

The Increasing Incidence of Boreal and Western U.S. Forest Wildfires and Its Causes: An Overview

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ABSTRACT: This overview of the voluminous wildfire literature addresses the following questions: "How seriously is the current spate of wildfires impacting the boreal forests and the forests of the western United States? Is the current rate of burning of these forests unprecedented? Has it been systematically increasing over the past few decades and, if so, is it in response to human-induced global warming?" The article contains diagrams and tables based on a suite of fire-related datasets: satellite measurements of burned area, fire-related carbon emissions, aerosol optical depth, dating back to around the year 2000, and longer ground-based records of area burned by fires in the western United States. The graphics and tables reveal the remarkable extent of the forested area burned. The average area burned per year has increased by roughly a factor of three since the year 2000. The area burned by severe fires with areas $> 100 \text{ km}^2$ has been increasing more rapidly than the area burned by smaller fires. Wildfire smoke has also increased appreciably over much of North America. Forested burned area and fire-related carbon emissions are highly sensitive to measures of aridity on time scales ranging from days to decades. Aridity has increased, mainly in response to the warming trend, which is comparable in magnitude to that in climate model simulations of the response to rising greenhouse gas concentrations. The evidence presented herein supports the widely held belief that the recent increase in wildfires is mainly due to human-induced global warming.

SIGNIFICANCE STATEMENT: Many news stories portray a worsening forest wildfire crisis, fueled by human-induced global warming. While there is widespread support for this view in the scientific community, there are some who argue that overly zealous fire suppression has caused the problem and that reformed forest management practices can solve it. This overview documents the roughly threefold increase in forested burned area and fire-related carbon emissions in the boreal forests and the western U.S. forests over the past 25 years. The evidence supports the view that the increase is mainly due to human-induced global warming.

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1. Introduction

The global annual mean area burned by wildfires has been decreasing in recent decades in response to the conversion of formerly wild savanna into cropland (Andela et al. 2017), while forest area burned has been increasing, as documented in the numerous papers summarized in this article. The forest wildfires have greater and longer-lasting environmental impacts, and they release much more carbon and smoke into the atmosphere. There are thousands of refereed papers relating to forest fires (Bargali et al. 2024). In their comprehensive review article on global and regional trends and drivers of fire under climate change, Jones et al. (2022) cite over 700 of them, and many more papers have appeared since that time. There also exists an extensive literature on forest fire smoke and its impacts on human health. Jaffe et al. (2020) offer a comprehensive review.

In 2022, the journal *Global Ecology and Biogeography* devoted a special issue to the topic of the increasing threat of wildfires. In that issue, Linley et al. (2022) discussed the emerging concept of the “megafire,” a single fire or complex of fires with a burned area typically greater than 100 km², originating from a single ignition event or multiple related events. Stoof et al. (2024) argued that the term megafire is ambiguous and emotive and is, therefore, best left to the popular media. Accordingly, we will use the terms severe and smaller to distinguish between fires with burned areas above and below the 100-km² threshold. Burned area in the largest wildfires on record ranges up to ~10 000 km², 100 times the threshold.¹

¹ In North America, the “Great Fire” of 20–21 August 1910 in the interior of the Pacific Northwest and the “Chinchaga Fire” in northern British Columbia and Alberta that burned from June to October 1950.

In this paper, we present a compact overview of the observational evidence pertaining to the increasing threat of wildfires, focusing on the boreal forests, here defined as the forested areas north of 50°N and the forests of the western (contiguous) United States to the west of the 103°W meridian. The boreal forests account for about 88% of the fire-related carbon emissions over the Northern Hemisphere poleward of 30°N, and the forests of the western United States account for another 5%. Another reason for including the western United States in the study is that ground-based fire records extend backward in time into the late twentieth century, whereas a unified surveillance of the world’s forests based on satellite-borne remote sensing did not begin until around the year 2000 (Chuvieco et al. 2019).

In the next section, we document the early twenty-first century cumulative wildfire footprint, i.e., the geographical distribution of cumulative forested burned area (BA) and fire-related carbon emissions (CE) in the extratropical Northern Hemisphere, approximately partitioned into severe and smaller fires. In section 3, we document the trends, focusing mainly on the early twenty-first century, for which satellite observations are available. In section 4, we summarize the evidence linking increases in wildfire activity to increasing aridity. In section 5, we consider the possible roles of carbon fertilization, lightning, and

forest management practices in mediating wildfire activity. In the final section, we present a few concluding remarks.

For the benefit of readers wishing to view the evidence first-hand without paging through numerous papers, we have created a set of diagrams and tables based on our own analyses, which make extensive use of an upscaled version of a much higher-resolution burned area dataset based on Landsat imagery.

2. Geographical distribution

The increasing incidence of damaging forest fires is now well documented on a planetary scale. In an article introducing a newly available high-resolution fire-related forest loss dataset based on Landsat imagery, Tyukavina et al. (2022) called attention to the extensive wildfires in the boreal forests, noting that in some areas, half or more of the forested areas burned at least once during the 20-yr period of their study. Figure 1 shows close-ups of the most heavily impacted areas in central Siberia, western Canada, and the western United States, based on their dataset,² plotted on maps showing the topography.

² The GLAD Fire-related Forest Loss dataset (Tyukavina et al. 2022) is derived from the forest loss (Hansen et al. 2013), in which forest loss is defined as the removal of woody vegetation greater than 5 m in height or where tree cover is lost. Each calendar year, $\sim 30 \text{ m} \times 30 \text{ m}$ pixels that were classified as forested at the end of the previous year and no longer qualified as forested were examined using supervised classification and regression to determine whether the forest loss was due to fire-related or non-fire-related causes. For purposes of this study, the $30 \text{ m} \times 30 \text{ m}$ fields in the GLAD Fire-related Forest Loss dataset are upscaled; (i.e., aggregated in $0.25^\circ \times 0.25^\circ$ latitude/longitude grid cells), resulting in a data compression of about 10^6 . We also upscale tree cover in Hansen et al. (2013). Forest cover in our upscaled dataset is computed by summing the $\sim 30 \text{ m} \times 30 \text{ m}$ pixels with tree cover $\geq 30\%$.

