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The Increasing Incidence of Wildfires and Its Causes: An Overview

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Abstract:	This overview addresses the questions: is the incidence of wildfires in the boreal forests and in the forests of the western United States increasing and, if so, is it in response to human-induced global warming? We present a concise summary of the voluminous wildfire literature that addresses these questions, along with our own concise analysis based on a suite of datasets including satellite measurements of fire-related carbon emissions, aerosol optical depth and areal coverage of trees dating back to around the turn of the millennium, longer ground-based records of area burned in fires over the western US, the normalized difference vegetation index, lightning flash rate, the temperature, humidity, and soil moisture fields from a global reanalysis, and climate model simulations of the response to the buildup of greenhouse gases. Our analysis clearly reveals the dramatic increase in wildfires over the boreal and western US forests, roughly a factor of three increase in burned area since the year 2000, and the remarkable sensitivity of wildfires to measures of the aridity (i.e., vapor pressure deficit and soil moisture) on time scales ranging from days to decades. The observed warming trend during the period of our study is comparable in magnitude to that in climate model simulations of the response to rising CO2 concentrations and is therefore likely human induced. It appears less likely that global warming contributes to increased wildfire activity by way of an increase in lightning.
Author Comments:	Reviewers should be aware that the main purpose of this article is not to present new research results, but to give readers an overview of research findings that are widely dispersed in the literature concerning the scope and causes of a steep increase in wildfires.
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The Increasing Incidence of Wildfires and Its Causes: An Overview

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ABSTRACT

This overview addresses the questions: is the incidence of wildfires in the boreal forests and in the forests of the western United States increasing and, if so, is it in response to human-induced global warming? We present a concise summary of the voluminous wildfire literature that addresses these questions, along with our own concise analysis based on a suite of datasets including satellite measurements of fire-related carbon emissions, aerosol optical depth and areal coverage of trees dating back to around the turn of the millennium, longer ground-based records of area burned in fires over the western US, the normalized difference vegetation index, lightning flash rate, the temperature, humidity, and soil moisture fields from a global reanalysis, and climate model simulations of the response to the buildup of greenhouse gases. Our analysis clearly reveals the dramatic increase in wildfires over the boreal and western US forests, roughly a factor of three increase in burned area since the year 2000, and the remarkable sensitivity of wildfires to measures of the aridity (i.e., vapor pressure deficit and soil moisture) on time scales ranging from days to decades. The observed warming trend during the period of our study is comparable in magnitude to that in climate model simulations of the response to rising CO_2 concentrations and is therefore likely human induced. It appears less likely that global warming contributes to increased wildfire activity by way of an increase in lightning.

SIGNIFICANCE STATEMENT

Many stories in the news media portray a worsening wildfire crisis, fueled by human-induced global warming. While there’s widespread support for this view in the scientific community, there are some who argue that past forest management practices have precipitated the crisis, if indeed there is one. This overview documents the roughly three-fold increase in fire-related burned area and carbon emissions in the boreal forests and the western US forests over the past 25 years. It supports the view that the increase is mainly due to an increase in aridity in response to the rising temperatures.

CAPSULE

The incidence of wildfires in the boreal forests and the western US forests has roughly tripled over the past 25 years, mainly in response to human-induced global warming.

1. Introduction

Papers calling attention to an increasing incidence of wildfires have been appearing in the literature for at least 25 years: early examples include Kasischke et al. (1999) and Kasischke and Turetsky (2006). Now there are thousands of refereed papers about the impacts of wildfires upon forests, many of them documenting the burned area (BA) per year and investigating what is causing the fires (Bargali et al. 2024). In their comprehensive review article, Jones et al. (2022) cite over 700 of them. In this paper, we present a much more compact overview, focusing on wildfires in the boreal forests (here defined as the forested area north of 50°N) and in the forests of the western United States (US) to the west of the 103°W meridian. In the next section, we review evidence indicative of an increase in wildfires in these domains. In section 3, we summarize the evidence linking increases in wildfire activity to increasing aridity. In section 4, we consider the possible roles of increased lightning, carbon fertilization, and forest management practices in mediating wildfire activity. In the final section, we present a short summary and 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 graphics based on our own analysis.

2. Evidence of an increasing incidence of wildfires

Based on a compilation of records from multiple government agencies, Williams et al. (2019) showed that annual BA within the state of California increased roughly fivefold from 1972 to 2018.[1] Parks and Abatzoglou (2020) generalized this result to the western US, using a composite of 20th century ground-based data together with estimates based on satellite

[1] 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 the logarithm of 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.

imagery from 2000 onward. They estimated an eightfold increase in annual BA from 1985 to 2017.

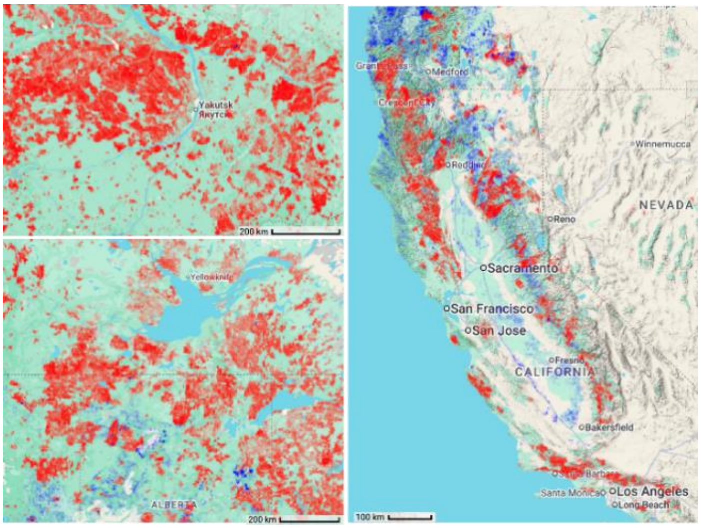

Fig. 1. Screenshots from the University of Maryland's Global Land Analysis and Discovery website https://glad.earthengine.app/view/global-forest-loss-due-to-fire. Pixels in which the forest burned at least once during the 23-year period from 2001 to 2023 are indicated in red. Blue pixels indicate forest losses due to non-fire causes. The top-left panel is centered near the city of Yakutsk, on the Lena River in central Siberia; the bottom-left panel near Yellowknife on the shore of Great Slave Lake in the Northwest Territories of western Canada; and the right panel covers California. The website is on a Google Earth platform, on which it is possible to zoom in much farther on areas of interest.

a. Forest loss inferred from Landsat imagery

During the past few years, the increasing incidence of damaging forest fires has been documented on a planetary scale. In an article introducing a newly available high resolution fire-related forest loss dataset based on Landsat imagery[2], Tyukavina et al. (2022) called attention to the extensive wildfires in the boreal forests, noting that in some areas, half or

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[2] The Global Land Analysis and Discovery (GLAD) fire-related forest loss dataset is based mainly on Landsat imagery. It uses the methodology described in Hansen et al. (2013), in which *forest loss* is defined as the removal of woody vegetation greater than 5 m in height. Each calendar year, ~30 m × 30 m pixels were classified using supervised classification and regression trees to determine whether the forest loss was due to fire-related or non-fire-related causes.

more of the forested areas burned at least once during the 20-year period of their study. Figure 1, based on their dataset, shows close-ups of the most heavily impacted areas in central Siberia, western Canada, and the western US.

