Global rise in forest fire emissions linked to climate change in the extratropics

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Abstract:

Climate change increases fire-favorable weather in forests, but fire trends are also affected by multiple other controlling factors that are difficult to untangle. Here, we use machine learning to systematically group forest ecoregions into twelve global forest pyromes, with each showing distinct sensitivities to climatic, human, and vegetation controls. This delineation revealed that rapidly increasing forest fire emissions in extratropical pyromes, linked to climate change, offset declining emissions in tropical pyromes during 2001-2023. Annual emissions tripled in one extratropical pyrome due to increases in fire-favorable weather, compounded by increased forest cover and productivity. This contributed to a 60% increase in forest fire carbon emissions from forest ecoregions globally. Our results highlight the increasing vulnerability of forests and their carbon stocks to fire disturbance under climate change.

One-Sentence Summary: Extratropical forest fire emissions are increasing as climate change promotes fire-favorable weather and greening.

Fire is a natural ecosystem disturbance that has shaped the global distribution of Earth's forests and controlled carbon (C) storage in vegetation and soils over geological time (*1–3*).

Nonetheless, anthropogenic climate change has contributed to an increase in fire-favorable weather conditions globally (*4–7*) and these enhanced risks have translated into increased burned area (BA) and fire C emissions in some forested regions during the past two decades or longer (*6–12*). Expanding land use or historic fire management policies have variably interacted with the effects of climate change to amplify forest fire activity and emissions (*13*, *14*). The increases in forest fire C emissions observed regionally contrasts with declines in the global savannahs (*8*, *15*).

A series of highly anomalous episodes of extreme forest fire C emissions have recently punctuated longer-term trends (*11*, *16–19*). During the 2019-2020 bushfire season in Australia, the area burned by fires was over double the previous record since 1930, and fire C emissions were also greater than in any other year since 2003 (*9*, *17*). In 2021, a new record was set for pan-boreal fire C emissions amidst a water deficit spanning both Eurasia and North America (*16*). In the 2023 fire season, fire C emissions from Canadian boreal forests were over nine times the 2001-2022 average (*19*).

The increased occurrence of fire, and particularly extreme fires, threatens the functioning and resilience of some forests as well as their ecosystem services, including C storage (*13*, *20*, *21*). The recovery of C stocks in vegetation and organic soils following forest fires can take decades to centuries, and so increases in annual fire C emissions and extreme emissions events lead to a lasting deficit of terrestrial C storage (*8*, *22–24*). Increased fire C emissions can thus reduce the capacity of global forests to absorb C from the atmosphere, posing a challenge for achieving climate targets. For example, increased fire activity in boreal North America alone is projected to result in net C losses equivalent to 0.3-3% of the remaining C budget necessary to limit global warming to 1.5°C (*25*).

Beyond their effects on C storage, extreme wildfires also cause major disruption or irreversible loss to society, including deaths, evacuations, reduced air quality, pressures on healthcare systems, and economic losses (*26–30*). Further, major declines in biodiversity have also been recorded in the wake of several extreme fire events and many of Earth's most threatened species are afflicted by an altered fire regime (*1*, *20*). Recent extreme wildfire seasons across the globe have demonstrated the power of the most extreme wildfires to affect both the environment and society.

One of the drivers of change in forest fire potential is anthropogenic climate change, which is causing more frequent and extreme periods of drought and fire-favorable weather, often referred to as fire weather (*4*, *6*, *31*). Increased hot and dry conditions create periods of low fuel moisture, promoting wildfire potential in ecosystems where ample stocks of fuels (vegetation biomass and organic soils) are available, notably in forests (*4*, *10*, *31*). Increased lightning frequency under climate change has also exacerbated the ignition of forest fires in some locations, particularly in ignition-limited forests of the high latitudes (*32–34*). Increased atmospheric instability has been linked to more erratic and extreme wildfire behavior that enhances fire spread and intensity and challenges the potential for firefighters to suppress fire (*35*, *36*). Several attribution studies have shown that climate change raised the likelihood of extreme fire weather conditions during a range of recent extreme wildfire seasons (*5*, *37*, *38*).

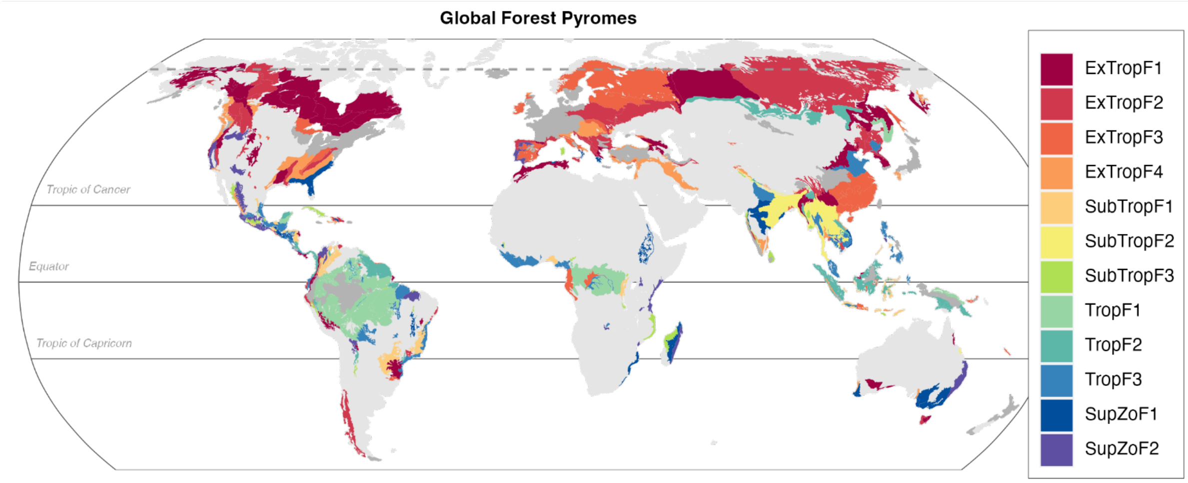
Alongside climatic factors, forest fire extent is controlled by various *in situ* human activities and by the ecological traits and productivity of vegetation (*6*, *39–42*). People influence patterns of forest fire in numerous ways, such as by using fire for forest clearing and land use (*43*), causing unwanted ignitions (accidental or arson) (*44*), suppressing wildfires via firefighting (*45*), managing stocks of fuel on the landscape (*46*, *47*), increasing forest edge length through fragmentation (*48*, *49*), or inadvertently amplifying fuel stocks by excluding fire from forests where it is a central element of a functioning ecosystem (*14*, *50*). The composition of forest ecosystems with species that have developed fire-adapted evolutionary traits, such as canopy structure, self-pruning, and leaf waxiness, also influence fire dynamics (e.g. crowning potential) and rates of spread (*51*, *52*). In addition, the productivity of vegetation during the growing season influences fuel availability during subsequent dry seasons (*40*, *53*, *54*).