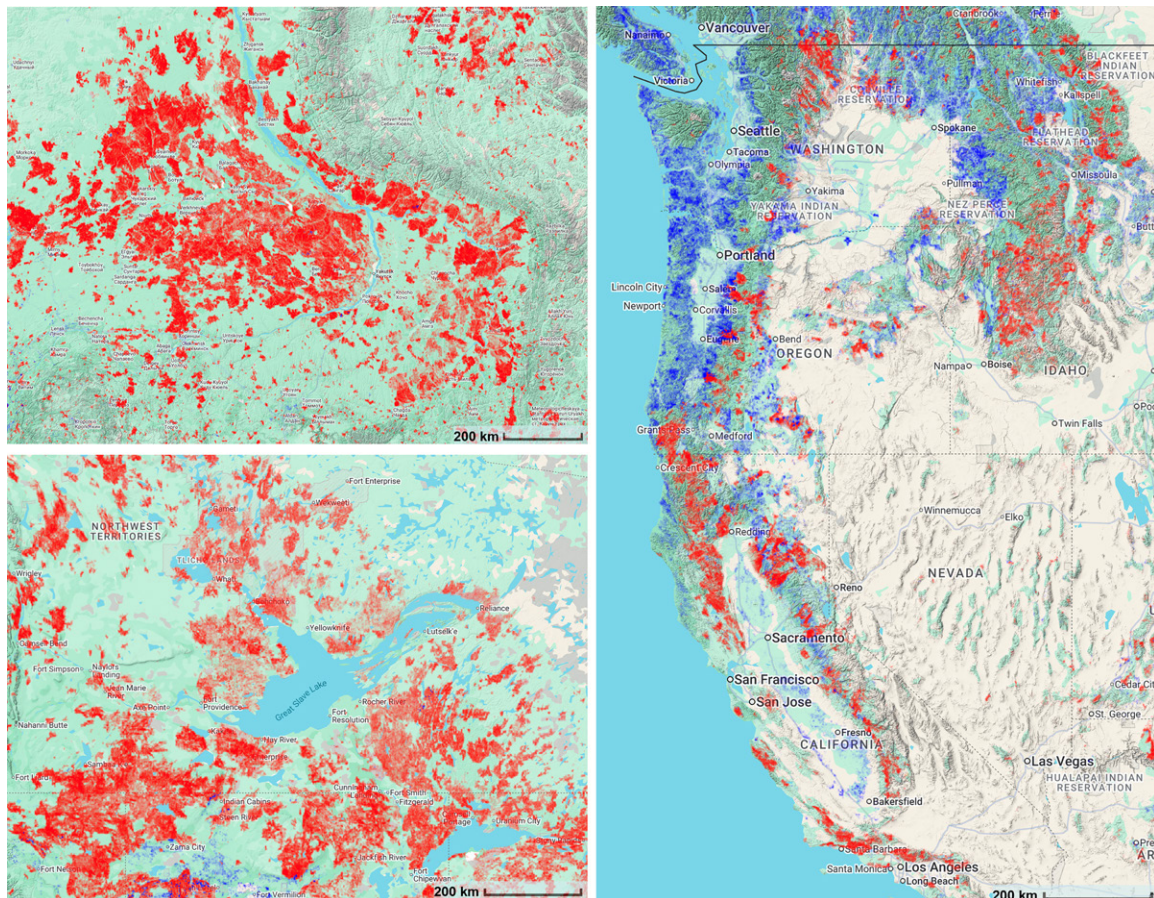


FIG. 1. Screenshots from the University of Maryland's Global Land Analysis and Discovery website (<https://glad.earthengine.app/view/global-forest-loss-due-to-fire>). Forested areas are indicated by green shading, and the topography is also indicated. Pixels in which the forest burned at least once during the 25-yr period from 2001 to 2025 are indicated in red. Blue pixels indicate forest losses due to nonfire causes. (top left) Near Yakutsk, on the Lena River in central Siberia; (bottom left) near Yellowknife on the shore of Great Slave Lake in western Canada; (right) most of the western United States. The website is on a Google Earth platform, on which it is possible to zoom in much farther on areas of interest.

The west-northwest (WNW)–east-southeast (ESE)-oriented hexagonally shaped patch in Siberia is situated on a plain bisected by the Lena River, bounded on the east and north sides by mountain ranges. Most of other heavily impacted areas of the boreal forests also lie on plains. In contrast, over the western United States, the forests and the wildfires that threaten them are largely restricted to mountainous regions.

The remainder of the figures in the text relating to BA are based on our upscaled ($0.25^\circ \times 0.25^\circ$ latitude/longitude) version of the Global Land Analysis and Discovery (GLAD) Forest Loss dataset (see footnote 2). A grid box at 50°N covers an area of 492 km^2 , roughly 5 times that of the smallest fires that qualify as severe on the basis of our $\text{BA} > 100\text{-km}^2$ criterion: In other words, a single severe fire burns an area equivalent to $\sim 20\%$ or more of the area of a grid box. The largest fires on record³ range up to ~ 20 grid boxes of this size. An unequivocal distinction between severe fires and smaller fires is not possible using our upscaled BA dataset, but we make a rough distinction by ascribing the BA in grid boxes with values above 100 km^2 in a single year to severe fires and the remainder to

smaller fires.⁴ The left panel of Fig. 2 shows the cumulative 2001–25 BA footprint, expressed in fractional area burned during the 25-yr interval, taking all fires into account. The most heavily impacted grid boxes, with fractional BA $> 50\%$, are shown in Fig. S2b in the online supplemental material. Most of the BA is concentrated in the sharp-edged, hexagonally shaped area on the plain around Yakutsk and the patch of comparable size over western Canada, both of which are discernible in Fig. 1.

In the right panel of Fig. 2, the severe fires are hidden by masking out (in white) the grid boxes that show color in the left panel and adjusting the color palette to make the grid box with fractional BA $< 10\%$ visible. It is evident that the smaller fires are much more evenly distributed than the severe fires. In both panels of Fig. 2, BA is much larger in the boreal forests of Asia and North America than in those of Europe, and it is also much larger in the

³ See footnote 1 above.

⁴ BA ascribed to a severe fire is subject to two types of error, the first resulting in an underestimate and the second resulting in an overestimate. Fires with BA slightly greater than the 100-km^2 criterion, but which do not fall completely within a single grid box, might not be classified as severe. Multiple smaller fires that occurred in the same grid box in the same year will be classified as a severe fire if the combined BA is greater than 100 km^2 .

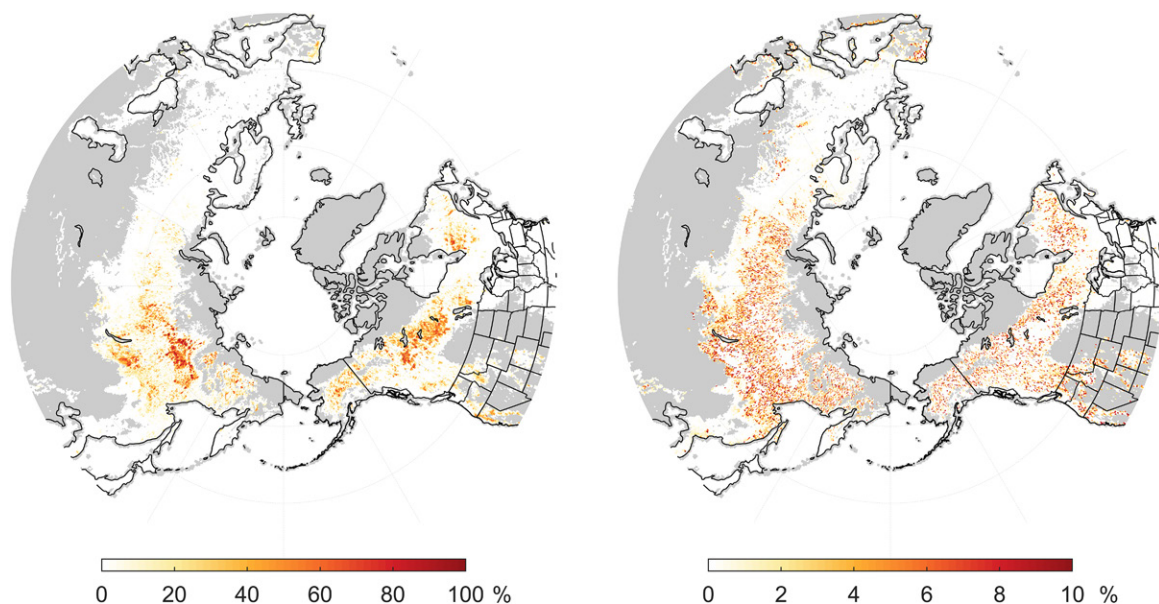


FIG. 2. Cumulative fractional BA (%) based on the upscaled version of the GLAD Forest Loss dataset (see footnote 2) during the interval 2001–25: (left) all grid points and (right) grid points with BA $< 10\%$. Grid points with less than 10% forest cover at the end of the year 2000 are masked out and indicated by gray shading. For ease of comparison, these panels are also shown as pairs of two-frame animations in Fig. S2a.

