

1 **Elevational Dependence of Global Forest Fires and Associated Aerosol Optical**
2 **Depth: Drivers and Decoupling**

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16

17 **Abstract**

18 Forest fires have become an escalating environmental and ecological issue
19 worldwide over the past decades. However, a knowledge gap persists in globally
20 assessing how topography modulates wildfire behavior. Here we quantify global
21 spatiotemporal patterns of forest fire activity and associated aerosol optical depth
22 (AOD), together with elevation-dependent controls, using satellite observations from
23 2012 to 2024. The analysis reveals a slight yet significant increase in fire occurrence,
24 accompanied by a strong positive association with fine-mode AOD (FAOD). In contrast,
25 coarse-mode AOD (CAOD) shows little response, implying that wildfire emissions
26 mainly contribute to the fine aerosol fraction. Forest fire occurrence declines
27 systematically with elevation, with most fires concentrated below 600 m. In contrast,
28 FAOD exhibits elevated mean values and increasing trends at mid-elevations (600–
29 1400 m), revealing a decoupling between fire frequency and aerosol loading. This
30 divergence is consistent with shifts in forest-type composition and topographically
31 modulated smoke transport, including aerosol self-lifting driven by radiative absorption
32 and atmospheric convection. Elevation-stratified multiple linear regression analyses
33 incorporating the Fire Weather Index, leaf area index, temperature, wind speed, and
34 precipitation indicate that fire activity is primarily governed by fuel availability and
35 aridity. Precipitation exerts a consistent suppressive effect across elevations, while wind
36 speed enhances fuel drying and fire spread at mid-elevations. Overall, these results
37 identify elevation as a key organizing factor linking forest fires, aerosol emissions, and
38 their underlying drivers, providing new constraints for wildfire risk assessment and
39 fire–aerosol interactions under a changing climate.

40

411. Introduction

42 Wildfires represent a key component of the Earth system, influencing ecosystems,
43 atmospheric composition, carbon cycling, climate, and public health on a global scale
44 (Bowman et al., 2009; Andela et al., 2017; Qian, 2025; Yang et al., 2022; Yang et al.,
45 2021a). Over the past decade, the societal and environmental consequences of wildfires
46 have attracted increasing scientific and public attention (Abatzoglou et al., 2025).
47 Concurrently, ongoing climate warming has intensified fire-conducive weather,
48 increasing the probability of wildfire occurrence, particularly large and extreme events
49 (Jones et al., 2024; Abatzoglou et al., 2025). Elevated temperatures and prolonged
50 dryness further reduce fuel moisture, raising fire susceptibility in biomass-rich forests
51 (Jones et al., 2024; Jolly et al., 2015).

52 Forests constitute the most extensive terrestrial biome and serve as a major
53 component of the global carbon budget (Pan et al., 2011). Despite their critical role,
54 these ecosystems are becoming increasingly vulnerable to wildfire disturbances
55 (Keywood et al., 2013). While the total burned area worldwide has shown a declining
56 tendency in recent decades, fire occurring in forested regions have become more
57 frequent and more severe, with average fire size, duration, and intensity increasing by
58 two- to threefold over recent decades (Zheng et al., 2021; Cunningham et al., 2024;
59 Parisien et al., 2023; Canadell et al., 2021). Escalating occurrences of extreme fires
60 threaten forest stability and recovery capacity, potentially undermining essential
61 ecosystem functions and services, including long-term carbon storage (Ward et al.,
62 2020; Gatti et al., 2021). In contrast to grasslands, forest fires release greater amounts
63 of carbon dioxide per unit area, and the reestablishment of carbon sinks after burning
64 is generally slow, which may generate a positive climate-fire feedback (Zheng et al.,
65 2021). These risks are further intensified by climate change, which promotes fuel aridity,
66 extreme fire weather, and longer fire seasons, thereby increasing the probability of
67 large-scale biomass burning (Kirchmeier-Young et al., 2024; Wang et al., 2025). Large
68 and extreme fires are also promoted by human disturbance and land-use change,
69 particularly in tropical forests where frequent human ignitions and ongoing forest

70 degradation strongly drive fire activity (Lapola et al., 2023; Yang et al., 2023). By
71 completely or partially removing aboveground vegetation, wildfires fundamentally
72 alter forest structure and function (Kim et al., 2025), making forest fire activity an
73 increasingly urgent global environmental and ecological concern.