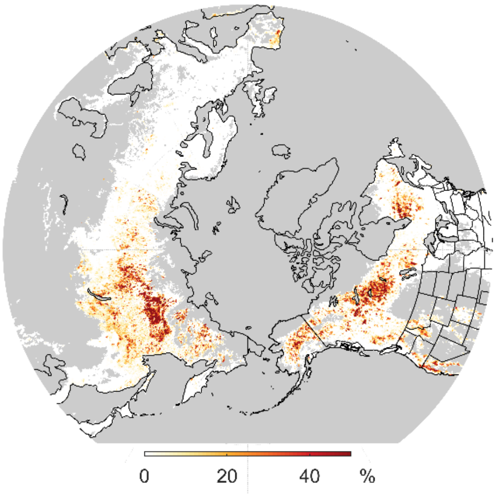

Fig. 2. Cumulative fractional BA based on an upscaled version of the GLAD dataset[3] during the interval 2001-2023 in percent.

Figure 2 shows the distribution of BA over the Northern Hemisphere extratropics, as defined in the Global Land Analysis and Discovery (GLAD) dataset. The most heavily impacted areas of the boreal forests stand out clearly. It should be borne in mind that *forest loss*, as defined in this panel, is not irreversible. Some of the more fire-resistant trees survive the fires and, within a few years, new vegetation becomes established in the burn scars. BA should thus be interpreted, not as a permanent loss of forests, but as an indicator of the recurrence time of fires. For example, a doubling of BA per year implies a halving of the recurrence time of fires.

To place the pattern of BA in context, the left panel of Fig. 3 shows the forest coverage that existed in the year 2000 and the right panel shows the same field minus the BA during

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[3] The GLAD forest loss to fire database, provided at roughly 30 m × 30 m resolution, is upscaled to a 2.5° × 2.5° latitude / longitude grid, resulting in a data compression of about 10^6.

the intervening years up to and including 2023.[4] (The differences between the left and right panels are more clearly revealed in the two-frame animation Fig. S3.) It is evident that the forested area has shrunk noticeably during this period, and some of the areas that remain have become riddled with burn scars.

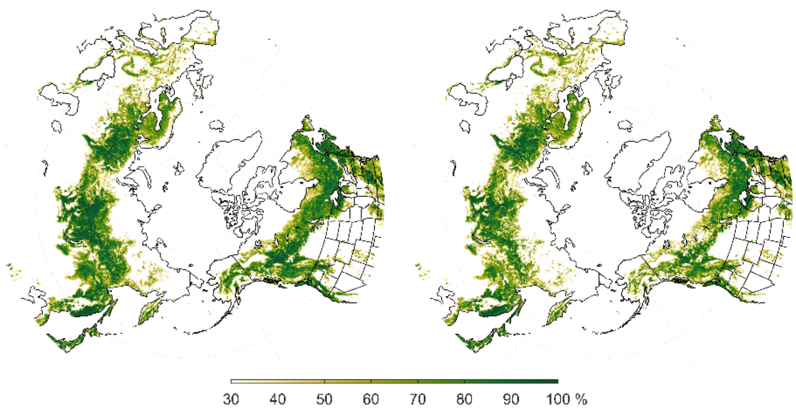

Fig. 3. (*Left*) percentage forest cover at the end of the year 2000 based on the GLAD forest extent dataset; (*right*) the field in the left panel minus the percentage of area that burned at least once during the interval 2001-2023 based on the GLAD fire-related forest loss dataset. Both panels are shown at 0.25° × 0.25° latitude-longitude resolution.

The right panel of Fig. 4 shows 2001-2022 trends in the normalized difference vegetation index (NDVI[5]), a crude indicator of gross primary productivity (GPP), which are seen to be negative in the regions heavily impacted by fires during this period. (For a more exacting comparison between BA and the NDVI trend, see the 2-frame animation in Fig. S4A.) The NDVI trends during the earlier period 1982-2001, shown in the left panel of Fig. 4 were generally more positive, but there are patches with smaller increases or small decreases that

[4] In this study, forests are defined using the original 30 m tree-cover dataset from Hansen et al. (2013), where ~30 m × 30 m pixels with greater than or equal to 30% tree cover are considered forested. Both the forest extent and the fire-related forest loss pixels are aggregated to 0.25° × 0.25° latitude-longitude grid cells. BA in the GLAD dataset is with reference to the forest area that existed in the year 2000. It is an underestimate of the actual BA, because with this definition a given area of forest can burn only once.

[5] The NDVI is derived from the Advanced Very High-Resolution Radiometer (AVHRR) sensors and provided bi-monthly on a 0.083° × 0.083° latitude-longitude grid (Pinzon et al. 2023).

are more or less coincident with the regions of fires and declining GPP in the later period. Hence, it appears that the areas that experience the highest incidence of wildfires haven't changed, but the fires have become more pervasive. A more refined index of GPP based on the NDVI, in combination with other indices derived from satellite imagery, also exhibits a relative decline of GPP in regions heavily impacted by wildfires (Fig. 2 of Berner and Goetz 2022).