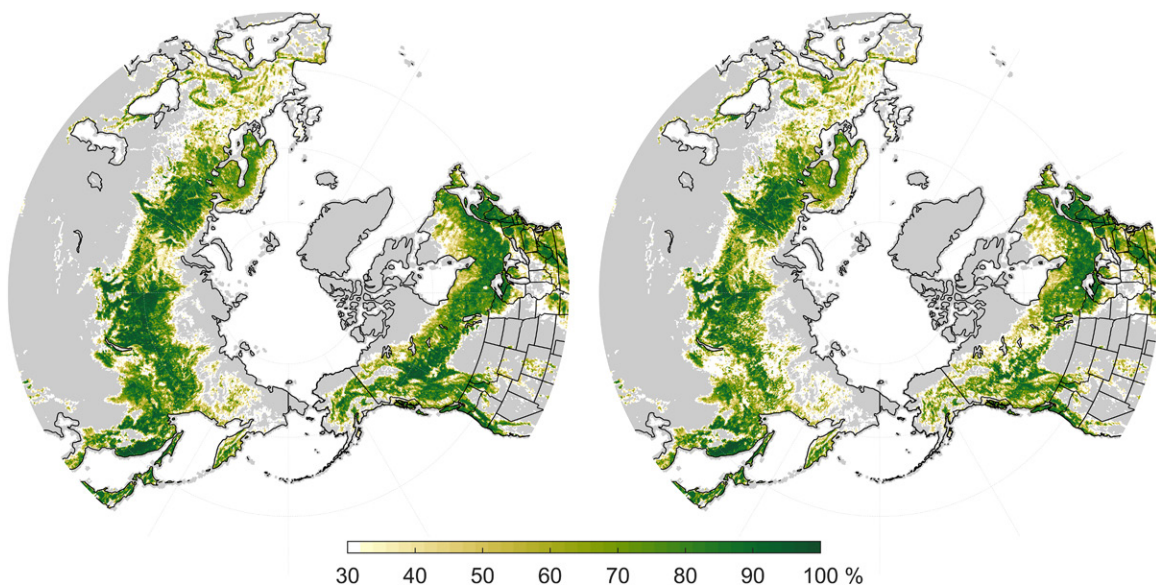


FIG. 3. (left) Percentage forest cover at the end of the year 2000 based on the upscaled GLAD Forest Loss dataset (see footnote 2); (right) the field in the left panel minus the percentage of area that burned at least once during the interval 2001–25 based on the GLAD Fire-related Forest Loss dataset. Gray shading is as in Fig. 2. The distinction between the left and right panels, more clearly revealed in the two-frame animation (Fig. S3), should not be interpreted as indicating a loss of coverage of forest coverage due to fires because it does not account for the regrowth of vegetation in the burn scars.

temperate forests of western United States than elsewhere in temperate latitudes. Based on our rough classification scheme, $\sim 1/3$ of the BA in the boreal forests was associated with severe fires.

To provide a broad-brush indication of what fraction of the forests has burned since the end of the year 2000, the left panel of Fig. 3 shows the forest coverage that existed at that time and the right panel shows that same field minus BA summed over the years 2001–25. The unburned forest-covered area in 2025 shown in the right panel is noticeably smaller than the total area covered by forests in 2000. The actual loss of forest coverage due to fire during this time interval is substantially less than might be inferred from Fig. 3 because of the regrowth of vegetation in the burn scars. The distinction between BA and actual forest loss is documented in Fig. S2c, based on GLAD fields of forest extent in Potapov et al. (2022) at the end of calendar years 2000 and 2020. Changes in forest extent are difficult to interpret because they are not exclusively due to burning in wildfires and regrowth. However, the comparison in Fig. S2c suggests that regrowth was occurring in the core areas of fire-related forest loss but that it was not sufficient during this 20-yr interval to fully restore the population of trees taller than 5 m. If the forests were in equilibrium with the climate, forest extent would be constant and the regrowth in the burn scars would evolve into the same mix of tree species as the forest that existed previously. But in a rapidly changing climate with a declining recurrence time of severe fires, forest extent and areal coverage of mature trees are likely to decrease. The secondary forest will likely contain a disproportionate fraction of the more fire-resistant and/or faster-growing tree species, and it could even shift to a mixture of a forest and shrub or grassland (Baltzer et al. 2021; Hill et al. 2023; Johnstone et al. 2016).

Another informative wildfire metric is fire-related CE derived from Moderate Resolution Imaging Spectroradiometer (MODIS) imagery.⁵ We consider CE during the fire season (May–September) at forested grid points, i.e., grid points with

⁵ The NASA GFED with small fires (GFED4.1s) contains a fire-related CE dataset based on MODIS imagery (van der Werf et al. 2017). It consists of monthly fields on a latitude–longitude grid with $0.25^\circ \times 0.25^\circ$ resolution from 2001 onward. Monthly fields derived from other satellite sensors are available dating back to and including 1997.

at least 10% forest cover at the end of the year 2000 in the upscaled Global Forest Change dataset of Hansen et al. (2013). In comparing distributions of CE and BA, it should be borne in mind that they are not quite the same thing. CE represents the emissions from all biomass burning in forested areas, whereas BA, as reflected in the GLAD dataset, relates to fires large enough to cause forested pixels to no longer be classified as forested. Figure 4 shows a scatterplot of cumulative CE as a function of BA at individual grid points in their respective “climatological mean maps,” shown in Fig. S4. For severe fires, log BA and log CE tend to be linearly proportional, and this relationship holds for grid points with BA down to about 20 km², beyond which the relationship breaks down, as CE from sources other than forest fires become increasingly important.

3. Trends

Based on a compilation of records from multiple government agencies, Williams et al. (2019) showed that annual BA of the forests of the state of California increased roughly eightfold from 1972 to 2018.⁶ Parks and Abatzoglou (2020) generalized this result to the western United States, using a composite of twentieth century ground-based data together with estimates based on satellite imagery from 2000 onward to estimate BA in fires determined to be of high severity.⁷ They estimated an eightfold increase in annual BA from 1985 to 2017. Potapov et al. (2025) showed that annual BA in the boreal forests rose steeply from 2001 to 2024. Figure 5 is reproduced from their paper.

Figure 6 contrasts wildfire metrics for the first and second halves of the observational record. BA for all grid points (top row) exhibits similar spatial patterns in the two halves of the record, with a marked increase from the first to the second half, in contrast to grid points with smaller fires (middle row), which are comparable in amplitude in the first and second halves. Hence, it is evident that a disproportionate fraction of the increase in BA from the first to second halves of the record is due to severe fires. The analogous breakdown of CE shown in Fig. S6c also suggests that wildfire activity was substantially greater during the second half of the record.

The bottom row of Fig. 6 shows aerosol optical depth (AOD), also inferred

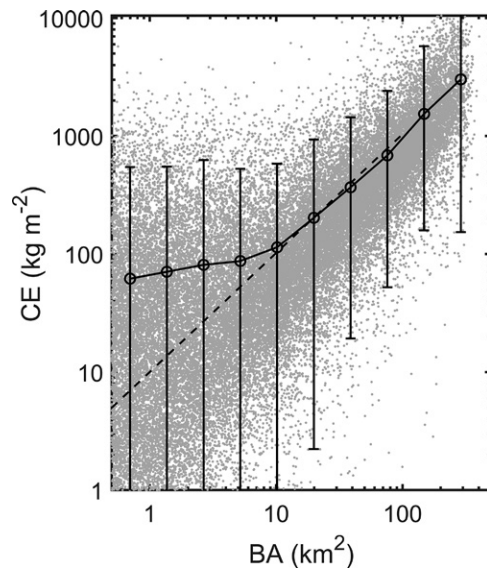


FIG. 4. Log-log scatterplot of cumulative CE as a function of BA at individual forested grid points poleward of 25°N in the respective “climatological mean maps” shown in Fig. S4. The small black circles are averages of cumulative CE in bins of equal width along the x axis. In a Gaussian distribution, 95% of the grid points on these maps would lie between the error bars: 2.5% above them and 2.5% below. The dashed guideline is indicative of a linear relation between log CE and log BA.