While climatic, human, and vegetation factors all affect patterns of fire in forests, the prominence of each control varies regionally (*6*, *40*, *55*, *56*). The relationships between climate and fire are generally modulated by non-climatic factors, and likewise non-climatic drivers of fire often depend on the episodes of fire-favorable weather. Hence, it has proven remarkably challenging to identify the forest regions where fires are most sensitive to climate change or other facets of environmental change (*39*, *55*, *56*). To identify the world regions where responses to future climate change or other environmental stressors are comparatively strong or weak, further study of the temporal and spatial relationships between fire and a comprehensive set of fire controls is required.

Here, we used the *k*-means clustering algorithm to group 414 forest ecoregions of the World (*57*) into twelve forest *pyromes* (**Fig. 1**), within which forest burned area (BA) (*58*) shares a common set of relationships with climatic, vegetation, and human controls (Fig. 2, Fig. S1-S2; see **Methods**). Having isolated the pyromes with a distinctive strong sensitivity to climatic controls, we analysed trends in annual forest BA (*58*) and fire C emissions (*59*) during the period 2001-2023 and evaluated their connection with trends in key climate variables.

We used a comprehensive set of fire controls to distinguish the pyromes. The climatic controls included fire weather (*4*, *60*, *61*), soil moisture (*62*), atmospheric instability (represented by the continuous Haines index) (*35*, *36*), and lightning frequency (*34*, *63*). The vegetation controls included potential fuel stocks related to land cover (*52*), vegetation productivity during the growing season (represented by the normalized difference vegetation index) (*64*, *65*), and forest continuity (represented by forest area density) (*49*). The human controls included population density (*15*, *66*), cropland and pasture cover (*15*, *67*, *68*), and road density (*69*). Terrain roughness (*70*) is also included for its potential to affect fire behavior (*71*). These variables have each shown power to explain spatial or temporal variability in BA in at least some world regions (see **Methods**).

The concept of the pyrome was first introduced by Archibald et al. (*72*) as a pyrogeographical counterpart to the biogeographical concept of the biome. Biomes are defined not only by their observable biological characteristics but also by the climatic and other environmental controls that cause particular biological characteristics to arise. In past work, pyromes have been characterized only by observable fire characteristics such as size, duration, intensity, and frequency (*72–75*). Here, we expand the pyrome concept to include a systematic grouping of ecoregions based on the strength of climatic and other environmental controls on fire. This novel approach enriches the pyrome concept with a dimension that mirrors the complexity inherent in the study of biomes, while also providing critical insights into the varying sensitivity of pyromes to different facets of global change. Delineating the global forest pyromes revealed a rapid increase in emissions from extratropical forest pyromes that exceeded declining emissions from tropical forest pyromes during 2001-2023. This increase demonstrates that climatic controls on forest fire are overwhelming human controls in global-scale emissions trends.



Pyrome	Associated Forest Biomes	Associated N-grams from Ecoregion Descriptions
ExTropF1	Boreal forests/taiga; Temperate broadleaf and mixed forests; Temperate coniferous forests	mixed forests; canadian shield; forests canadian; siberian taiga
ExTropF2	Tropical and subtropical moist broadleaf forests; Tropical and subtropical dry broadleaf forests; Temperate broadleaf and mixed forests; Temperate coniferous forests	atlantic; deciduous forests; evergreen forests; mixed forests; conifer forests; dry forests; sclerophyllous; subtropical
ExTropF3	Temperate broadleaf and mixed forests; Tropical and subtropical moist broadleaf forests; Temperate coniferous forests; Mediterranean forests, woodlands, and scrub or sclerophyll forests	mixed forests; mountains; dry forests; conifer; deciduous forests; moist forests; sclerophyllous
ExTropF4	Tropical and subtropical moist broadleaf forests	moist forests; conifer forests; lowland rain forests; montane rain forests; new; sumatran; swamp forests
SubTropF1	Temperate broadleaf and mixed forests; Temperate coniferous forests; Tropical and subtropical moist broadleaf forests; Mediterranean forests, woodlands, and scrub or sclerophyll forests	mixed forests; montane; broadleaf forests; conifer forests; forest steppe; forests himalayan; kurile; sclerophyllous; swamp forests
SubTropF2	Tropical and subtropical moist broadleaf forests; Tropical and subtropical dry broadleaf forests; Tropical and subtropical coniferous forests; Mediterranean forests, woodlands, and scrub or sclerophyll forests	dry forests; pine oak forests; montane forests; rain forests; sierra madre
SubTropF3	Tropical and subtropical moist broadleaf forests; Tropical and subtropical dry broadleaf forests	dry deciduous forests; rain forests
TropF1	Tropical and subtropical moist broadleaf forests	moist forests; congolian lowland forests; swamp forests
TropF2	Tropical and subtropical moist broadleaf forests; Tropical and subtropical dry broadleaf forests	dry forests; lowland; montane rain forests; coastal forests; moist forests; pine; swamp forests
TropF3	Tropical and subtropical moist broadleaf forests; Tropical and subtropical coniferous forests	moist deciduous forests; subtropical
SupZoF1	Tropical and subtropical moist broadleaf forests; Tropical and subtropical dry broadleaf forests; Tropical and subtropical coniferous forests	dry forests; montane forests; pine
SupZoF2	Mediterranean forests, woodlands, and scrub or sclerophyll forests; Tropical and subtropical moist broadleaf forests; Temperate coniferous forests; Temperate broadleaf and mixed forests	forests; woodlands; coastal

Figure 1: World map of the twelve forest pyromes and a summary of their tendencies to associate with biomes and ecoregion types. 414 forest ecoregions are attributed to one pyrome using k-means clustering, which identifies ecoregions sharing a similar set of correlations between burned area (BA) and 14 predictor variables (**Fig. 2** and **Fig. S1-S2**). Grey areas are not included in the analysis, either because they are not within forest biomes (light grey) or because fire is extremely rare (the mean annual fraction of forest area burned by fire is below 0.01%; dark grey). **Fig. S21** shows an alternative mapping of the pyromes for the ecoregions that were clustered most ambiguously. The table shows the most common biome associations for each pyrome and the most common text substrings (n-grams, up to 3 words) that appear in the ecoregion descriptions, based on the ecoregion descriptions in the Terrestrial Ecoregions of the World dataset (ref. (*57*)).

Results

Twelve global forest pyromes emerged from the clustering analysis (**Fig. 1**), and this grouping revealed large increases in forest fire C emissions in extratropical forest pyromes. By contrast, forest fire C emissions declined in tropical and subtropical forest pyromes.

Geography and Traits of the Pyromes

To characterize the key controls on fire in each pyrome, we examined the correlations between forest BA and each variable representing the fire controls amongst the constituent ecoregions of the pyromes (**Fig. 2, Fig. S1-S2**). We consider the mean correlations within each pyrome to indicate sensitivity of the forest BA response to each control, and we consider these relationships to be a trait of a pyrome when at least 75 percent of the constituent ecoregions display a correlation of the same sign (**Fig. 2, Fig. S1-S2**). Significant differences in correlation were observed in 58% of pairwise comparisons, indicating a robust grouping of the ecoregions into pyromes with distinctive fire controls (see **Methods**). A more complete description of pyrome characteristics is provided in Supplementary Text 2.