74 The combustion of biomass in forest fires releases significant quantities of
75 aerosols and trace gases into the atmosphere, leading to pronounced air quality
76 deterioration not only near source regions but also in distant areas affected by long-
77 range smoke transport (Ma et al., 2025; Zhang et al., 2025; Fan et al., 2021; Xu et al.,
78 2025). Smoke-related pollution markedly increases annual mean PM_{2.5} exposure,
79 contributing to thousands of premature deaths and billions of U.S. dollars in economic
80 losses each year (Ma et al., 2025; Zhang et al., 2025). In addition to these air quality
81 impacts, smoke aerosols influence the Earth's radiation balance and climate system
82 through both direct interactions with solar radiation (scattering and absorption) and
83 indirect effects associated with cloud microphysics (Keywood et al., 2013; Andreae et
84 al., 2004; Blanchard-Wrigglesworth et al., 2025). Wildfire emissions induce contrasting
85 thermal effects, characterized by surface cooling and atmospheric warming, which
86 modify atmospheric stability, vertical transport, circulation patterns, and regional
87 hydrology, ultimately driving significant climatic responses (Menon et al., 2002; Koren
88 et al., 2004; Lau et al., 2006; Blanchard-Wrigglesworth et al., 2025; Pei et al., 2025).
89 Moreover, wildfire-derived aerosols affect atmospheric and oceanic biogeochemistry
90 by modulating nutrient deposition and photosynthetic activity in marine ecosystems
91 (Hamilton et al., 2022; Tang et al., 2021). Consequently, wildfire emissions exert broad
92 effects on air quality, the global radiation balance, and coupled climate–biogeochemical
93 systems.

94 Substantial studies have elucidated that vegetation cover, fire weather, climate and
95 topography jointly govern the probability and severity of forest fires (Parks et al., 2018;
96 Birch et al., 2015; Whitman et al., 2018; Wang et al., 2022c; Yu et al., 2020). Besides
97 fire weather and climate forcing, vegetation characteristics and topographic controls are
98 critical determinants of fire severity, particularly in mountainous terrain (Birch et al.,

99 2015; Walker et al., 2020). Live fuel availability, represented by vegetation cover, has
100 been shown to strongly regulate wildfire severity. Analyses of 19 forested ecoregions
101 across the western United States for 2002–2015 highlighted it as the dominant control
102 (Parks et al., 2018), with comparable relationships documented in both the northern
103 Rocky Mountains (Birch et al., 2015) and North American boreal forests (Walker et al.,
104 2020; Whitman et al., 2018). Using a machine-learning approach, Jones et al. (2024)
105 categorized global forest ecoregions into 12 pyromes and showed that increases in
106 forest cover and ecosystem productivity substantially enhanced wildfire emissions.
107 Topographic factors—such as elevation, aspect, and slope—have also been shown to
108 exert substantial influence on burn severity across diverse regions, including China and
109 Canada (Huang et al., 2020; Whitman et al., 2018). Notably, investigations from the
110 Canadian Rocky Mountains reported strong associations between elevation and fire
111 activity (Rogean and Armstrong, 2017). Despite these advances, global-scale
112 assessments of the relationship between topography and fire regimes remain limited
113 relative to the extensive focus on vegetation-related drivers. This gap is notable given
114 that topography can substantially enhance fire spread and promote erratic fire behavior
115 (Sharples et al., 2012).

116 This work examines the influence of topography on global forest fire activity
117 through a comprehensive analysis of spatial fire patterns. Building on evidence from
118 Canadian forests identifying elevation as a key topographic control (Wang et al., 2025),
119 we focus on elevation as a central organizing factor. This study focuses on three main
120 objectives: (i) describing the global spatial distribution of fire pixel counts and their
121 associations with aerosol optical depth (AOD) over forested regions; (ii) assessing the
122 extent to which elevation shapes the spatial patterns of both fires and AOD; and (iii)
123 determining the key factors that control the elevation–fire relationship. To interpret
124 these patterns, multiple explanatory variables, including fuel load, forest type, and fire
125 weather, are jointly analyzed. By elucidating elevation-dependent fire dynamics, this
126 work provides a scientific basis for adaptive fire management, elevation-informed fuel
127 treatments, post-fire hazard mitigation, and ecologically informed fire use to support

128 biodiversity conservation in the face of persistent climate warming.