⁶ In the literature, trends in the incidence of wildfires are usually expressed in terms of exponential growth rates rather than linear rates of change because time series of log BA and other indicators of wildfire activity are more strongly correlated with time series of meteorological variables than with time series of the fire metrics themselves. Juang et al. (2022) offer a plausible physical explanation of this inherent nonlinearity.

⁷ In Table 2 and Fig. 9, we will refer to this blended record of burned area over the western United States by the symbol BA* in order to distinguish it from the shorter (2001) record based entirely on the GLAD data, designated by BA.

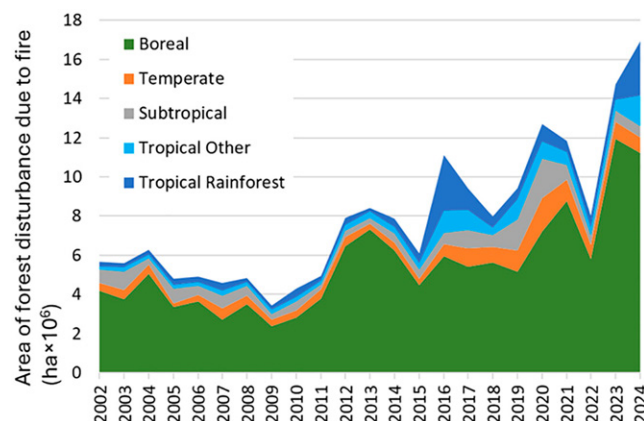


FIG. 5. Annual BA since the year 2001 in millions of hectares per year in various domains as indicated, reprinted from Potapov et al. (2025).

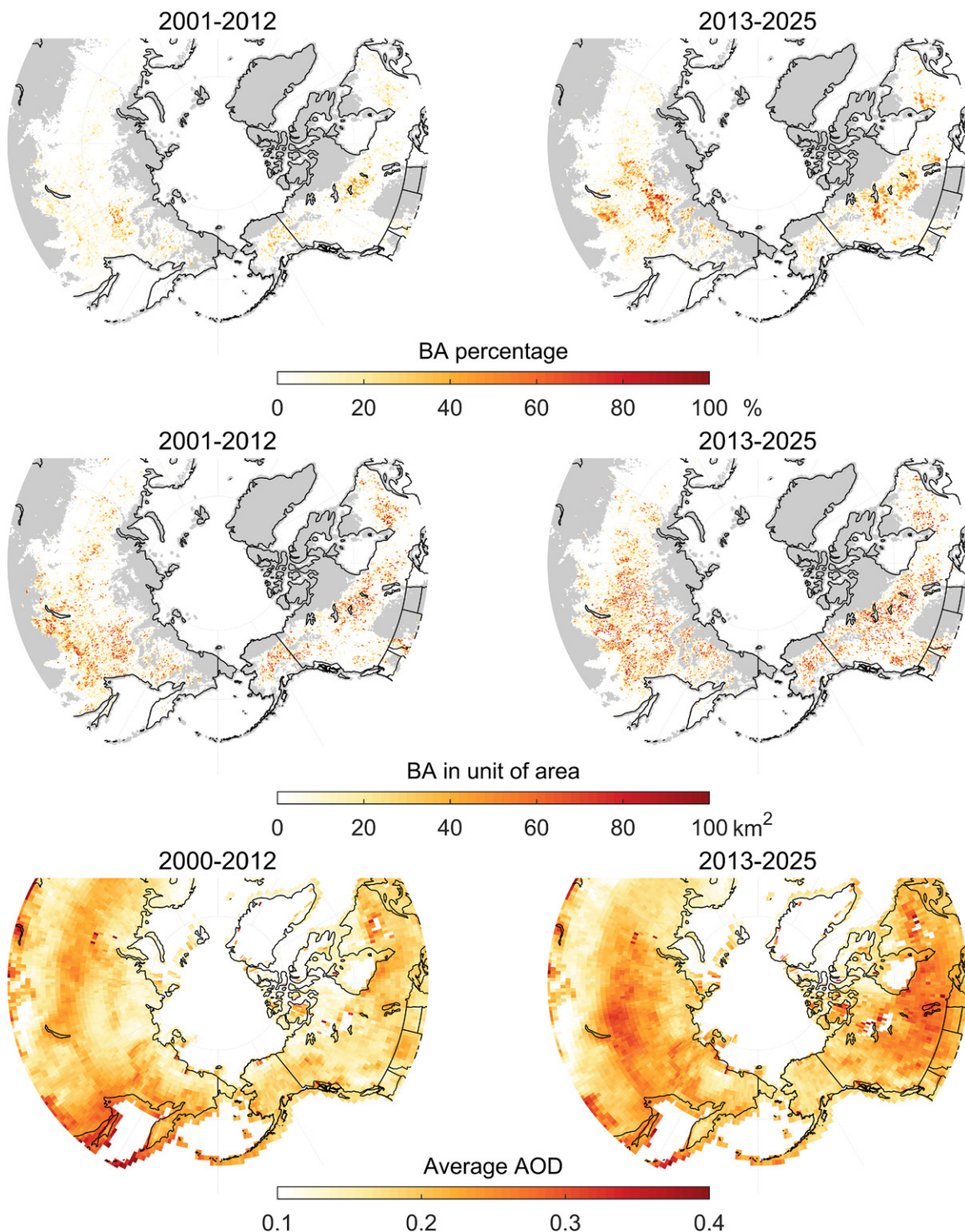


FIG. 6. Wildfire impacts during the (left) first and (right) second halves of the study period. Gray shading is as in Fig. 2. (top) Annual BA, defined here as the fractional area that has burned at least once during the periods, expressed as a percentage, based on the GLAD Forest Loss dataset (see footnote 2). (middle) As in (top), but showing only the grid points with BA < 100 km² and expressed in terms of area rather than fractional area for each grid box. (bottom) The distributions of AOD for the fire season (May–September). For ease of comparison, these panels are also shown as pairs of two-frame animations in Fig. S6b.

from MODIS imagery, averaged over the fire season.⁸ AOD is a measure of the cumulative depletion of a direct beam of solar radiation due to scattering and absorption as it passes through the atmosphere. It exhibits marked increases over Siberia, Canada, and the northern United States. BA and AOD over the

⁸ Data for AOD are available with 1° × 1° resolution, and they include the effects of both anthropogenic and natural aerosol emissions such as those from wildfires (Platnick 2015).