Pyromes in Extratropical Forests

Pyromes ExTropF1 and ExTropF2 encompass the North American and Eurasian boreal forests and some temperate and high-altitude tropical forests (Fig. 1). Forest BA in these pyromes correlates positively with fire weather and atmospheric instability, negatively with seasonal soil moisture, and shows no correlation with population density, agricultural land cover, and road density (Fig. 2, Fig. S1-S2). ExTropF1, more common in North America, has BA strongly correlated with lightning flash density, indicating lightning as a key ignition source (*33*, *34*). In ExTropF2, more common in Eurasia, BA correlates with NDVI from the prior growing season, suggesting that previous climatic conditions impacting vegetation growth and the production of fine fuels bear an influence on subsequent fire extent (*76*, *77*). Forest fire extent in pyromes ExTropF1 and ExTropF2 is governed by different combinations of climatic factors affecting fuel moisture, fuel growth, and natural ignition.

Pyromes ExTropF3 and ExTropF4 include forests of Scandinavia, western Russia, and certain areas of North American, Europe, and China (Fig. 1). While BA in these pyromes correlates with fire weather, the strength of correlations is lower than in ExTropF1 or ExTropF2 and especially weak in ExTropF4 (Fig. 2, Fig. S1-S2). Additionally, in ExTropF4, no correlation with soil moisture further indicates that fires are also relatively insensitive to water deficits (Fig. 2, Fig. S1-S2). Weak correlations with most variables in ExTropF3 and ExTropF4 likely relate to infrequent burning in these stable humid climates (Fig. S8, Table S1), which challenges diagnoses of controls on fire over a two-decade time period.

Pyromes in Tropical Forests

TropF1 and TropF2 are widespread in the tropical deforestation zones of Amazonia, Congo, and equatorial southeast Asia (Fig. 1). Forest BA correlates positively with population density, road density, agricultural land cover, and fire weather, and negatively with forest continuity and soil moisture (Fig. 2, Fig. S1-S2). These traits characterize a region with widespread deforestation and degradation fires that, particularly in TropF2, are facilitated by dry conditions (*48*, *78*, *79*). TropF1, primarily in Amazonia and the Congo, shows a strong correlation with pasture cover (Fig. S1), reflecting cattle ranching-driven deforestation (*80*, *81*). TropF2, found in

Sumatra, Kalimantan, Borneo, Guianas, and southeast Russia, has stronger correlations with soil moisture and weaker with population, roads, and pasture cover than TropF1, highlighting particularly prominent role of drought in facilitating peak fire activity (*79*, *82*, *83*). Several forest ecoregions in southeast Russia, a global hotspot of extratropical forest loss through fire linked to forestry operations (*83*), are also grouped with TropF2 (Fig. 1).

TropF3 characteristically maps to older, heavily-fragmented deforestation frontiers in Brazil, Mexico, West Africa, and some southeast Asian islands (Fig. 1) (*84*, *85*). Here, forest BA correlates positively with fire weather and negatively with soil moisture but not with population or agriculture density, most likely caused by saturation of ignition sources in these highly populated regions during fire-favorable weather conditions.

Pyromes in Subtropical Forests

SubTropF1, SubTropF2, and SubTropF3 span subtropical or dry tropical forest ecoregions in regions such as northern Colombia, Madagascar, northeast India, southeast Asia, Sri Lanka, East Africa, and drier parts of the Brazilian atlantic forests (Fig. 1). BA consistently correlates with forest continuity and fuel stocks in these pyromes, in addition to fire weather (Fig. 2, Fig. S1-S2). This indicates a tendency for greater fire extent when meteorological conditions allow in locations where fuel production is greater or flammable natural landscapes are less fragmented (*15*, *49*). In SubTropF1 and SubTropF2, negative correlations with population density, cropland cover, and road density, particularly strong in SubTropF2, suggest reduced fire activity in the areas most fragmented by human activity. Lightning frequency often correlates with BA in SubTropF2, pointing towards a greater frequency of natural ignitions.

In contrast to SubTropF1 and SubTropF2, BA in SubTropF3 shows no consistent correlation with population density, cropland cover, or road density, indicating that natural factors (e.g. topographic and hydrological) are more important controls on fuel loads and continuity than human factors. SubTropF3 also lacks strong correlations between BA and soil moisture, indicating sensitivity to short-term fire-prone weather rather than seasonal moisture deficits (*15*, *49*).

Pyromes in Zones of Fire Suppression

The final two pyromes, **SupZoF**1 and **SupZoF**2, span tropical, subtropical, and temperate forest ecoregions and are common in regions with significant fire management efforts, such as the southeast US, western US, southeast and western Australia, and parts of Iberia (Fig. 1). In these pyromes, forest BA negatively correlates with population density, road density, and agriculture, indicating reduced fire extent in proximity to human activities (*46*, *86*). Positive correlations with forest continuity and fire spread suggests that continuous forests facilitate fire spread, especially in topographically complex areas with fewer human activities (*46*, *87*).

Fire suppression, fuel load management, and community programs are in place to reduce fire extent in these areas (*46*, *88*). Despite these efforts, fires can still occur during fire-prone weather (*37*, *89*), and stronger positive correlations with fire weather and negative correlations with soil moisture in **SupZoF**2 suggest that climatic factors bear stronger influence on forest BA than in **SupZoF**1 (Fig. 2). In **SupZoF**1, forest BA often (but inconsistently) correlates with lightning frequency, highlighting the role of natural ignitions, an effect that is seen most strongly in southeast Australia (*90*) (Fig. S2). Additionally, **SupZoF**1 shows a correlation between forest BA and vegetation productivity from the prior growing season, emphasizing the role of fuel production as a driver of fire extent (*9*, *42*, *91*).