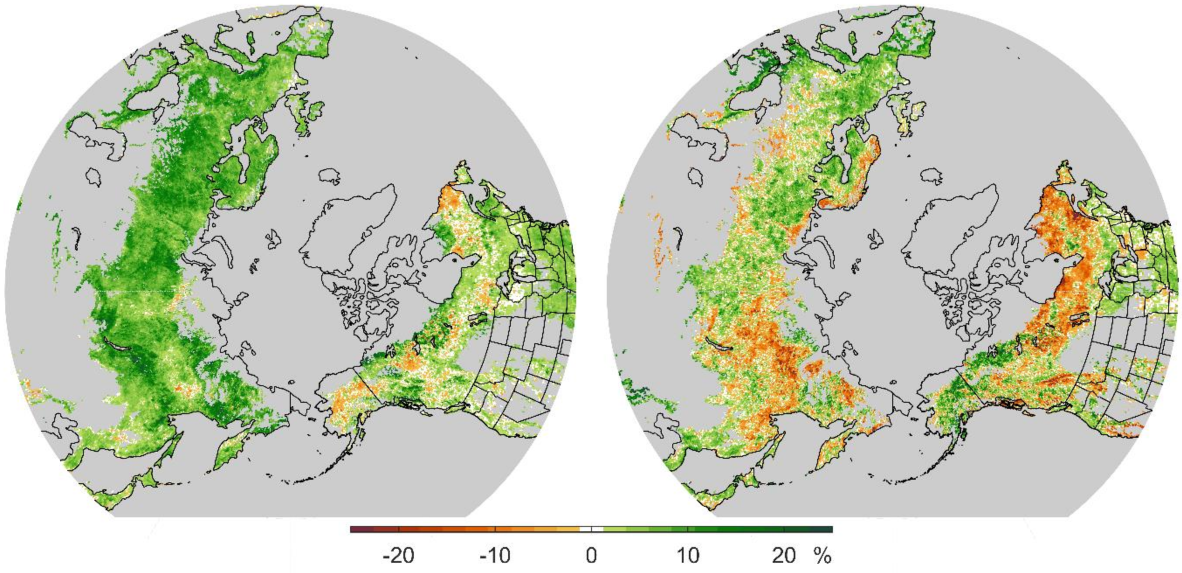

Fig. 4. NDVI trends per decade during the fire season (May-September) expressed as percent changes from the climatology (1982-2022). (*Left*) 1982-2001; (*right*) 2001-2022.

Using the GLAD dataset, MacCarthy et al. (2024) estimated that roughly 70% of the globally integrated forest area that has burned at least once since 2001 is in the boreal forests, and that the annual BA rose steeply from 2001 to 2024. Figure 5 from Potapov et al. (2025) shows BA partitioned into the contributions from various domains. It illustrates both the prominence of the trends and the large contribution of the trends in the boreal forests to the trends in global annual BA.

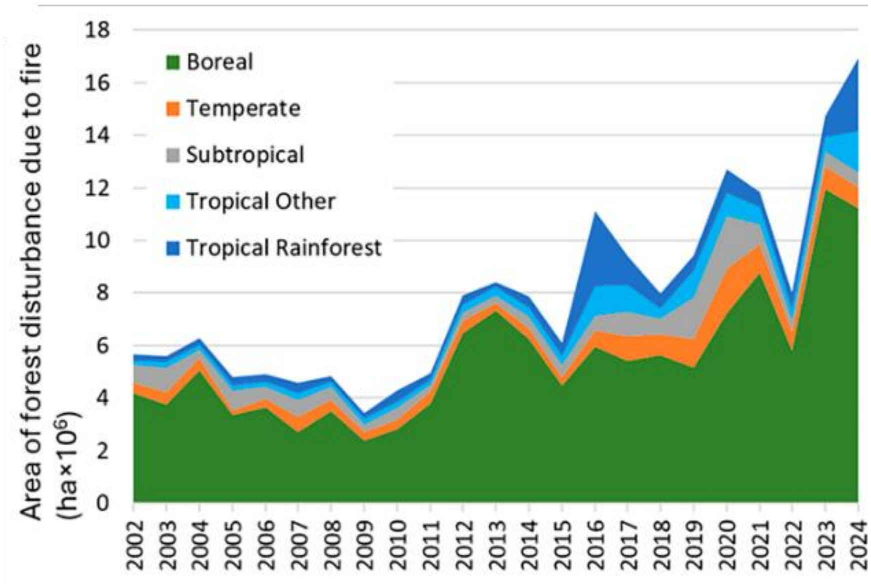

Fig. 5. Annual BA since the year 2001 in millions of hectares per year in various domains as indicated, based on the GLAD dataset, reprinted from Potapov et al. (2025).

The boreal forests and western US forests are not the only ones that experience wildfires. The cumulative BA in the forests of southern Australia (Fig. S1) is roughly comparable to that in the western US. The GLAD dataset also shows small patches of forest loss due to wildfires over Portugal, Galicia, Greece, Italy, Chile, and the tropical rainforests.[6] Forests elsewhere in the world have largely been spared thus far.

b. Burned area inferred from both Landsat and MODIS imagery

Other informative wildfire metrics are fire-related carbon emissions (CE) and aerosol optical depth (AOD) derived from MODIS imagery[7], for which there exist global gridded

[6] The World Resources Institute provides a detailed documentation of the fire-related losses of the tropical forests, broken down by region (https://gfr.wri.org/latest-analysis-deforestation-trends).

[7] The NASA Global Fire Emissions Database (GFED) v4 contains a fire-related carbon emissions (CE) dataset based on Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. It consists of monthly fields on a latitude-longitude grid with 1/4° × 1/4° resolution from 2001 onward. Monthly fields

datasets with monthly time resolution dating back roughly to the turn of the millennium. Annual mean CE is dominated by the CE during the months of May through September, when the forests experience the greatest aridity and the highest frequency of lightning, the primary cause of forest fires. To set the stage for diagnosing causality in the following section, we will focus on the fires that occur during this “fire season”, as we will refer to it.

Figure 6 contrasts wildfire metrics for the first and second halves of the observational record. In most areas, annual BA (top row) and CE during the fire season (middle row) exhibit very similar spatial patterns, with a marked increase from the first to the second half of the record. AOD averaged over the fire season (bottom panels) exhibits marked increases over Siberia, Canada, and the northern US from the first to the second half of the record.

The increasing incidence of wildfires over the past few decades is evident in the time series shown in Fig. 7. Over the boreal forests, annual BA and fire season CE have both been increasing more or less exponentially with time. The logarithmically fitted trend lines in CE are indicative of roughly 3-fold increases in the past 25 years. A 3-fold increase in BA implies that the recurrence interval of wildfires at a fixed location is now only about 1/3 as long as it was in 2000. Also included in Fig. 7 is an extended version of the BA time series that appears in Abatzoglou et al. (2021), a hybrid of ground-based Monitoring Trends in Burn Severity (MTBS) dataset and MODIS imagery. Burned area, as represented by this time series (denoted as BA* in the diagrams), exhibits an eightfold increase over the past 40 years, consistent with the value reported by Parks and Abatzoglou (2020).

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derived from other satellite sensors are available dating back to and including 1997. Data for aerosol optical depth is based on MODIS Terra imagery at 1° × 1° resolution, which includes the effects of both anthropogenic and natural aerosol emissions such as those from wildfires.