129 **2. Materials and methods**

130 **2.1 Satellite-based wildfire observations**

131 We utilized active fire observations from the Visible Infrared Imaging Radiometer
132 Suite (VIIRS) sensors carried by the Suomi NPP and NOAA-20 platforms. These
133 measurements capture combustion-related thermal signals at approximately 375 m
134 resolution. To facilitate large-scale analysis, individual fire detections were spatially
135 aggregated onto a $0.1^\circ \times 0.1^\circ$ global grid, and the number of detections within each cell
136 was used as a metric of fire occurrence. Daily wildfire activity was characterized using
137 the combined daytime and nighttime VIIRS observations, accounting for both fire
138 occurrence and intensity. Fire detections were spatially overlaid with a forest land-cover
139 mask to extract events occurring within forested pixels, and only grid cells with more
140 than one active fire detection during 2012–2024 were retained to ensure data robustness.
141 To enhance data reliability, fire pixels flagged as “low confidence” (confidence level
142 ‘1’) were excluded from the analysis.

143 **2.2 Vegetation types, elevation, and fire weather data**

144 Land cover information was characterized by using the MODIS land cover type
145 dataset at 500 m resolution, available through NASA’s Land Processes Distributed
146 Active Archive Center (LP DAAC). Topographic characteristics were represented using
147 the General Bathymetric Chart of the Oceans (GEBCO) 2024 gridded data, which
148 provides global elevation and bathymetry data at 15-arc-second resolution (~500 m)
149 (Harper and Sandwell, 2024). To ensure spatial consistency, land cover and elevation
150 datasets were resampled to match the analysis grid. Forest categories and elevation
151 values at fire locations were then extracted using nearest-neighbor interpolation.
152 Forested regions were grouped into five major types: evergreen needleleaf (ENF),
153 evergreen broadleaf (EBF), deciduous needleleaf (DNF), deciduous broadleaf (DBF),
154 and mixed forest (MF). Elevation was stratified into 20 zones using 100 m intervals
155 below 2000 m. Given the relatively low number of fire detections at higher elevations,
156 all regions above 2000 m were combined into a single category to ensure sufficient

157 sample sizes and enhance the robustness of subsequent trend analyses.

158 We employed the Canadian Forest Fire Weather Index (FWI) system to
159 characterize weather conditions that favor wildfire development and to assess climate-
160 driven variability in fire danger (Su et al., 2025; Liu et al., 2023; Van Wagner, 1987).
161 The index is calculated from standard meteorological inputs, including near-surface air
162 temperature, wind speed, relative humidity, and accumulated total precipitation over
163 the preceding 24-hour (Van Wagner, 1987). Daily FWI data with a resolution of 0.25°
164 $\times 0.25^\circ$ from 2012 to 2024 are obtained from the historical fire danger index archives.
165 Supplementary meteorological parameters, such as 2 m air temperature (2mT), 10 m
166 wind speed (10mW), and the max daily total precipitation, were extracted from the
167 ERA5 reanalysis produced by the European Centre for Medium-Range Weather
168 Forecasts (ECMWF). Monthly means of FWI and meteorological variables were
169 calculated for subsequent analyses with forest fire activity.