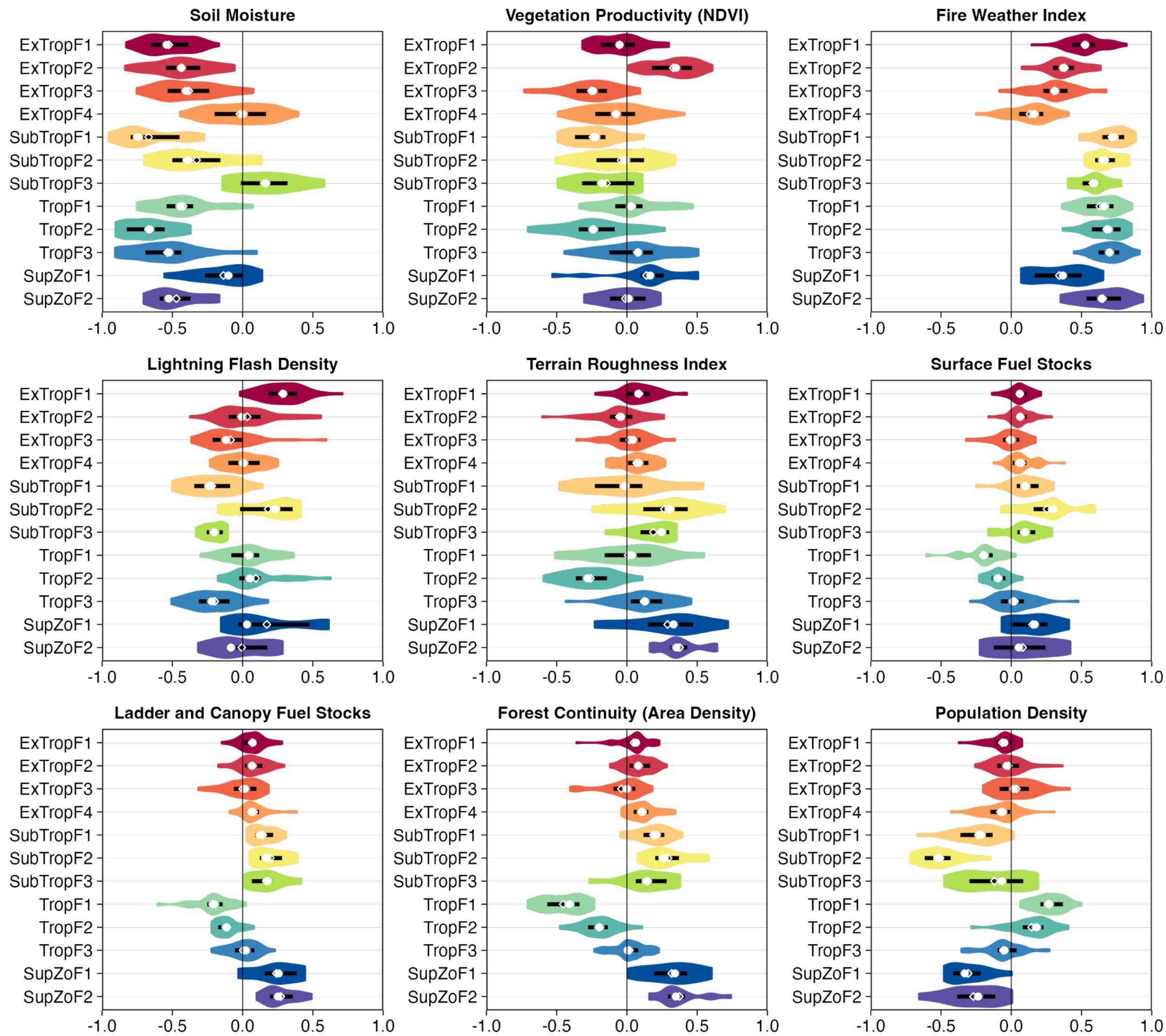


Figure 2: Variation in the relationship between forest burned area (BA) and nine predictors across the global forest pyromes. The violins plot the kernel density distribution of correlations values (spearman's ρ) for each predictor amongst the constituent ecoregions of each pyrome. White dots mark the median correlation value for the ecoregions of a pyrome, black line ranges mark the interquartile range, and open diamonds mark the mean value. See **Methods** for a description of all correlation analyses and the motivation for including each predictor. Distributions are shown for all predictor variables in Fig. S1. Correlations are mapped for each forest ecoregion in **Fig. S2**.

Increased Fire Emissions in Extratropical Forest Pyromes

Forest fire C emissions increased in several of the pyromes between 2001 and 2023 (**Fig. 3**), however the most striking trend was a 194% increase in fire C emissions in pyrome **ExTropF2** (+116 Tg C year^{-1}; **Table S1**). This large increase in fire C emissions was driven by a 167% increase in forest BA (+35 thousand km^2 year^{-1}) and a 58% increase in C combustion rate (C emissions per unit BA; **Fig. 3, Table S1**). Increased forest BA was a widespread feature of the ecoregions in pyrome **ExTropF2**, with over half showing significant increases and fewer than 5% showing significant decreases (**Fig. 4**, **Fig. S11**). Consequently, the increases in forest fire C emissions were also widespread. For example, forest fire C emissions increased significantly in parts of Russia (east and northeast Siberian taiga), Europe (e.g. Balkan mixed forests, Pindus and Dinaric mountains mixed forests), western North America (e.g. Sierra Nevada forests, North-Central Rockies forests, Muskwa-Slave lake forests, Fraser Plateau and Basin complex, and Northwest Territories taiga), Chile (Valdivian temperate forests), and China (Northeast China Plain deciduous forests and Hengduan Mountains conifer forests; **Fig. 4**).

The increases in forest BA and fire C emissions in pyrome **ExTropF2** align with changes in the variables that control temporal variability in forest BA. During 2001-2023, the annual number of extreme fire weather days increased by 5 days per year on average across the ecoregions of the pyrome (**Fig. 4**, **Fig. S14**, **Table S2**). The average soil moisture content during the fire season reduced by around 3% on average, in contrast to other extratropical pyromes where soil moisture either increased or remained level (**Fig. 4, Fig. S15**, **Table S2**). Mean NDVI during the growing season also increased at a rate comparable to the other extratropical pyromes (**Fig. 4, Fig. S16, Table S2**). These trends were also widespread and consistent. For example, over half of the ecoregions in pyrome **ExTropF2** synchronously experienced an increase in extreme fire weather days, increased NDVI and reduced soil moisture, with over one-quarter of ecoregions showing *significant* changes for all three variables. This evidence suggests that the trends in forest BA and fire C emissions in pyrome **ExTropF2** were driven by changes in the climate of the fire season, which led to reduced fuel moisture, combined with changes in the climate of the growing season, which led to increased vegetation growth and fuel production.

The increase in forest productivity during the growing season in pyrome **ExTropF2** also corresponds with a 30% increase in forest area in the pyrome (+1 million km^2; **Fig. S3**) during 2001-2023. This striking rate of forest expansion is consistent with reported rates exceeding 1% per year in some of these regions during 2001-2019 based on MODIS observations (*92*) and with the accumulating evidence for increased vegetation greenness and biomass stocks in the high-latitudes (*77*, *93*, *94*). On the other hand, such a large increase in forest area has not been seen in Landsat-based estimates of change in forest cover, likely due to differences in the resolution (see further discussion in **Methods**) (*95–97*). Dual increases in forest area and productivity highlight how a warming climate and CO_2 fertilization have enhanced forest growth at higher latitudes and contributed to both a greater forest area available to burn and greater rates of fuel production (*98*, *99*). Nonetheless, growth in forest BA has outpaced growth in forest area, as indicated by a 158% increase in the fraction of forest area that burned annually during 2001-2023 (i.e. the forest BA fraction; **Table S1**, **Fig. S3**).