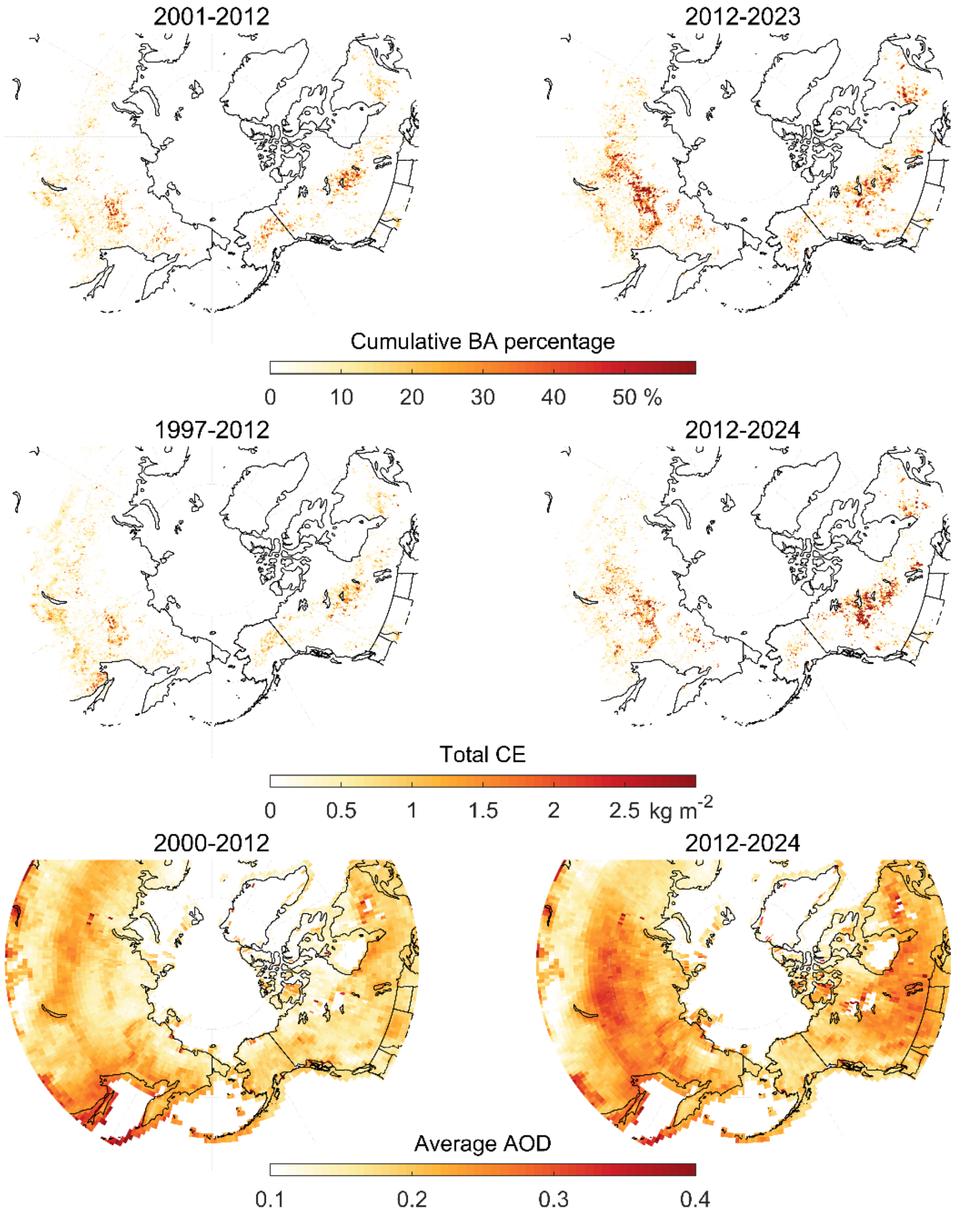

Fig. 6. Wildfire impacts during the first (*left*) and second (*right*) halves of the study period. Top row: BA, defined here as the total area that has burned at least once during the 12-year interval, expressed as a percentage, based on the GLAD forest loss dataset. Middle row: the total CE during the first and second halves of the study period, per unit area in kg m^{-2} at $0.25° \times 0.25°$ resolution. Both BA and CE are based on grid points with more than 10% forest cover. Bottom row: AOD averaged over the first and second halves of the study period. The distributions of CE and AOD are for the fire season (May-September). For ease of comparison, these figures are also shown as two frame animations in the supplementary materials.

Based on their analysis of “hotspots” in 1 × 1 km MODIS imagery, which are considered to be representative of large fires, Cunningham et al. (2024) produced a suite of time series documenting wildfire activity on a regional basis, covering the interval, 2003-2023. 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.