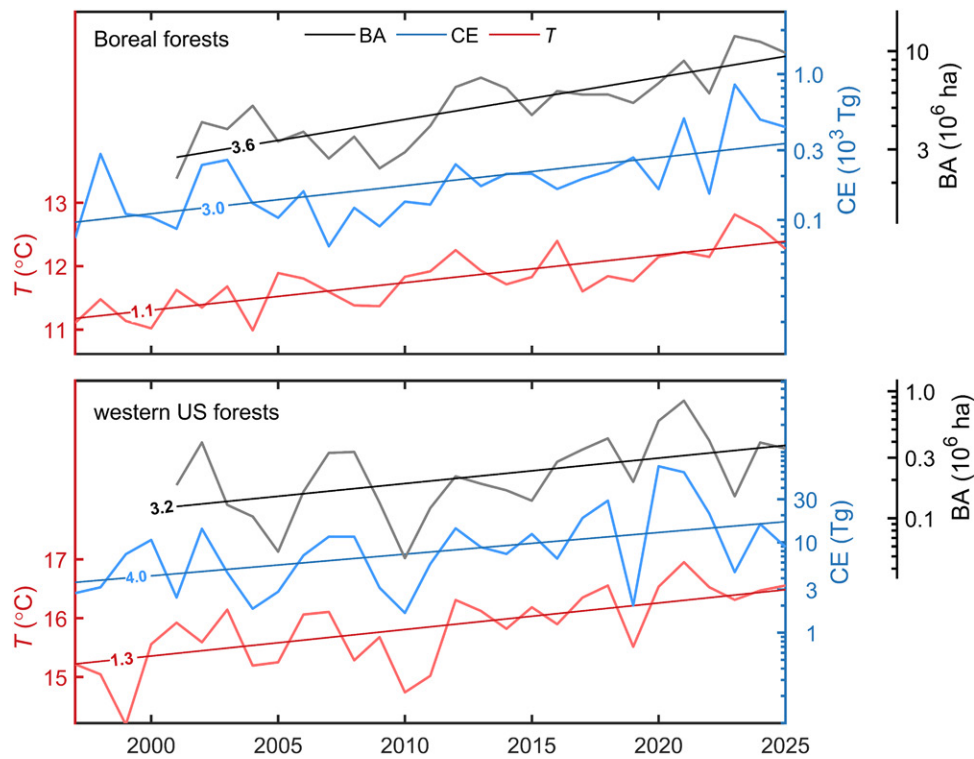


FIG. 7. Time series of fire-related variables over the (top) boreal forests and (bottom) western U.S. forests based on grid points with more than 10% forest cover: CE integrated over the fire season (May–September) from the Global Fire Emissions Database (GFED) dataset (see footnote 5), annual BA from the GLAD Forest Loss dataset (see footnote 2), and May–September-averaged surface air temperature (T) from the ERA5 reanalysis. The BA and CE time series are plotted on a logarithmic scale, and the T time series is plotted on a linear scale. The sloping straight lines represent least squares best-fit trends, labeled in units of fraction per 25 years for CE and BA and Kelvins per 25 years for T . The curves are scaled in proportion to their standard deviations.

western U.S. forests (Fig. S6a) also exhibit increases from the first to the second halves of the record. The increase in AOD is mainly attributable to the increasing incidence of wildfires (Ehret et al. 2025). The strongest increases in AOD are over North America poleward of 45°N and east of 120°W , where climatological May–September mean has increased from 0.13 to 0.21 from 2000 to 2025, as estimated by fitting a linear trend to the annual values, which is statistically significant ($p < 0.001$).

The increasing incidence of wildfires over the past few decades is also evident in the time series shown in Fig. 7. Over both the boreal forests and the western U.S. forests, annual BA and fire-season CE have been increasing more or less exponentially with time, and the logarithmically fitted trend lines in CE are indicative of roughly threefold increases in the past 25 years. The statistical significance of the logarithmic trends, assessed on the basis of the t statistic, is shown in Table 1. The trends in log BA and log CE are significant in both domains—but much more so in the boreal forest domain by virtue of the much larger number of fires and the fact that the domain is large enough that in the area average, circulation-related year-to-year variations in wildfire activity tend to average out, resulting in a smaller standard error. In analogous time series for severe and smaller wildfires (Fig. S7a), the logarithmic trends in BA (per 25 years) in the boreal forests are 1.9 for the smaller fires versus 15.5 for the severe fires in accord with the prevailing view that the observed increase in annual average BA is mainly due to the larger fires. The number of severe fires over the western United States is not sufficient to enable us to make such a comparison.

Based on their analysis of “hotspots” in MODIS imagery at its native $0.2^{\circ} \times 0.2^{\circ}$ resolution, which are considered to be representative of severe fires, Cunningham et al. (2024) produced

TABLE 1. Statistics used in estimating the statistical significance of the logarithmic trends in BA and CE. The N_{eff} is the number of degrees of freedom as defined in Bretherton et al. (1999), equivalent to $N(1 - r^2)/(1 + r^2)$, where N is the number of years in the record and r is the domain average of the 1-yr lag correlations in the detrended data, calculated for each grid box (Fig. S7b) and domain averaged. The probability of occurrence by random chance p is estimated on the basis of a one-sided Student's t test.

	log BA (2001–25)		log CE (1997–2025)	
	Boreal forests	Western United States	Boreal forests	Western United States
N_{eff}	24.93	24.72	28.85	28.82
Trends (per year)	0.052	0.046	0.044	0.055
Standard error	0.0077	0.0171	0.0106	0.0192
t value	6.70	2.70	4.19	2.87
p value (one-sided test)	3.9×10^{-7}	6.5×10^{-3}	1.3×10^{-4}	3.9×10^{-3}

a suite of time series documenting wildfire activity on a regional basis, covering the interval 2003–23. Their time series for the boreal forests and the coniferous temperate forests exhibit exponential rates of increase roughly comparable to those in our Fig. 7. Prominent features in the year-to-year variability are also similar.

4. Role of aridity in mediating wildfire activity

In numerous published studies, the authors have concluded that the incidence of fires is increasing in response to a trend toward increased aridity induced mainly by the rising temperatures. The analyses in support of this conclusion are based on a suite of climatic variables including near-surface temperature (T) and relative humidity (RH), antecedent rainfall, and soil moisture (SM). Seager et al. (2015) showed that much of the multivariate information on the environmental conditions experienced by the trees is encapsulated in a single variable: the vapor pressure deficit,

$$\text{VPD} = e_s(T)(1 - \text{RH}), \quad (1)$$

where e_s is the saturation pressure, given by the Clausius–Clapeyron equation. Based on data over the southwestern United States, they showed that BA and vapor pressure deficit (VPD) are strongly correlated on a year-by-year basis. Juang et al. (2022) showed that VPD is also strongly correlated with the number of fires, fire size, and fire duration. In their studies of wildfires over the western United States, Williams et al. (2019), Parks and Abatzoglou (2020), and Zhuang et al. (2021) attributed the increasing incidence of wildfires to increasing aridity, as represented by the rising VPD.

The strong influence of VPD upon wildfire activity on a daily basis is illustrated in Fig. 8, which contrasts the distributions of cumulative CE on days with above and below normal VPD. The distinction is so pronounced that to see the latter, it is necessary to resort to a nonlinear scale on the color palette. The same patches of enhanced wildfire activity are apparent in both composites, but CE is strongly enhanced on days with high VPD relative to those with low VPD. Averaged over the boreal forest domain, the ratio is on the order of 8:1 (3:1 over the western United States), even stronger than the corresponding ratios for temperature.

Table 2 shows year-to-year correlations between time series of fire metrics log BA, log BA*, and log CE and aridity metrics T , VPD, and SM⁹ averaged over the boreal and western U.S. forest

⁹ Direct measurements of SM are very limited. In the ERA5 reanalysis, it is derived from a hydrologic model driven by surface air temperature and RH and antecedent rainfall. We used SM in the topmost 7 m, which responds most rapidly to atmospheric conditions and has the strongest direct influence on surface fuel moisture, particularly for fine dead fuels and litter that play a key role in fire ignition and early fire spread. Deeper soil layers generally vary more slowly and are less directly linked to short-term changes in surface fuel dryness.