Pyrome **ExTropF1** also showed large and significant increases in forest BA (+30%, or 6 thousand km^2 year^{-1}) and fire C emissions (+65%, or 30 Tg C year^{-1}) during 2001-2023, though these trends were not quite as pronounced as in pyrome **ExTropF2** (**Fig. 3, Table S1**). Trends in forest BA were also more mixed amongst the ecoregions of pyrome **ExTropF1**, with around one-third showing a significant increase in forest BA and around 15% showing a significant decrease (**Fig. 4**, **Fig. S11, Table S1**). The varied trends in forest BA can be explained by mixed trends in fire weather and soil moisture across the pyrome. The annual number of extreme fire weather days increased significantly in around 35% of the ecoregions of pyrome **ExTropF1** but also decreased in 15%, while very few ecoregions experienced a significant increase in soil moisture (**Fig. 4, Fig. S14-S15, Table S2**). Only around 10% of ecoregions in pyrome **ExTropF1** showed synchronous significant increases in extreme fire weather, soil moisture and lightning density, which are the three key controls on fire activity that emerged from our clustering analysis in this pyrome (**Fig. 2, Fig. S1-S2**).

Increased Fire Emissions in Pyromes with Fire Suppression

In pyromes **SupZoF1** and **SupZoF2**, forest fire C emissions increased by 43-44% during 2001-2023(**Fig. 3, Table S1**). In both pyromes **SupZoF1** and **SupZoF2**, the increased fire C emissions were driven primarily by significant 37-79% increases in the C combustion rate, combined with smaller non-significant increases in forest BA of 8-18% (**Fig. 3, Table S1**). Within pyromes **SupZoF1** and **SupZoF2**, significant increases in fire C emissions were spatially concentrated in forest ecoregions of Australia (e.g. Blue Mountains forests, Naracoorte woodlands, Jarrah-Karri forests), southern Europe (e.g. Southwest Iberian Mediterranean sclerophyllous forests, Northwest Iberian montane forests, and Aegean and Western Turkey sclerophyllous forests), the western USA (Klamath-Siskiyou and coastal forests and California interior chaparral and woodlands), Madagascar (subhumid and lowland forests; **Fig. 4**). The large upticks in emissions from forests in the western US and eastern Australia during 2019 and 2020 (*17*, *18*) are clearly visible in the emission time series for pyromes **SupZoF1** and **SupZoF2** and influence the slope of the trends in these pyromes (**Fig. 3**).

Reduced Fire Emissions in Tropical Forests

Forest fire C emissions showed opposing trends in the pyromes occupying the tropical deforestation zones, with the 96% decline (-26 Tg C year^{-1}) in forest fire C emissions in pyrome **TropF2** outweighing 56% increases (+24 Tg C year^{-1}) in forest fire C emissions in pyrome **TropF1** (**Fig. 3**). In pyrome **TropF1**, the increase in fire C emissions was caused by an increase in forest fire C combustion rate combined with a 19% increase in forest BA (**Fig. 3, Table S1**). Increased forest BA was widespread throughout the pyrome, with around two-thirds of the constituent ecoregions of pyrome **TropF1** showing an increase during 2001-2023 (**Fig. 4; Table S1**). In pyrome **TropF2**, the decline in forest fire C emissions was predominantly driven by a 56% reduction in forest BA (**Fig. 3; Table S1**). The reductions in fire C emissions were consistent across the ecoregions of pyrome TropF2, with around 80% of the constituent ecoregions of the pyrome showing a decrease during 2001-2023 (**Fig. 4**, **Fig. S11, Table S1**).

Figure 3: Changes in the burned area (BA) in forests and carbon (C) emissions from forest fires during 2001-2023. By row, the panels show **(a-c)** forest BA, **(d-f)** fire C emissions per unit burned area of forest, **(g-i)** C emissions from forest fires, and **(j-l)** the forest fraction of total (forest plus non-forest) fire C emissions. By column the panels show **(a,d,g,j)** show annual data (solid lines) and trendlines (dashed lines) for each pyrome, **(b,e,h,k)** absolute changes during the data period, and **(c,f,i,l)** relative changes (%) for the same period. Trendlines are fitted using Theil-Sen regression. Fire C emissions are extrapolated for 2001 and 2023 based on the trend in C combustion rate during 2002-2020 and the observed annual BA in 2001 and 2023. Absolute

changes are calculated as the difference between the trendline values at the start and end of the period, and relative changes are calculated conservatively as the absolute change divided by the period mean. **Figs. S3-S5** present various aspects of forest and total (forest + non-forest) fire trends, including changes in burned area, C emissions, and combustion rates. **Figs. S6-S11** show mapped trends for individual forest ecoregions and the distribution of these values across the ecoregions of each pyrome.