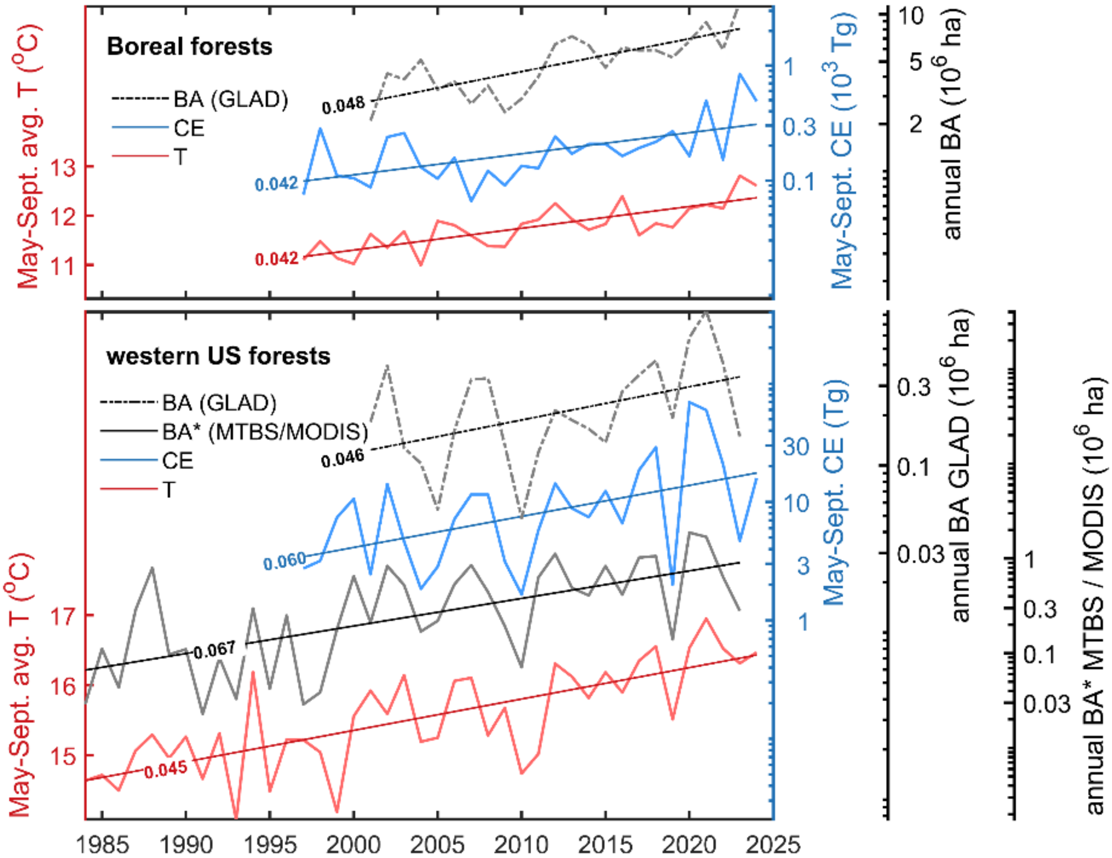

Fig. 7. Time series of fire-related variables over the boreal forests (*top*) and western US forests (*bottom*) based on grid points with more than 10% forest cover: CE integrated over the fire season (May–September), annual BA based on the GLAD forest loss dataset and BA* based on MTBS and MODIS datasets that appears in Abatzoglou et al. (2021), and fire-season-averaged surface air temperature (*T*).[8] All the time series are plotted on a logarithmic scale, except for *T*, which is plotted on a linear scale. The straight lines represent the least squares best fit trends, labeled in units of % per year for CE and BA, and K per year for *T*. The curves are scaled in proportion to their standard deviations.

[8] Based on data from the fifth generation of a global climate reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ERA5).

3. Role of aridity in mediating wildfires

Dating back to the earliest papers on the increasing incidence of wildfires, many authors have argued that the incidence of fires is increasing in response to a trend toward increased aridity. Some of these papers present evidence based on a suite of climatic variables, including temperature (T), relative humidity (RH), antecedent rainfall, and soil moisture (SM). Seager et al. (2015) showed that much of this multivariate information on the environmental conditions experienced by the trees is encapsulated in a single variable: the vapor pressure deficit (VPD)

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

where e_s is the saturation pressure. VPD is described by the authors as “an accurate metric of the ability of the atmosphere to extract moisture from the land surface”. Based on data over the southwestern US, they showed that BA and VPD are strongly correlated on a year-by-year basis. Juang et al. (2022) showed that VPD exerts a strong influence not only upon BA, but also on the number of fires, fire size and fire duration. In their studies of wildfires over the western US, Williams et al. (2019) and Parks and Abatzoglou (2020) attributed the increasing incidence of wildfires to increasing VPD.

At individual grid points, CE much higher on days when VPD is above normal than on days when it’s below normal as shown in the two-frame animation, Fig. S4B. Averaged over the Northern Hemisphere poleward of 30°N, the ratio is about a factor of 10. The frequency distributions shown in Fig. 8 further illustrate the strong VPD dependence of CE on the day-to-day time scale. In both domains, the peaks of the CE distributions (dotted curves) are shifted toward above normal VPD. For the boreal forests, the peak CE occurs at a value more than one standard deviation of the daily mean VPD (~3 hPa) above the mean. About 1/3 of the emissions occur on the days on which VPD is greater than two standard deviations above the mean. That’s a disproportionate share, but it’s notable that most of the fires occur under conditions that would not be classified as extreme events as defined in terms of a VPD anomaly metric.

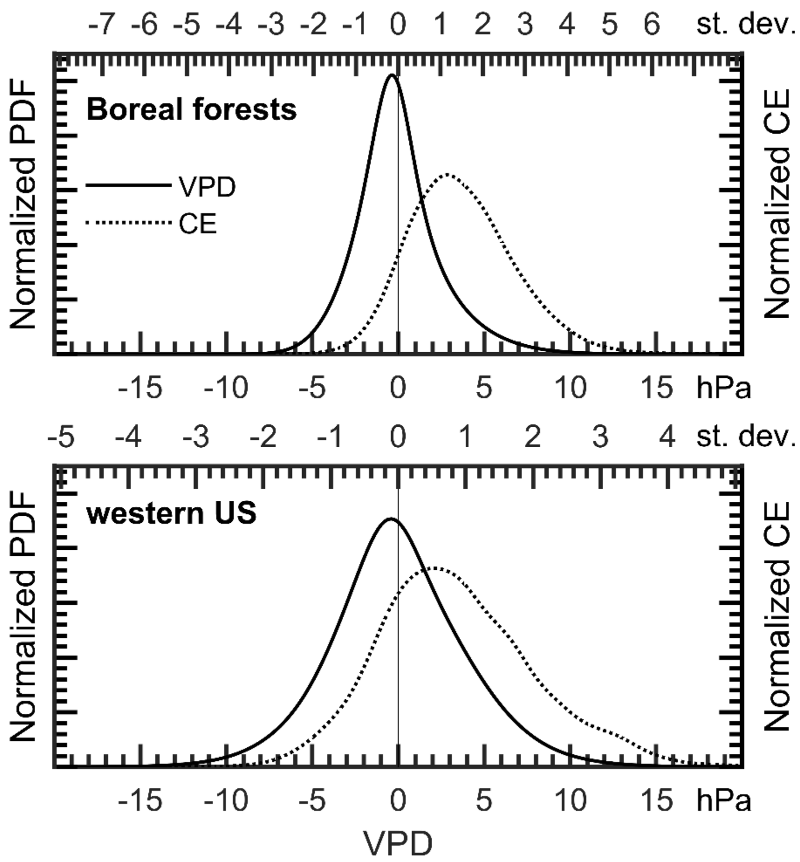

Fig. 8. Normalized PDF of VPD anomalies (solid curve) and the normalized histogram of daily integrated CE summed over days within each VPD anomaly bin (dotted curve) over the boreal and western US forests, as indicated. The scales at the top of the frames indicate standardized VPD anomalies and the scales at the bottom are in dimensional units.

To illustrate how wildfires are mediated by aridity on annual and longer time scales. Table 1 provides a summary of the year-to-year correlations between the fire metrics log BA and log CE, and three aridity metrics: *T*, VPD, and SM. All the correlations shown in the table are statistically significant at the 95% level and above. Because all the time series exhibit trends (downward for SM and upward for all the other variables), the correlations between the raw time series are stronger than those between the detrended series. Owing to the remarkable strength of the correlation between SM and VPD, these two variables exhibit very similar correlations with the fire metrics—both are stronger than the correlations for *T*. The strongest correlations are those involving the extended BA* time series for the western

US forests, shown in Fig. 9, superimposed upon VPD (*top*)[9] and SM (*bottom*) averaged over the fire season. The relationships are seen to be even stronger than those between *T* and BA* shown in the bottom panel of Fig. 7.