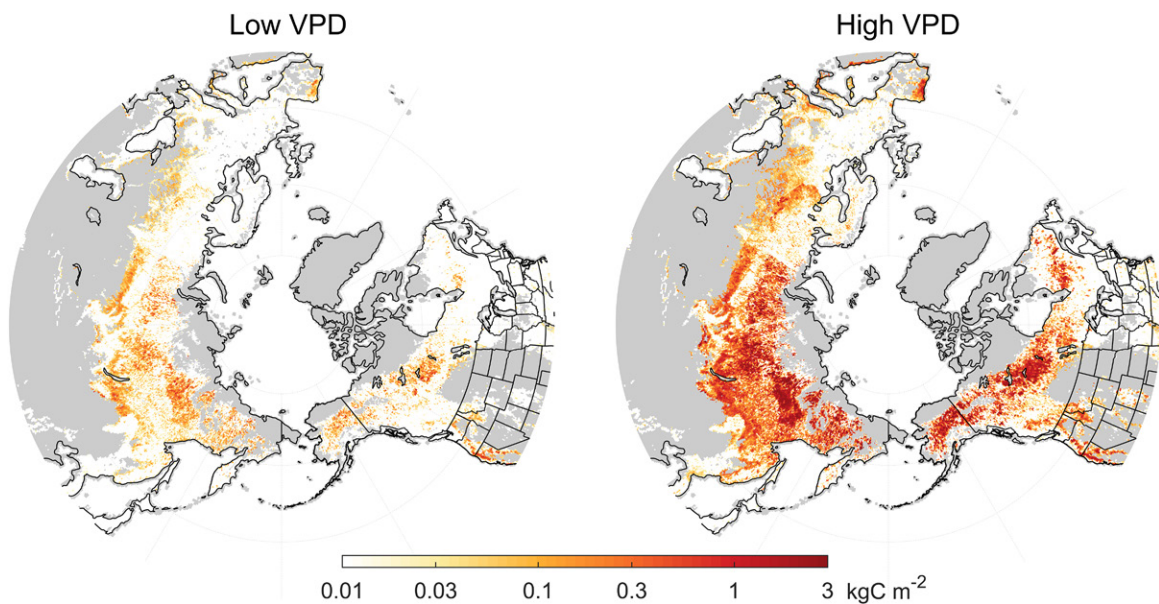


FIG. 8. Composite maps of cumulative CE on a logarithmic scale on May–September days with VPD below and above normal. Gray shading is as in Fig. 2. These panels are also shown as pairs of two-frame animations in Fig. S8. The NASA GFED, version 5 (GFEDv5), provides daily fire-related CE derived from satellite observations on a $0.25^\circ \times 0.25^\circ$ latitude–longitude grid from 2001 to 2022 (van der Werf et al. 2025).

domains. The statistical significance of the correlations involving the raw time series is difficult to assess because they could conceivably be inflated by the presence of trends that are not physically related. Hence, correlations based on detrended data are shown as well. For

TABLE 2. Correlation matrices based on (left) raw and (right) detrended time series of annual values, domain averaged over the (top) boreal and (bottom) western U.S. forests. Annual values for BA and values of the other variables are averaged over the fire season (May–September). The observed correlations between the detrended time series of the fire metrics and aridity metrics indicated in boldfaced type.

	Boreal forests												
	Total variability					Interannual variability							
	log BA	log CE	<i>T</i>	VPD	SM	log BA	log CE	<i>T</i>	VPD	SM			
log BA (2001–25)	1.00	0.85	0.70	0.72	−0.73	log BA	1.00	0.74	0.40	0.38	−0.48		
log CE (1997–2025)		1.00	0.67	0.71	−0.77	log CE		1.00	0.43	0.47	−0.54		
<i>T</i> (1984–2025)			1.00	0.92	−0.77	<i>T</i>			1.00	0.75	−0.36		
VPD (1984–2025)				1.00	−0.91	VPD				1.00	−0.77		
SM (1984–2025)					1.00	SM					1.00		
	Western U.S. forests												
	Total variability					Interannual variability							
	log BA	log CE	log BA*	<i>T</i>	VPD	SM	log BA	log CE	log BA*	<i>T</i>	VPD	SM	
log BA (2001–25)	1.00	0.84	0.77	0.73	0.81	−0.76	log BA	1.00	0.84	0.76	0.53	0.72	−0.66
log CE (1997–2025)		1.00	0.83	0.66	0.72	−0.65	log CE		1.00	0.81	0.38	0.50	−0.36
log BA* (1984–2023)			1.00	0.79	0.88	−0.88	log BA*			1.00	0.52	0.69	−0.64
<i>T</i> (1984–2025)				1.00	0.92	−0.84	<i>T</i>				1.00	0.82	−0.70
VPD (1984–2025)					1.00	−0.96	VPD					1.00	−0.94
SM (1984–2024)						1.00	SM						1.00

reference, in the absence of autocorrelation, the 95% significance level based on a one-sided t test for a time series 25-yr long is 0.34. The observed correlations between the detrended time series of the fire metrics and aridity metrics are all statistically significant. SM and VPD are strongly (negatively) correlated with one another, and they exhibit very similar correlations with the fire metrics.

Figure 9 shows time series of the aridity metrics VPD and SM together with the extended log BA* time series for the western United States dating back to 1984. The correspondence between the series is impressive, and it is even stronger for the post-2000 segments of the time series in which BA* is based on satellite measurements.

The temperature dependence of VPD is a reflection of the increased evaporative demand (Williams et al. 2020). Hence, VPD varies in response to the evolving atmospheric circulation pattern in real time. In contrast, the RH dependence derives not only from the present circulation pattern but also from antecedent conditions that affect SM. That log BA* and log CE over the forests of the western United States are even more strongly correlated with VPD and SM than with temperature in Table 2 is further evidence that antecedent conditions affect aridity matter. To separate the T and RH dependences of VPD, we make use of Eq. (1), estimating the warming contribution by holding RH fixed and vice versa. The two components do not exactly sum to the total because we have ignored the interdependence of T and RH, but the discrepancy is only a few percent. The hemispheric distributions of the VPD trends and the contributions from rising T and declining RH are shown in Fig. 10: The distributions over the western United States are shown in greater detail in Fig. S10. Over the boreal forests, the trend toward higher VPD is primarily due to the warming, whereas over the western United States, the drying contribution is dominant.

Holden et al. (2018) examined trends in summer rainfall over the western United States during the period of record 1979–2016 and found evidence of a widespread decline, which is verified by our own analysis shown in Fig. S11. However, we find that the period of record

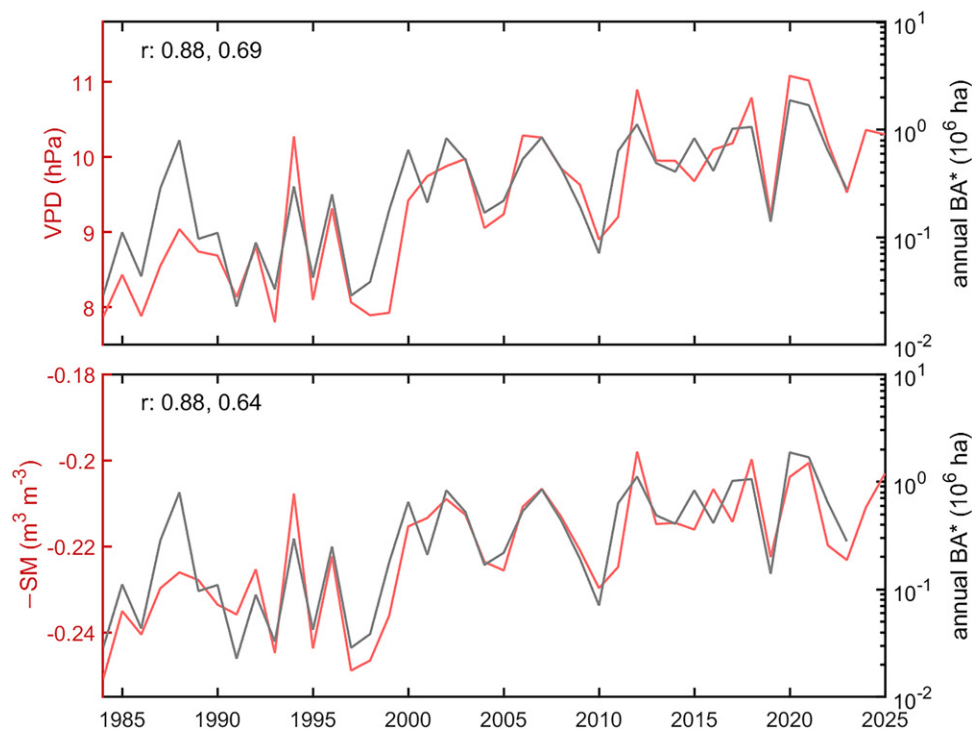


FIG. 9. Time series of annual log BA* over the western United States shown together with metrics of aridity averaged over the fire season (May–September). (top) VPD and (bottom) SM with polarity reversed. Correlations based on the raw and detrended time series are indicated at the top left of each panel.