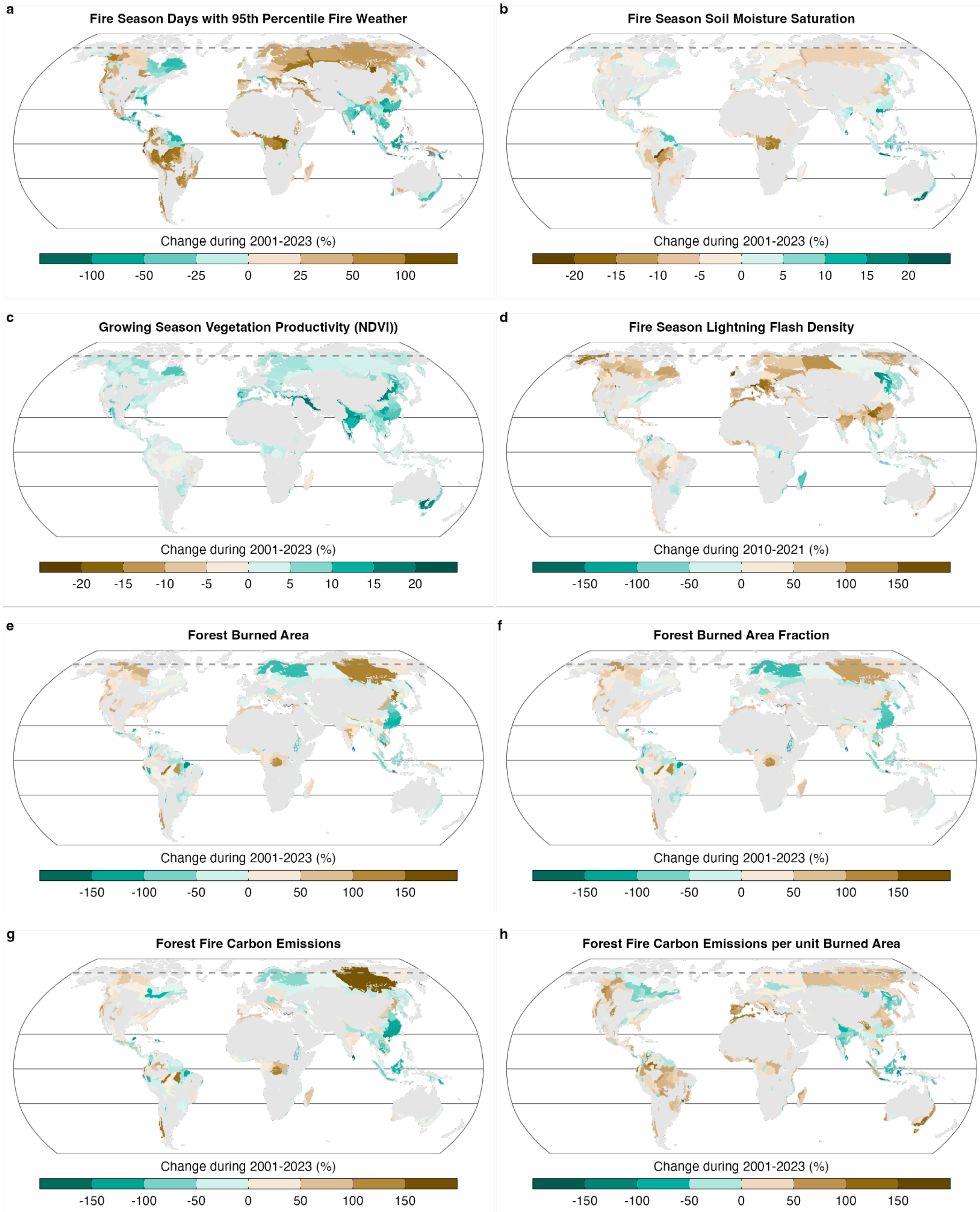


Figure 4: Changes in bioclimatic variables and fire observations at ecoregion level. The panels show relative changes in four bioclimatic variables used to distinguish pyromes(a-d), forest burned area (BA; **e**), forest burned area fraction (km^2 burned km^{-2} forest; **f**), forest fire carbon (C) emissions (**g**) and the forest fire C combustion rate (g C km^{-2} burned) during the period 2001-2023 (2010-2021 for lightning flash density), mapped to forest ecoregions. The climate variables

are (**a**) days during the fire season with 95th percentile fire weather index (FWI) values relative to all days in the period 1980-2009, (**b**) average soil moisture content during the fire season, (**c**) mean normalized difference vegetation index (NDVI) during the prior growing season, and (**d**) lightning flash density during the fire season. The strength of the relationships between forest BA and fire weather, soil moisture, vegetation growth and lightning varies across pyromes (**Fig. 2**) and there is lesser variability within the constituent ecoregions of each pyrome (**Fig. S1-S2**). Changes in forest fire C emissions (**g**) relate to changes in forest burned area (**e**) as well and emissions per unit BA (**h**). **Fig. S6-S17** additionally show the mapped mean values of these variables for individual ecoregions and the distribution of trends across the ecoregions of each pyrome.

Discussion

Our mapping of pyromes has revealed variation in the controls on forest fire extent across the world's forest ecoregions. The pyrome boundaries tend to align with the boundaries of climate zones or biomes (**Fig. 1**), though not precisely due to significant variation in the drivers of fire within those zones. The expected first-order patterns of macro-scale pyrogeography are apparent in the distinctive traits of fire control that emerge from the clustering analysis (**Fig. 2, Fig. S1-S2**). For example, human controls on fire emerge as a stronger trait of the tropical pyromes than of the extratropical pyromes, consistent with the expectation that the tropical fire regime is dominated by human activities (*2*, *100*, *101*).

In the largest extratropical pyromes (**ExTropF1** and **ExTropF2**), forest fires are influenced by climatic factors affecting fuel moisture during the fire season and variably by the production of vegetation fuels in the growing season or by opportunities for lightning ignition. The near tripling of fire C emissions in pyrome **ExTropF2** can be explained by pervasive increases in fire-favorable weather during the fire season, increased vegetation productivity in the growing season, and expanding forest cover. Increased forest extent and productivity at higher latitudes have been linked to climate changes that are favorable for vegetation growth and CO_2 fertilization (*98*), and our results show that these trends have coupled with reduced fuel moisture to drive an increase in forest BA and fire C emissions in pyrome ExTropF2. The weaker increases in fire C emissions in pyrome ExTropF1 can be attributed to less consistent trends in fire-favorable weather across the pyrome.

During 2001-2023, forest fire C emissions grew by 60% across all forest ecoregions globally, principally driven by trends in the extratropical pyromes (**Fig. 3, Table S1**). Forest BA and fire C emissions were redistributed from tropical and subtropical pyromes to extratropical pyromes (**Fig. 5**). Amidst these geographical shifts, the C combustion rate of forest fires also increased by 47% across all forest ecoregions globally, reflecting greater fuel consumption per unit of forest BA (**Fig. 3**, **Table S1**). Extreme examples of C combustion per unit area have been recorded during recent extreme wildfire episodes and tied to extremes in fire-favorable weather (*8*, *11*, *16*, *17*, *102*), whereas our findings support a more general trend towards increases in fuel consumption in forests. In addition, the contribution of forest fires to total (forest plus non-forest) BA and fire C emissions has also increased globally and in most forest pyromes, with the exception of the subtropical forest pyromes (**Fig. 3**, **Table S1**), signaling that the increased susceptibility of forests to fire has generally outpaced that of non-forest environments experiencing similar environmental changes.

Our mapping of the pyromes enabled us to link rising fire C emissions in extratropical forests to climate change. For example, without distinguishing pyrome **ExTropF2** and the climatic factors that influence its forest BA, the increase in fire emissions that has occurred there could be overlooked or masked. The emissions trend in pyrome **ExTropF2** potentially signals that a step-change in the fire regime and a destabilization of forest C stocks is underway in some extratropical ecoregions. Recent studies have identified a rise in forest productivity and fire-favorable weather as compounding drivers of increased fire C emissions in Siberia (*16*, *103–105*), whereas our results indicate that similar dynamics are leading to increased fire C emissions more broadly across the ecoregions of pyrome **ExTropF2**.

Even in the pyromes where non-climatic factors, particularly *in situ* human activities, exert significant control on forest BA, climatic factors remain a key enabler of fire. Increased fire weather under climate change can be expected to increase the windows of opportunity for fires to occur even in regions with significant fire suppression (*31*, *106*, *107*). For example, the uptick in the forest BA and fire C emissions in the pyromes **SupZoF1** and **SupZoF2**, which encompass many zones of aggressive fire suppression and management, are consistent with warnings that the effectiveness of wildfire suppression is waning in a warming climate (*108*, *109*). These findings highlight a potential for the relationships between climate and fire to strengthen in future climates.

Forest ecoregions with the most ambiguous cluster assignment (as measured by silhouette width statistics), are scattered globally with little tendency to concentrate in particular world regions (Fig. S21), suggesting that the pyromes arising from our clustering procedure were largely free of regional bias (Supplementary Text 1). One exception is the Iberian Peninsula, where almost all ecoregions showed low silhouette widths, indicating a relatively low parity with other world regions. Among pyromes, clustering ambiguity was highest in SubTropF3, SupZoF1, and SupZoF2, with the most common alternative assignments to pyromes ExTropF1, ExTropF2, ExTropF3, ExTropF4, and SubTropF3, indicating a higher level of confusion between various climate-sensitive and extratropical pyromes (Supplementary Text 1).