170 **2.3 Satellite-based FAOD and CAOD retrievals**

171 Size-resolved aerosol optical depths at 500 nm, including the fine (FAOD) and
172 coarse (CAOD) fractions, were estimated using SIDN (Simultaneous FAOD–CAOD
173 Inversion Deep Neural Network) algorithm. The inversion is physically constrained by
174 incorporating interactions between the two aerosol size classes, thereby enhancing
175 retrieval reliability (Luo et al., 2024; Chen et al., 2025). SIDN integrates multi-source
176 satellite observations with meteorological reanalysis data and is trained against high-
177 quality AERONET measurements using a shared representation learning strategy based
178 on the EntityDenseNet architecture. By dynamically balancing FAOD and CAOD
179 contributions during training, SIDN improves retrieval accuracy and internal
180 consistency across diverse aerosol regimes. A comprehensive description of the model
181 architecture, training procedure, and validation is provided in the above references and
182 is not repeated here. Extensive evaluations against independent ground-based
183 observations demonstrate that SIDN outperforms conventional satellite products,
184 yielding reduced uncertainties and improved spatial completeness, particularly under
185 cloudy and complex surface conditions. In addition, the deep-learning framework

186 trained with AERONET observations substantially improves retrieval accuracy and
187 stability across different aerosol regimes, making the dataset particularly suitable for
188 investigating wildfire–aerosol interactions on a global scale. The resulting daily global
189 FAOD and CAOD dataset spans 2012–2024 at a spatial resolution of 0.5°. Because the
190 spatial resolution of the AOD data is coarser than that of the forest fire dataset, a nearest-
191 neighbor approach was used to match the datasets. This method preserves the original
192 aerosol observations without introducing artificial smoothing or interpolation effects
193 and has been widely applied in satellite data matching studies. Although the spatial
194 resolution mismatch may introduce some uncertainties, its impact is expected to be
195 limited for the large-scale analyses conducted in this study.

196 **2.4 Temporal trends analysis**

197 Temporal trends in wildfire activity were assessed using linear regression applied
198 to annual fire pixel counts aggregated at 0.1° × 0.1° resolution. For each grid cell, a
199 linear regression was fitted between the natural logarithm of annual fire pixel counts
200 and time, with statistical significance determined at $p < 0.05$. The regression slope was
201 exponentiated to estimate the annual percentage change in fire occurrence. For the
202 global and forest-type–specific assessments, annual records were further processed
203 with a 3-year centered moving average, which filters out short-term interannual noise.
204 To verify the stability of the detected trends, we employed the Mann–Kendall non-
205 parametric test in combination with the Theil–Sen estimator, which provide outlier-
206 insensitive assessments of trend direction and magnitude. The Theil–Sen slope was then
207 derived for grid cells showing significant changes, expressed as

$$208 \quad SFC = \text{median} \left(\frac{FC_j - FC_i}{j - i} \right), 2012 \leq i < j \leq 2024$$

209 where SFC denotes the median rate of change, and FC_i and FC_j represent fire pixel
210 counts at moments i and j , respectively.

211 Trends in AOD over 2012–2024 were analyzed using the same logarithmic linear
212 regression framework to ensure comparability with fire pixel count trends. AOD values
213 were restricted to the range 0–5 to exclude extreme outliers.

214 **2.5 Correlation and multivariate regression analysis**

215 To quantify the influence of forest fires on aerosol loading, linear regressions of
216 the form $AOD = a + k \times \log_{10}[\text{fires}]$ applied separately to FAOD and CAOD. The
217 regression slope (k) represents fire sensitivity, with larger values indicating stronger
218 aerosol responses to fire activity. The $\log_{10}[\text{fires}]$ was adopted as the explanatory
219 variable, following common practice in wildfire research (Zhao et al., 2024; Abatzoglou
220 and Williams, 2016). We applied linear regressions to individual $1^\circ \times 1^\circ$ grid cells that
221 contained no fewer than 10 fire observations. Where statistically significant
222 associations were identified ($p < 0.05$), both the slope parameter (k) and the
223 corresponding R^2 values were mapped to illustrate their spatial variability. Differences
224 in regression slopes among grid cells were evaluated using two-tailed t tests.