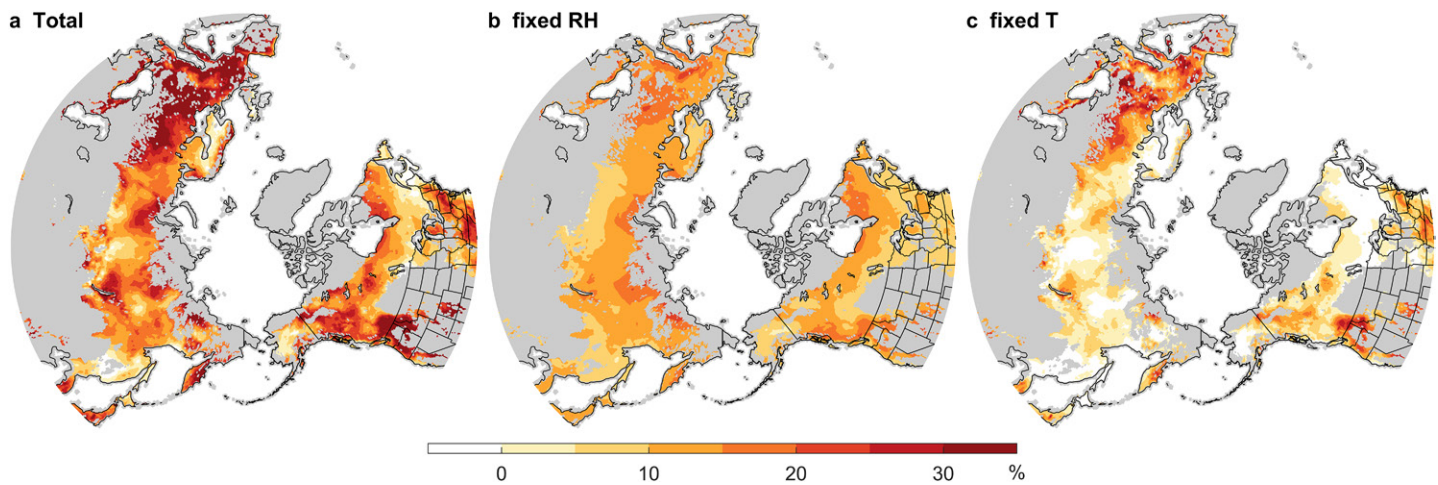


FIG. 10. Fire-season (May–September) VPD trends in units of percentage change over the 50-yr interval 1974–2024 based on the ERA5 reanalysis: (left) total change, (middle) change attributable to warming, and (right) change attributable to the trend in RH, based on the partitioning scheme described in the text. Gray shading is as in Fig. 2.

from 2000 onward does not exhibit a downward trend. Hence, the trend toward increasing aridity in the western U.S. forests during the study period must be due to other causes, such as increased evapotranspiration due to warming and the earlier melting of winter snowpack (Abatzoglou and Kolden 2013).

The warmer summers in our study area are an integral part of the global warming signature. Domain-averaged T trends are shown in Table 3. Averaged over the boreal and western U.S. forests, the observed T rises from 1974 to 2024, estimated on the basis of these various datasets ranged from 1.5 to 2.1 K: They are somewhat stronger in ERA5 than in the other datasets. The trend has been almost linear: During our 25-yr study period (2000–24), the warming was on the order of 1 K, roughly half as much as during the 50-yr interval (1974–2024).

The bottom row of Table 3 shows the trends in the multimodel mean of the Coupled Model Intercomparison Project phase 6 (CMIP6) runs.¹⁰ The simulated trends are similar to those in ERA5. Hence, the observed warming is consistent with the

¹⁰ A combination of the historical simulations up to 2015 with the “middle of the road scenario” SSP2-4.5 from 2015 to 2024. For this short segment, it makes little difference which of the emissions scenarios is used.

TABLE 3. Domain-averaged fire-season (May–September) surface air temperature trends from the ERA5 reanalysis; Berkeley Earth; GISS Surface Temperature Analysis, version 4; NOAA Merged Land Ocean Global Surface Temperature Analysis, version 6; Met Office Hadley Centre HadISDH 4.6.1.2024f, expressed in units of Kelvins per 50 years for 1974–2024 and Kelvins per 25 years for 2000–24. The domain averages are based on grid boxes with at least 10% forest cover in the GLAD Forest Loss dataset. The bottom row shows the trends in the multimodel mean of the CMIP6 simulations, under the historical forcing before 2015 and the shared socioeconomic pathway (SSP) 2-4.5 “middle of the road” scenario starting in 2015.

	1974–2024		2000–24	
	Boreal forests	Western United States	Boreal forests	Western United States
ERA5	1.84	2.09	1.13	1.07
Berkeley Earth	1.66	1.62	0.90	0.74
GISS	1.71	1.69	0.91	0.87
NOAA	1.77	1.54	1.00	0.75
Hadley	1.61	1.45	0.90	1.02
CMIP6	2.18	2.10	1.05	1.18

hypothesis that it is the forced response to the buildup of greenhouse gases. Trends in the individual model simulations are shown in Table S3.

5. Other possible drivers of the increasing incidence of wildfires

There are factors other than increasing aridity that could be contributing to the increase in wildfire activity. The burning of fossil fuels could be contributing to it by way of carbon fertilization. Increased photosynthesis results in increased growth of leaves and needles, which ultimately senesce and become fuel. On the basis of modeling evidence, Haas et al. (2023) argued that carbon fertilization induced by the increasing atmospheric carbon dioxide (CO₂) concentration since the time of the last glacial maximum is primarily responsible for the increased incidence of fires since that time. Allen et al. (2024) found that carbon fertilization resulting from a CO₂ doubling relative to 1850 concentrations would result in roughly a 60% increase in fire-related carbon emissions globally and almost a threefold increase over the western United States. These enhancements are appreciable but not nearly enough to account for the observed threefold increase in CE since the year 2000.

Another proposed driver is lightning, which is believed to be responsible for igniting most of the wildfires in the boreal forests (Janssen et al. 2023), and most of the burned area in the western U.S. forests (Abatzoglou et al. 2016). Most of these ignitions are associated with “dry lightning,” i.e., cloud-to-ground lightning flashes that are not accompanied by significant rainfall. To distinguish between wet and dry lightning in the observations requires rainfall measurements with time resolution on the order of an hour and a spatial resolution on the order of a few kilometers, higher than currently exists, over a period of two or more decades.

Koshak et al. (2015), Lavigne et al. (2019), and Burrows et al. (2025) have all reported declining (total) lightning flash rates over parts of the western United States. Holzworth et al. (2021) reported a sharp increase in flash rate averaged over the area poleward of 55°N, relative to the rest of the world, during the decade of the 2010s, but R. H. Holzworth (2026, personal communication) cautions against reading too much into inferences drawn from the analysis of such a short period of record. Attribution is further complicated by the fact that CE depend not only upon how many fires are ignited but also upon the size distribution of the fires, which, in turn, depends upon the aridity (Andrews 2018; Juang et al. 2022). It is shown in Table 4 that in the year-to-year variability, CE is negatively correlated with flash rate, likely by virtue of the mutual correlations (of opposing sign) with VPD. Hence, it should not be taken for granted that the frequency of the occurrence of dry lightning is increasing as a consequence of global warming. In any case, it seems unlikely that it could be increasing fast enough to account for the roughly threefold increase in burned area since the year 2000.