Overall, we have contributed a new geographical mapping of forest pyromes based on distinctive fire drivers and discovered significant increases in forest BA and fire C emissions in some of the pyromes where they are most expected. Our work complements previous studies that used machine learning to disentangle the effect of multiple fire controls on global patterns or trends in BA (*7*, *40*, *55*, *56*). For example, prior studies also indicated that increased vegetation productivity and fire-favorable weather both contributed to increased BA in boreal Eurasia during 2001-2014 (*7*, *40*). Our explicit focus on forest BA and fire C emissions has also provided novel insights. For example, we find strong spatial contrasts in the effect of human activities on forest BA across different tropical and subtropical pyromes, whereas prior work indicated that human activities reduce total BA more uniformly across the tropics (*7*, *40*).

Our work complements prior endeavors to define pyromes based on observable fire characteristics (*72–75*). While a novel and insightful aspect of our study is its focus on grouping regions with similar fire drivers, by doing so, we concentrated exclusively on BA as a target variable, foregoing information about other observable fire traits that vary geographically and are important aspects of the fire regime. Future work could aim to integrate geographical distinctions in both fire traits and fire drivers to provide a more holistic definition of the pyrome. This approach would further enhance the analogy with the term ‘biome’, which encapsulates both the biological properties and physical presentation of grouped ecosystems, as well as the climatic and other environmental factors that cause those properties to emerge.

Looking forward, our pyrome classification could play a key role in the development of global fire models to better represent observed fire dynamics by creating opportunities to tailor model parameters in regions with distinct fire drivers. For example, parameters that represent the influence of people on fire processes could be optimized by pyrome in DGVMs to better represent the distinct relationships between human activities and fire across pyromes, in a manner akin to optimizing biological processes across plant functional types. Moreover, the pyromes layer also serves to highlight priority areas for the study of changes in fire weather, drought or vegetation productivity, since some pyromes are distinctly more sensitive to changes in these factors than others.

A caveat of our approach is that it provides a global zonation of fire controls at the macro-scale – a scale that is particularly suited to questions concerning global environmental change, including differential responses to climate change. We do not suggest that all areas within an ecoregion are uniformly sensitive to the same fire controls. For example, differences in land use and management approaches across landowner types can be expected to produce varying relationships between fire and human factors within an ecoregion, as seen between protected areas, Indigenous areas, and private land (*110*, *111*). Hence, our analysis identifies the dominant controls that emerge at the ecoregion scale but omits the local effects associated with specific actors at sub-ecoregion level. The application of similar techniques to smaller (or larger) world regions would provide a finer (or coarser) geography of fire controls to which a different set of environmental questions may apply. In addition, our mapping of pyromes should not be viewed as fixed in time. For example, regional changes in policy, land use or population dynamics or ongoing shifts in climate or vegetation types could all lead to the re-allocation of an ecoregion to a different pyrome in future (*75*).

Relatedly, although our analysis provides valuable insights into the impacts of climate change on fire dynamics over a two-decade period, it is important to recognize the limitations inherent in using relatively short datasets to interpret fire regimes that operate over much longer intervals. Many forest ecosystems are subject to fire return intervals spanning decades to centuries, which can obscure the detection of longer-term trends. This is particularly the case in pyromes ExTropF3 and ExTropF4, where long fire return intervals (~1,000 years; **Figure S7; Table S1**) likely contributed to low correlations between BA and all explanatory variables and challenged the identification of fire drivers by clustering. Therefore, while our findings indicate significant trends such as the increase in emissions in the extratropics, increased combustion rates, and a shift from savannas and grasslands to forests as major fire emissions sources, these must be interpreted with some caution. Future studies extending beyond the 20-year timeframe are essential to fully understand the long-term fire regimes and validate the persistence of such trends (*9*, *112*).

Both observations and models suggest that extratropical forests are greening and becoming more productive due to a combination of climate change and CO_2 fertilization (*98*, *99*, *113*). Dynamic global vegetation models (DGVMs) also generally project that C storage will continue to increase in the future in high latitude forests, although some variability is seen across models and climate scenarios (*114*, *115*). Nonetheless, DGVMs currently show a limited capacity to reproduce historical trends and contemporary spatial patterns of fire (*6*, *116*), raising concerns as to whether future change in fire disturbance is reliably captured in projections of future vegetation distribution and C storage. Additional uncertainty in future C storage stems from the potential for post-fire ecosystem shifts to occur due to increased fire severity not captured by models (*117*, *118*). Our finding of increased forest fire C emissions lends further support to previous warnings that fire could offset projected gains in C storage in extratropical forests (*119–121*).

As forest fire C emissions grow, so does their relevance to carbon accounting, including the greenhouse gas (GHG) inventories submitted to the United Nations (UN). For example, C emissions from wildfires in Canada during 2023 alone are likely to have overturned a significant portion of the C sink to Canadian forests that accumulated over the prior decade *(19, 122, 123)*. Wildfires in Canada are not free of anthropogenic influence and are becoming more likely due to anthropogenic climate change *(19)*, yet they are designated as natural disturbances in Canada's national emissions inventory and thus their influence is largely omitted from UN records *(122, 123)*. Prior work has advocated for more comprehensive reporting of fire emissions on both managed and unmanaged land, to facilitate routine assessments of how fires impact national and global inventories of anthropogenic emissions *(122)*. Our work further highlights the importance of this comprehensive reporting by revealing the growing role that forest fire C emissions play in the carbon budget of boreal forests.

Relatedly, enhancing C storage in forests using forestry practices is viewed as a promising strategy for C dioxide removal (CDR) from the atmosphere to offset anthropogenic C emissions (*124*, *125*). One recent study estimated that an additional 60 Pg C could be stored on extratropical land that is highly suitable for forestry (*126*), or 600-3,000 Tg C year^{-1} when annualized over a period of 20-100 years representing the time taken for potential C stocks to accumulate (*127*). The estimates of potential C storage from ref. (*126*) derive from relationships fitted to the C stocks held in current intact forests, yet these forests were established in historical fire regimes inferring that potential C storage is overestimated in forests where fire regime shifts are underway. For a crude comparison, we estimate that forest fire C emissions grew by 114 Tg C year^{-1} across all extratropical pyromes between 2001 and 2023. We suggest that a continued increase in forest BA and fire C emissions could reduce the potential for CDR in extratropical forests by a nontrivial margin, particularly in the absence of effective fuel and fire management.