Table 1. Correlation matrices based on raw and detrended time series as indicated, domain averaged over the boreal and western US forests. Annual values for BA and values of the other variables are integrated or averaged over the fire season (May-September).

Boreal forests — *raw*

	log BA	log CE	*T*	VPD	SM
log BA (2001-2023)	1.00	0.81	0.63	0.72	-0.72
log CE (1997-2024)		1.00	0.65	0.73	-0.78
T (1984-2024)			1.00	0.93	-0.76
VPD (1984-2024)				1.00	-0.91
SM (1984-2024)					1.00

Boreal forests — *detrended*

	log BA	log CE	*T*	VPD	SM
log BA	1.00	0.75	0.37	0.42	-0.51
log CE		1.00	0.43	0.52	-0.57
T			1.00	0.75	-0.36
VPD				1.00	-0.77
SM					1.00

Western US forests — *raw*

	log BA	log CE	log BA*	*T*	VPD	SM
log BA (2001-2023)	1.00	0.85	0.77	0.71	0.80	-0.75
log CE (1997-2024)		1.00	0.83	0.67	0.72	-0.66
log BA* (1984-2023)			1.00	0.79	0.88	-0.88
T (1984-2024)				1.00	0.92	-0.84
VPD (1984-2024)					1.00	-0.96
SM (1984-2024)						1.00

Western US forests — *detrended*

	log BA	log CE	log BA*	*T*	VPD	SM
log BA	1.00	0.84	0.76	0.53	0.72	-0.70
log CE		1.00	0.82	0.39	0.49	-0.39
log BA*			1.00	0.52	0.69	-0.64
T				1.00	0.82	-0.70
VPD					1.00	-0.94
SM						1.00

[9] Lest the reader be concerned that the trends in VPD and SM might be unreliable because of possible RH biases in the ERA5 reanalysis, it is shown in Fig. S9 that the VPD time series in the top panel of Fig. 9 is barely changed if trends in RH are neglected in calculating it.

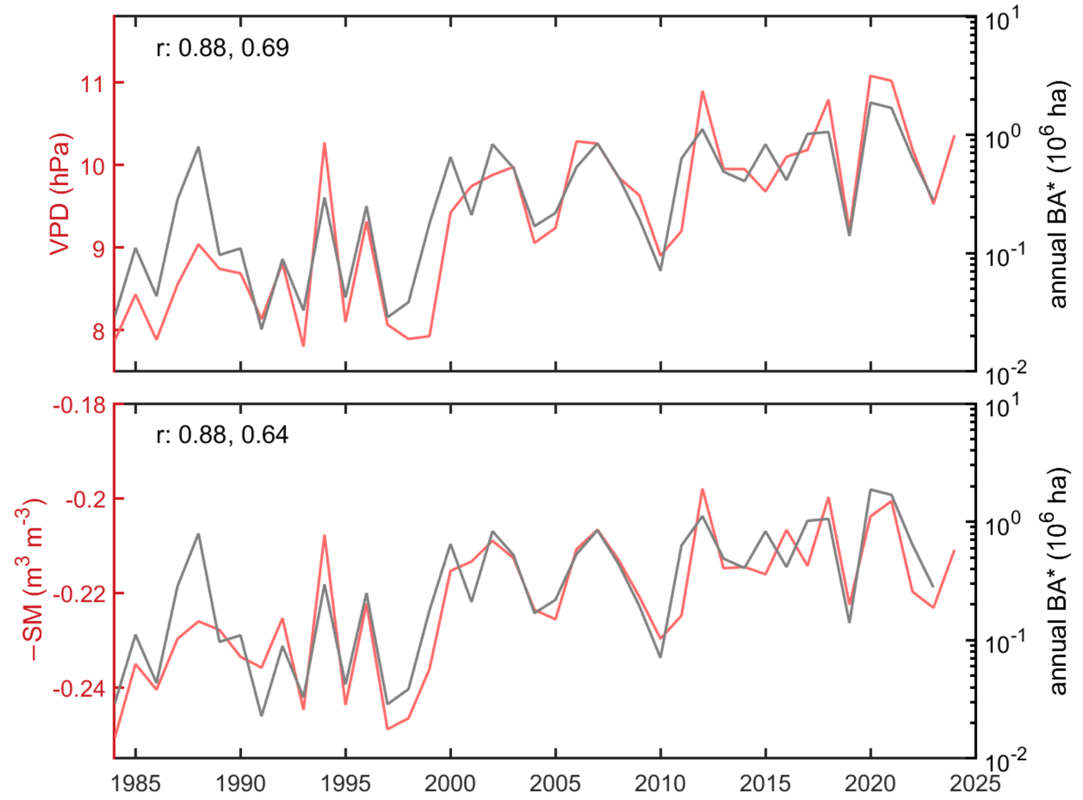

Fig. 9. Time series of the log of annual BA* over the western US shown together with metrics of aridity averaged over the fire season (May-September). (*Top*) vapor pressure deficit (VPD); (*bottom*) soil moisture (SM) with polarity reversed. Correlations for the raw and detrended time series are indicated at the upper left of each panel.

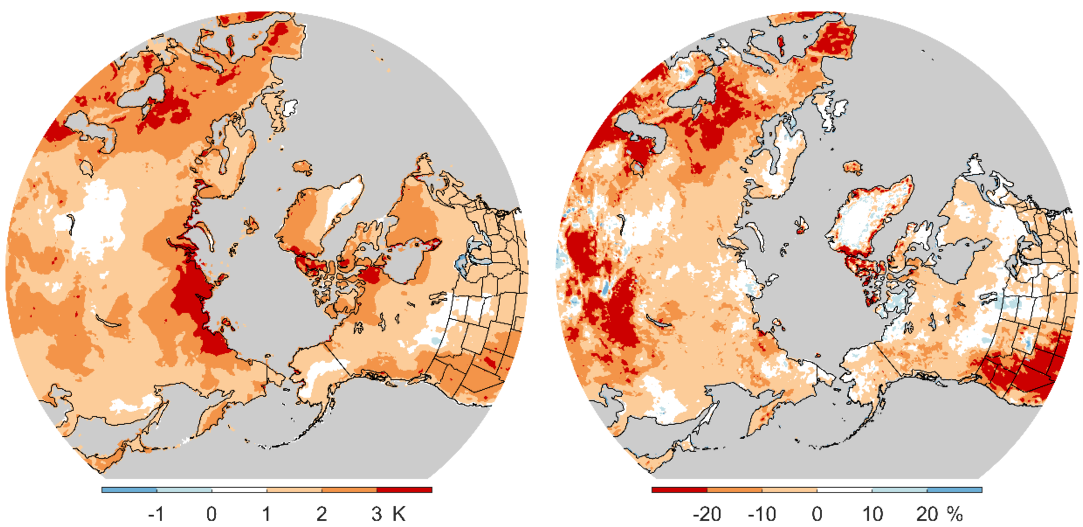

Fig. 10. Fire-season (May-September) trends per 50 years over the interval 1974-2024 based on ERA5 reanalysis: (*Left*) surface air temperature in K; (*right*) soil moisture in percent change per 50 years.