Forest management practices also play a role in mediating wildfire activity over the western United States. Figure 11 shows an idealized record of wildfire activity as deduced from the analysis of the prevalence of tree ring burn scars, which occur mainly in dry climatic zones, where fires are the most important kind of forest disturbance. On the basis of such proxy evidence, Marlon et al. (2012) hypothesized that prior to 1880, variations in wildfire activity were mainly climate driven. After that time, the presence of a growing number of European settlers began to reduce the forest area burned. Extensive grazing of cattle and the

TABLE 4. Linear correlations between detrended CE, lightning days (LD), and VPD based on annual data averaged over the fire season for 2012–24. LDs are calculated using data from the World Wide Lightning Location Network (WWLLN).

	CE vs LD		CE vs VPD		LD vs VPD	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
Boreal forests	−0.39	0.21	0.61	0.03	−0.03	
Western United States	−0.73	0.01	0.88	0.0002	−0.77	0.004

fragmentation of the forest landscape by railroad lines and towns inhibited the spread of fires. The implementation of increasingly effective fire suppression practices reduced BA dramatically from the 1930s to the 1960s [Natural Resources Defense Council (NRDC) 2003]. Human-induced warming, which favors more frequent fires, in combination with fire suppression, has created a growing “fire deficit” (i.e., a disparity between the area burned and the area that would have burned if the incidence of wildfires had been entirely climate driven) that persists to this day.

Based on the analysis of the same burn scar records, Parks et al. (2025) showed that there were many years during their reference period 1600–1880 with a much higher percentage of forested sites recording fires than in any of the years in the recent historical record, consistent with the schematic depiction in Fig. 11. The reduction in the average annual burned area due to fire suppression has enabled the forests in the drier climatic zones of the western United States to expand into areas that were formerly savanna, and to fill in mosaic landscapes within the forests, allowing wildfires to spread through the crowns of trees. These changes are indicated schematically in Fig. 11 by the declining spacing between the trees. Wildfire suppression is thus widely believed to be contributing to today’s heightened level of wildfire activity over the western United States, acting as an amplifier, rendering fires more severe than they would have been if nature had been allowed to take its course.

Parks et al. (2025) found that, in contrast to the tree ring burn scar records at sites over the western United States, the fires at sites in the boreal forests in the Canadian Northwest Territories from 1984 onward are unprecedented in the historical record, a finding consistent with paleoclimatic evidence (Hoecker et al. 2020; Kelly et al. 2013). Hence, there appears to be much less of a fire deficit in the boreal forests, consistent with the smaller human imprint (Pugh et al. 2024).

6. Concluding remarks

Although neither the number of fires nor the size of the largest ones is unprecedented in the historical record, the forested burned area per year in recent decades is arguably greater than at any time in the past hundred years. A strong case has been made that current spate of fires is a consequence of human-induced global warming, which resumed around 1980, following an extended mid-twentieth-century hiatus. The case rests largely on observations demonstrating the strong sensitivity of forested burned area and fire-related carbon emissions to aridity metrics such as vapor pressure deficit and soil moisture on interannual and shorter time scales. Carbon fertilization and the fire deficit due to the history of fire suppression may be contributing to the severity of today’s wildfires, but it seems unlikely that they could have produced a large enough increase in burnable fuels to account for such a large increase in annual average burned area over the course of just a few decades.

Over 90% of the forested burned area in the extratropical Northern Hemisphere is in the boreal forests and the forests of the western United States. The boreal forests cover an

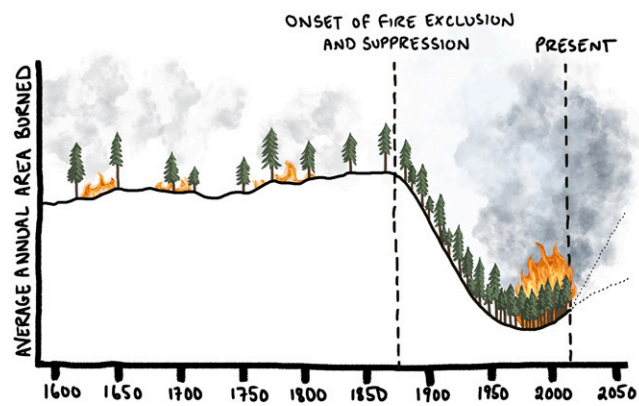


FIG. 11. Schematic illustrating the role of fire suppression in rendering late-twentieth-century forest fires in the western United States less frequent, but more intense. The curve is based on the density of burn scars in the tree ring record from sites in the forests in dry climatic zones of western United States. Adapted from Parks et al. (2025). Graphic courtesy of Jessie Thoreson.

area of an order of magnitude greater than the western U.S. forests, and from 2000 to 2025, they experienced a burned area of an order of magnitude larger. Not having been subjected to a strong human imprint, they do not exhibit as widespread a fire deficit. Fire-season temperatures are several degrees cooler, and relative humidities are substantially higher than over the western U.S. forests (~70% vs ~55%). Yet despite these differences, the logarithmic trends in forested burned area and fire-related carbon emissions in these two domains were quite comparable: Both have increased roughly threefold since the year 2000. Both domains have experienced increasing aridity in response to the rising temperatures during the fire season. In the western U.S. forests, the drying is augmented by declining relative humidity, apparently in response to the increasing evaporative demand and the earlier melting of winter snowpack.

Damaging wildfires have occurred outside our study areas. Figure S1a shows patches of enhanced wildfire activity centered in Portugal and Greece that are captured in the zoomed-in version of the Fire-related Forest Loss dataset on the GLAD website but are too small in scale to exhibit a prominent signature when the data are upscaled to our $0.25^\circ \times 0.25^\circ$ latitude/longitude grid. It is notable that Greece and Portugal are in the Mediterranean biome, the same as California and Oregon, which have experienced numerous severe fires. Conversely, there are parts of our study area that have been relatively unscathed thus far. A notable example is the coastal forests of the Pacific Northwest (Fig. S1b), which lie in mountainous terrain within the Pacific temperate rain forest biome.

There are strong contrasts in BA within our study areas. For example, in the hexagonal-shaped patch around Yakutsk, more than half the forest has burned since the year 2000, while the region to the south and west of it, which is equally flat, has been much less heavily impacted. Why the severe fires tend to be so concentrated within core areas is not clear. The sharp edges of these patches are certainly not climatic. Are they ecological boundaries relating to the dominant tree species or geological boundaries that impact the ground hydrology or soil type? Determining exactly what they are will require mapping the relevant fields on a planetary scale, as in the climatologies used in atmospheric research.

To determine the long-lasting impacts of the increasing incidence of severe wildfires upon the forests, it will be necessary to map successional trajectories (i.e., the evolving mix of plant function types) in the regrowth in the burn scars over a period of decades, as discussed in Van Cleve and Viereck (1981). This is already being done on a limited basis, using Landsat data in conjunction with other datasets (Bhoot et al. 2026; Kim et al. 2024; Orndahl et al. 2022), and there is the prospect of more comprehensive analyses with the lengthening of the observational record and the future development of more refined, space-based observing techniques.

Wildfire smoke has emerged as an important environmental and health issue in its own right, eroding the substantial improvements in air quality over the United States resulting from regulatory actions (Burke et al. 2021; Feng et al. 2025; Jaffe et al. 2020). This is not a new phenomenon—e.g., see the historical account of “the great smoke pall of 1950 . . .” (Hamilton 2026)—but with the rapidly increasing incidence of severe wildfires, these episodes are becoming increasingly common.

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Data availability statement. An upscaled version of the GLAD Fire-related Forest Loss and Forest Extent datasets with $1/4^\circ \times 1/4^\circ$ latitude–longitude resolution is available at <https://doi.org/10.5281/zenodo.16930105>.

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