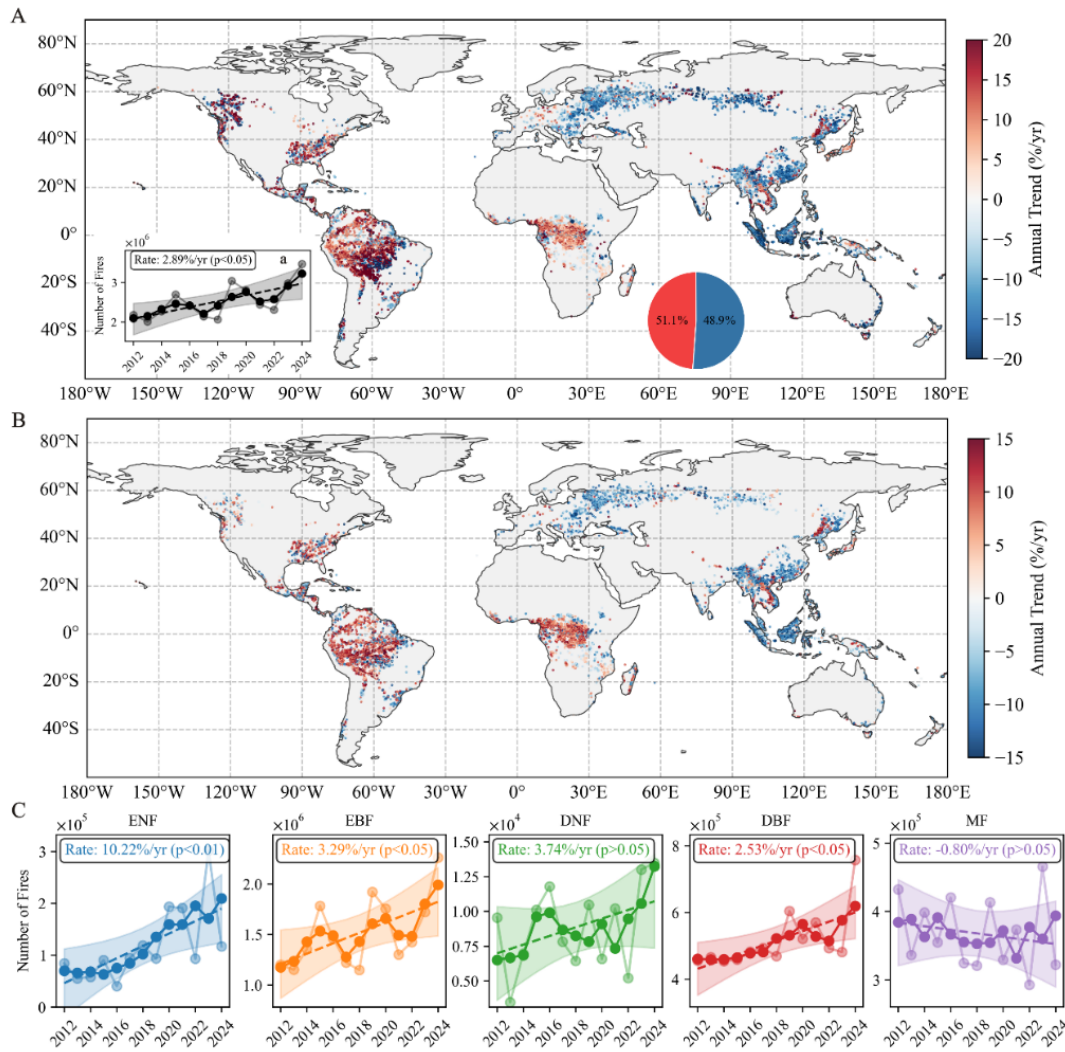
225 For the elevation-based analysis of forest fire activity, all monthly fire,
226 meteorological, vegetation, and topographic variables were spatially resampled to a 1°
227 $\times 1^\circ$ grid. For each grid cell, multiple linear regression model was conducted with
228 $\log_{10}[\text{fires}]$ as the response variable and FWI, leaf area index (LAI), 2mT, 10mW, and
229 daily maximum total precipitation as predictors. Year and month were additionally
230 included to represent long-term trends and seasonal variability. We employed ordinary
231 least squares (OLS) models to obtain baseline relationships, and statistical inference
232 was conducted using heteroskedasticity-robust standard errors ($p < 0.05$). To mitigate
233 multicollinearity among predictors, ridge regression with L_2 regularization was
234 additionally applied after standardizing all variables, with the optimal regularization
235 parameter selected via cross-validation. Variance inflation factors (VIFs) were
236 calculated to diagnose collinearity, and partial correlation analysis was applied to
237 isolate the independent effects of each driver after accounting for temporal influences.
238 Regression coefficients and model performance metrics were subsequently summarized
239 within elevation bins to characterize altitude-dependent fire–environment relationships.