Figure 10 shows the spatial patterns of the trends in *T* and SM over the extratropical Northern Hemisphere from 1974 to 2024 during the fire season. In temperate latitudes, there is a strong correspondence between warming and drying. The trend toward a warmer and drier climate is particularly strong over the western US.

The pervasive trend toward increasing aridity is driven by global warming. Domain-averaged *T* trends are shown in Table 2. Averaged over the boreal and western US forests, the observed *T* rises during this period estimated on the basis of these 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 intensive 25-year study period 2000 to 2024, the *T* rises were roughly half that large as during the 50-year interval, i.e., on the order of 1 K.

Table 2. 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 K per 50 years for 1974–2024 and K per 24 years for 2000–2024. The domain averages are based on grid points with at least 10% forest cover in the GLAD forest extent dataset. The bottom row shows the trends in the multi-model mean of the climate model intercomparison project (CMIP6) simulations, under the historical forcing before 2015 and the SSP2-4.5 “middle of the road” scenario starting in 2015.

	1974-2024		2000-2024	
	Boreal forests	western US	Boreal forests	western US
ERA5	1.84	2.09	1.09	1.03
Berkeley Earth	1.66	1.62	0.87	0.71
GISS	1.71	1.69	0.88	0.84
NOAA	1.77	1.54	0.96	0.72
Hadley	1.61	1.45	0.86	0.98
SSP2-4.5	2.18	2.10	1.01	1.13

The bottom row of Table 2 shows the trends in the multi-model mean of the CMIP6 simulations.[10] The simulated trends are similar to those in ERA5. Hence, the observed warming is consistent with the hypothesis that it is the forced response to the buildup of greenhouse gases (possibly offset to some degree by cooling due to increasing anthropogenic aerosols). Trends in the individual model simulations are shown in Table S2.

The studies of Williams and Abatzoglou (2016), Zhuang et al. (2021), and Turco et al. (2023) provide quantitative estimates of the fraction of the observed increase in the incidence of wildfires that is attributable to rising atmospheric CO_2 concentrations. In the first, the environmental controls on fires are represented by an index of fuel aridity (F), the average of eight simpler indices that include VPD and measures of soil moisture and surface evapotranspiration. F is even more highly correlated with BA than with VPD or SM. The anthropogenically induced increase in F is inferred from climate model simulations with and without anthropogenic forcing. The second study is based on observations alone, with environmental conditions represented by VPD. In the third, fields derived from climate models are used to drive a statistical model that relates daily maximum near surface air temperature to BA. Results of all three studies indicate that most, if not all of the observed increase in the incidence of wildfires is attributable to human induced global warming. That temperature and the fire metrics are strongly correlated and their trends as represented in Fig. 7 are nearly equivalent supports this conclusion.

4. Other possible drivers of the increasing incidence of wildfires

The burning of fossil fuels could conceivably impact wildfires by way of mechanisms other than by inducing increased aridity. Lightning is known to be responsible for igniting most of the wildfires in the boreal forests (e.g., see Janssen et al. 2023). Based on an analysis

[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 no difference which of the emissions scenarios is used.

of the relationships between lightning and wildfires in Alaska and the Canadian Northwest Territories, Veraverbeke et al. (2017) concluded that lightning is a major driver of large fires in the boreal forests on both interannual and climatic time scales. Their analysis was indirect in the sense that it related observed lightning flash rate to a modelled flash rate; the modelled flash rate to the number of observed ignitions, and the number of observed ignitions to the observed burned area. Here we consider the relationship between the occurrence of lightning and CE without reference to intermediate variables, making use of data from the World Wide Lightning Location Network (WWLLN), which preferentially detects powerful cloud-to-ground strokes (Abarca et al. 2010).

To show that locally, on a day-to-day basis, fires occur much more frequently on days with lightning than on average, we construct a contingency table for days with fires (CE > 0) and without fires (CE = 0), and days with and without lightning in individual 0.25° × 0.25° latitude-longitude grid boxes for all the May-September days in the 12-year lightning record. L is the fraction of days with lightning, F is the fraction of days with fires, and LF is the fraction of days with both lightning and fires. If lightning and fire were independent of one another, the expected value of LF would be L × F. The left panel of Fig. 11 shows the ratio of the observed LF to the expected value (L × F). It is evident that at many grid points in the boreal forests, fires occurred on a substantially higher fraction of the days with lightning than on randomly selected days.

For the area burned by wildfires to increase in response to global warming by way of increased lightning, two conditions must be met: (*i*) the incidence of lightning must increase with *T* and (*ii*) BA must increase as the incidence of lightning increases. There are indications that the incidence of lightning may be increasing over the boreal forests, but decreasing over the western US forests.[11] The requisite data for investigating whether BA increases with the incidence of lightning on climatic time scales are not available, but we can get some insight

[11] Holzworth et al. (2021) found that lightning flash rate in that domain poleward of 55°N increased substantially, relative to global lightning, in the decade of the 2010s. The trend from 2020 to 2024 has been downward (Holzworth, personal communication). Koshak et al. (2015), Lavigne et al. (2019), and Burrows et al. (2025) have all reported declining lightning flash rates over parts of the western US.

as to how it might behave by examining the relationship between domain-averaged lightning and CE in the month-to month-variability, using lightning days (LD) at individual 0.25° × 0.25° points in the WWLLN dataset and CE based on the GFEDv4 dataset. Mindful of the large uncertainty in the LD trends in this short record, we have detrended the time series of LD and CE for each of the five calendar months of the fire season. We find that in both domains, LD is negatively correlated with CE (r = -0.35 for the boreal forests and -0.25 for the western US forests). The correlations are negative, rather than positive, because increasing aridity tends to enhance CE and suppress LD. Hence, it's not meaningful to diagnose the relationship between lightning and fires without consideration of their mutual dependence on aridity.

