This pattern is consistent with previous studies (Veira et al., 2016; Jones et al., 2022), which reported increasing BA at higher latitudes but declines in the tropics. Climate driven alternations in temperature and precipitation patterns introduce uncertainties in fire regimes across different biomes, highlighting the complexity of climate-fire interactions (IPCC, 2014; Fasullo et al., 2018).

Seasonal variations further illustrate the complexity of factors governing wildfire dynamics. Despite rising temperatures in boreal summer and winter, the sharp rise in BA and carbon emissions in the boreal region is confined to summer, as winter wildfires are suppressed by persistent cold temperatures and snow cover. Additionally, in temperate regions (30–50°N), high warming scenario extended the fire season, leading to longer fire durations (Senande-Rivera et al., 2022). Moreover, in the recent two decades, the extreme wildfire events have increased by twofold, particularly in boreal and temperate conifer regions (Cunningham et al., 2024). These findings emphasize the need for seasonally and regionally tailored fire management strategies. In temperate, populated regions, targeted interventions such as

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controlled burns, thinning or fuel reductions, and soil moisture enhancement can mitigate wildfire risks. However, in sparsely populated boreal regions, where large-scale fires occur in remote landscapes with limited accessibility, direct intervention is often challenging due to larger fire size and lower government priority. Thus, integrating wildfire risks into climate impact assessments, carbon sequestration estimates, and long-term climate feedback analysis is crucial for understanding the broader implications of boreal wildfires. Predictive models incorporating wind speed, precipitation patterns, and fuel accumulation dynamics can further aid in resource allocation and preparedness efforts. A nuanced approach that considers both management feasibility and the role of boreal fires in global climate systems will be essential for mitigating their impacts on air quality, biodiversity, and human health under future climate scenarios.

Several limitations of this study warrant further investigation. Our model primarily focuses on future climate change as the key driver of wildfires, but other influencing factors, such as land-use changes and population growth, are not fully accounted for (kept constant to the present day), which also influence wildfire dynamics. The CLM5 model, with its relatively coarse spatial resolution (~100 km) struggles to capture short-term and small-scale fires, which can have significant ecological and atmospheric impacts. Additionally, natural ignitions are prescribed based on NASA lightning frequency data averaged from 1995 to 2011, limiting the scope of future variability. Future studies should integrate interactive lightning simulations that evolve with changing climate conditions. Improved representations of fire behavior, vegetation dynamics, two-way feedback mechanisms, and socioeconomic drivers will be essential to comprehensively understand wildfire risks in a changing climate. Coupling fire models to atmospheric models can also enhance our understanding of how wildfires influence regional meteorology and, in turn, how these altered conditions impact fire activity.

Our findings have broader implications for sustainable forestry and global climate policies. Balancing biomass harvesting with carbon sequestration goals is crucial for maintaining ecosystem resilience. Strengthening policies that limit deforestation and promote afforestation/reforestation in fire-prone regions can reduce fire risks while enhancing carbon storage. A comprehensive understanding of climate-fire interactions is essential for developing robust adaptation and mitigation strategies that align with global sustainability objectives.

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