While climatic factors show a varying strength of control on the extent of forest fires across pyromes, their effects are nonetheless pervasive. This result emphasizes the need to address the primary causes of climate change, by reducing emissions from fossil and land use sources, in order to mitigate the increased fire-related risks to C sinks (*128*, *129*). Moreover, our findings inform forest management and Net Zero policies by identifying pyromes where specific human actions can support forest C sinks by reducing C emissions from fires. In tropical pyromes, where fire shows a strong dependence on human ignition patterns, reducing ignitions during extreme fire-favorable weather and preventing forest fragmentation should enhance C retention (*30*, *130*). In pyromes with a history of aggressive wildfire suppression, shifting focus and funds from active fire suppression to managed, ecologically beneficial fires may prevent C sink-to-source conversion (*7*, *30*, *131*). In extratropical pyromes where climatic factors have the most direct and unmodulated control on fire extent, monitoring changes in vegetation and productivity can guide the prioritization of areas for forest management (*7*, *30*, *131*). In all pyromes, substantial financing is required to support strategic programs of forest management, stakeholder engagement, and public education, all of which represent a meaningful shift of fire management strategy from largely reactive to increasingly proactive (*7*, *30*, *131*). Overall, global forest C sinks could be undermined by wildfire without action to address the leading causes of climate change, while forest management strategies for mitigating the problem are likely to be most effective when tailored to pyromes. Cutting anthropogenic emissions is central to securing resilient forests for the future.

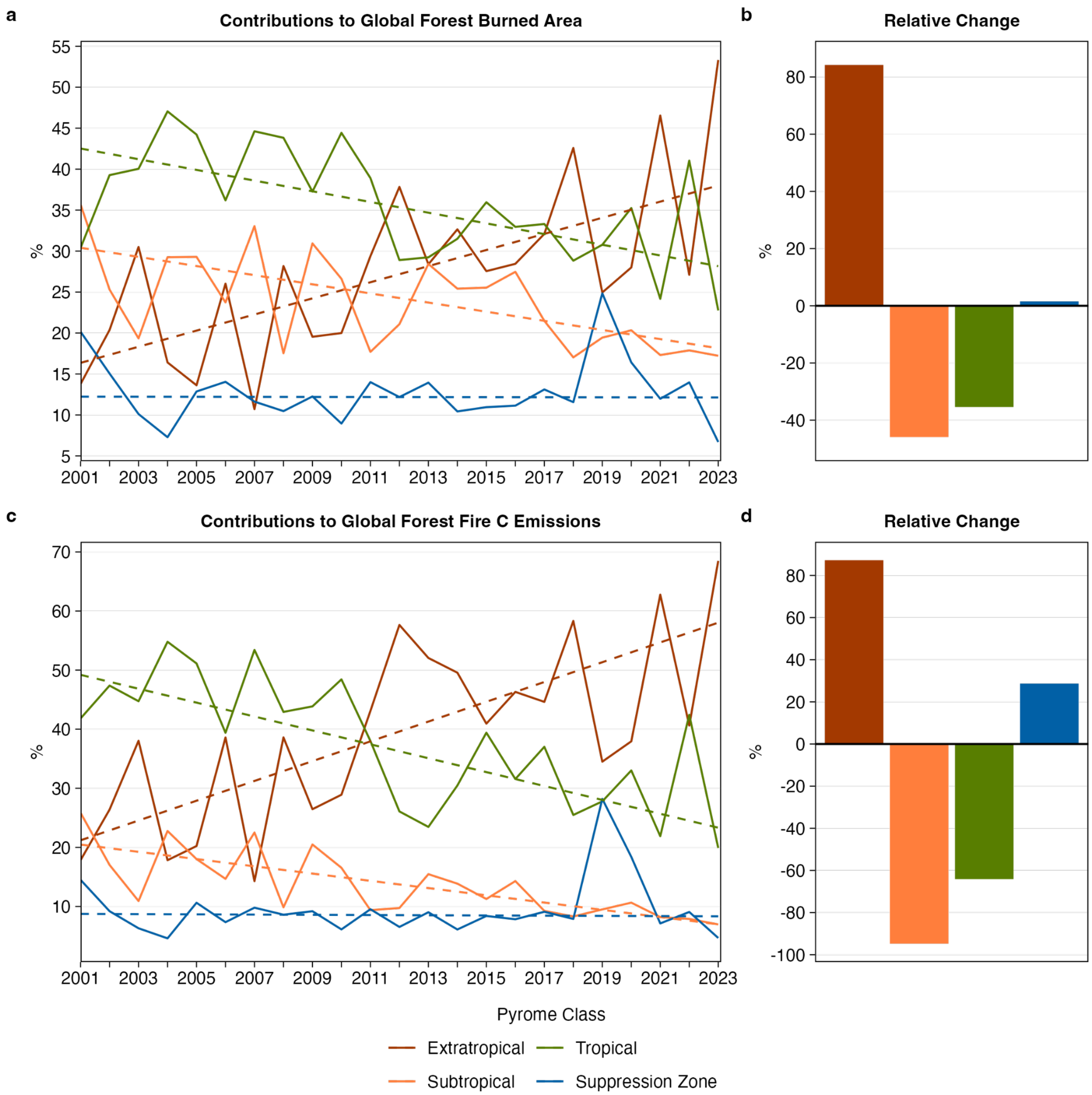


Figure 5: Geographical shifts in forest burned area (BA) and fire carbon (C) emissions from the tropics to the extratropics during 2001-2023. The plot shows contributions of groups of pyromes in the tropics, subtropics, extratropics and zones of suppression to **(a-b)** forest BA in all forest ecoregions globally and **(c-d)** the fire C emissions in all forest ecoregions globally. By column the panels show **(a,c)** annual data (solid lines) and trendlines (dashed lines) for each pyrome, **(b,d)** relative changes during 2001-2023. Trendlines are fitted using Theil-Sen regression. Fire C emissions are extrapolated for 2001 and 2023 based on the trend in C combustion rate during 2002-2020 and the observed annual BA in 2001 and 2023. Absolute changes are calculated as the difference between the trendline values at the start and end of the period, and relative changes are calculated conservatively as the absolute change divided by the period mean.

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Conceptualization: MWJ.

Methodology: MWJ, SV, JTA.

Resources/Software: NA, MLP, TR, DvW, GRvdW.

Investigation/Formal analysis: MWJ.

Visualization: MWJ, JTA.

Writing—original draft: MWJ.

Writing—review & editing: All co-authors.

Competing interests: The authors declare no competing interests.

Data and materials availability: Pyromes are provided in three geospatial formats via the Zenodo data repository (ref. *(132)*): shapefiles; 0.25° grids; and 0.05° grids. Gridded correlations for all variables are also available via the Zenodo data repository (ref. *(132)*). R code used for clustering forest ecoregions into pyromes is also archived at the Zenodo repository (ref. *(132)*). The raw data representing burned area, carbon emissions, and all predictor variables in our analysis are publicly available via refs. *(49, 58, 59, 61, 62, 67-70, 133)*, except for the lightning flash data from the WWLLN (*ref. (63)*), which are subject to a commercial agreement but can be provided in a gridded and coarsened form upon request.

Supplementary Materials

Materials and Methods

Supplementary Text 1

Supplementary Text 2

Figs. S1 to S22

Tables S1 to S2

References (*134–182*)