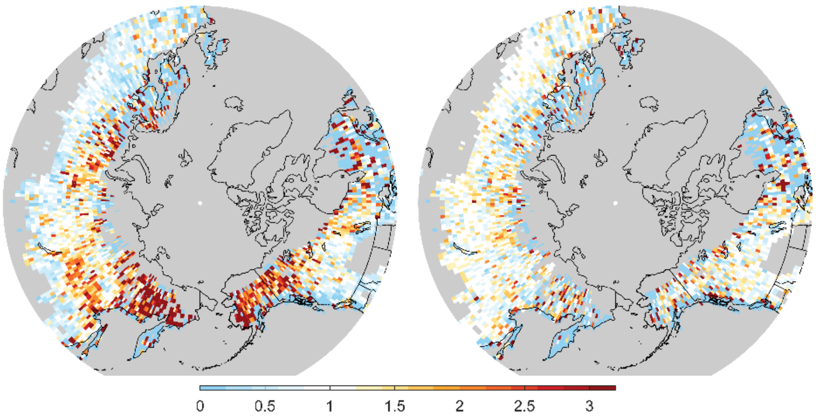

Fig. 11. (*Left*) The geographical distribution of the ratio of LF, the days with both lightning and fires, to L × F, the expected value, aggregated for 1° × 1° latitude-longitude grid boxes: May-September days, 2013-2022. (*Right*) The same distribution, except that the order of the days is shuffled for lightning.

It is conceivable that carbon fertilization could also be contributing to the increasing incidence of wildfires. Increased photosynthesis results in increased growth of leaves and needles, which ultimately senesce and become fuel. The absence of substantial interannual variability in the CO_2 time series precludes the possibility of inferring the sensitivity of BA to CO_2 concentration on the basis of statistical evidence.

Forest management practices also play a role in mediating wildfire activity over the western US. Figure 12 shows a record of tree ring burn scars, a measure of the prevalence of forest fires. In the early part of the record, the curve is relatively flat, apart from slight upward trend. In the 1880s, the curve begins to drop and it reaches a minimum about 100 years later. It has risen slightly since then, but remains far below pre-1880 levels. Marlon et al. (2012) hypothesized that prior 1880 variations in wildfire activity were mainly climate driven and that the slight upward trend in the burn scar record is attributable to the weak warming trend that has prevailed since the peak of the Little Ice Age. Beginning in 1880, the presence of a growing number of European settlers began to change the balance. Extensive grazing of cattle and the fragmentation of the forest landscape by railroad lines and towns resulted in a reduction in the BA. Further reductions from the 1940s onward resulted from the implementation of increasingly effective fire suppression practices. Human-induced warming 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 in which a much higher percentage of sites recorded fire than in any of the years in the recent historical record, consistent with Fig. 12. The reduction in the average annual burned area due to fire suppression has enabled the forests to expand and become lusher, as indicated by the declining spacing of the trees in Fig. 12. In this sense, the history of wildfire suppression is widely believed to be contributing to today's heightened level of wildfire activity over the western US, acting as an amplifier, rendering fires more intense than they would have been in the absence of fire suppression. However, the change in fuel density due to management practices cannot account for the remarkable upward trend in western US wildfires, which didn't begin until around 1980.

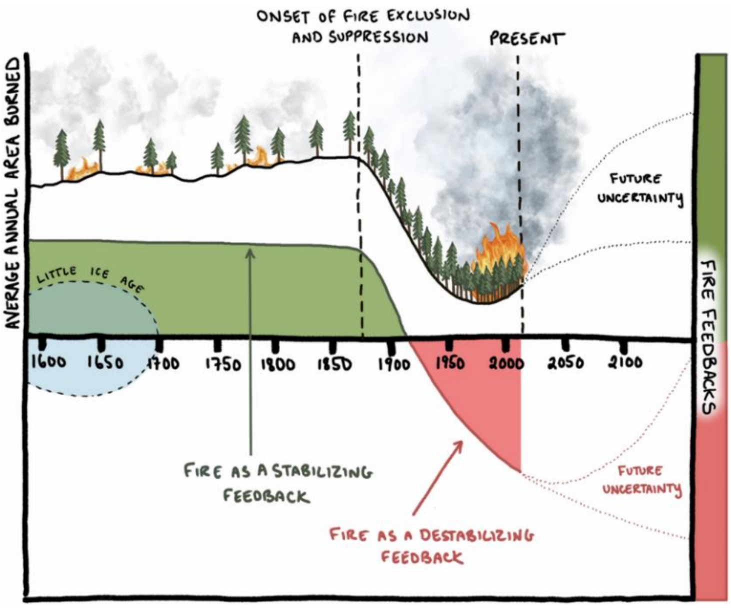

Fig. 12. Schematic illustrating the role of fire suppression during the 20th century in rendering today's forest fires in the western US more intense. The curve at the top is the density of burn

scars in the tree ring record. “Stabilizing feedbacks” refers to the tendency for fires to maintain the forests as they are, while “destabilizing feedbacks” connotes acting as a catalyst for ecological transformation or vegetation type conversion. From Parks et al. (2025), graphic courtesy of Jessie Thoreson, reproduced with permission of ..….

In contrast to the tree ring burn scar records at sites over the western US, Parks et al. (2025) found that the fires at sites in the boreal forests in the Canadian Northwest Territories from 1984 onward are unprecedented in the historical record. The absence of a fire deficit in the boreal forests may be a reflection of the fact that human settlements are sparser and fire suppression efforts are more thinly spread there than in the western US forests and are consequently not as effective.

5. Concluding remarks

The three-fold increase in the burned area in the GLAD forest loss dataset since the turn of the millennium is indicative of a factor of three decrease in the recurrence time of fires, resulting in a reduced average age of the trees and a shift toward higher proportions of the more fire-resistant and faster growing species, possibly including a shift from coniferous to deciduous trees and/or a shift from forests to shrubs and grasses (Baltzer et al. 2021; Johnstone et al. 2016). A reduction in the recurrence interval also has important implications for the cycling of carbon in the terrestrial biosphere (Mack et al. 2021; Pellegrini et al. 2018; Wang et al. 2021). With the large increase in fire-related carbon emissions, the pervasiveness of wildfire smoke has emerged as an important environmental issue in its own right.

Given that the increasing incidence of wildfires is mainly driven by the trend toward increased aridity induced by global warming, the incidence of wildfires is likely to continue to increase unless greenhouse gas concentrations are brought under control.

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Data Availability Statement.

An upscaled version of the GLAD forest extent in the year 2000 and fire-related forest loss datasets with 1/4° × 1/4° latitude-longitude resolution is available at https://doi.org/10.5281/zenodo.16930105.

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Fig. S3

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Fig. S4A

Fig. S4B

Fig. S6