240 **3. Results and discussion**

241 **3.1 Spatiotemporal patterns of forest fires and AOD**

242 Analysis of satellite-derived fire pixel counts across global forested regions from

243 2012 to 2024 reveals a modest but statistically significant increasing trend. Spatially,
244 51.1% of forest grid cells exhibit positive trends, exceeding the 48.9% showing
245 negative trends, with a global mean linear increase of 2.89% yr⁻¹ ($p < 0.05$, Figure 1A).
246 Our results indicate a growing number of forest fires, in agreement with the previously
247 reported global increase in forest burned area and mean fire pixel counts over last two
248 decades (Zheng et al., 2021; Yu and Ginoux, 2022). Geographically, significant positive
249 trends in fire pixel counts are concentrated in North America, northern South America,
250 and central Africa, whereas predominantly negative trends occur in Southeast Asia,
251 western and central Siberia, and eastern Europe (Figure 1A). The spatial patterns
252 derived from linear regression are consistent with those identified using the Mann-
253 Kendall test (Figure 1B). Notably, regions exhibiting increasing trends largely overlap
254 with areas of enhanced burned area and fire-driven carbon emissions in the tropical
255 moist broadleaf forest pyrome identified by Jones et al. (2024) for the period 2001–
256 2023. Increasing fire activity has also been reported in selected extratropical forest
257 ecoregions, including Canada (Wang et al., 2025) and Northeast China (Liu et al., 2023).



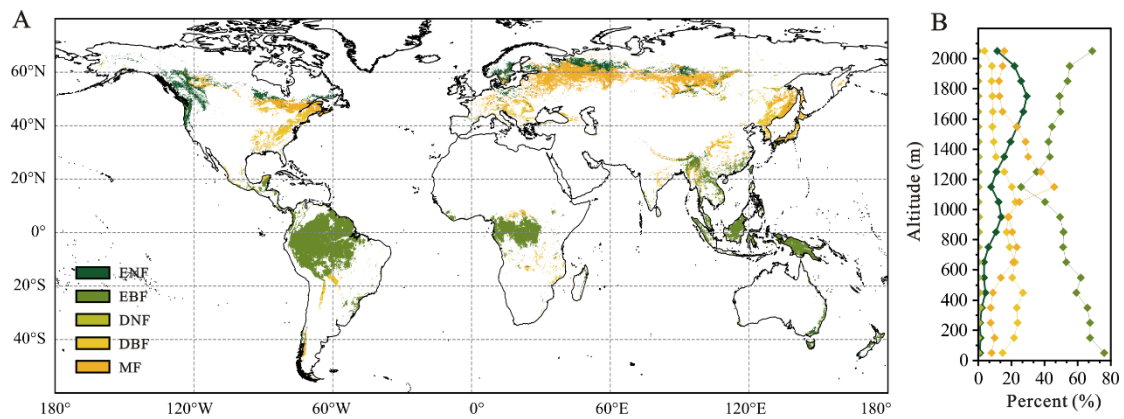
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259 Figure 1. Global trends in forest fire occurrence during 2012–2024. (A) Spatial distribution of
 260 statistically significant ($p < 0.05$) trends in annual fire pixel counts. The inset (a) shows the
 261 corresponding global time series, including annual values (light circles), a 3-year centered moving
 262 average (dark circles), and the fitted linear trend with its 95% confidence interval (dashed line and
 263 shaded envelope). The accompanying pie chart summarizes the relative fractions of increasing (red)
 264 and decreasing (blue) trends. (B) Significant spatial changes in yearly fire frequency, with
 265 significance assessed by the Mann–Kendall test and slope magnitudes estimated using the Theil–
 266 Sen method. (C) Distribution of significant interannual trends by dominant forest type, using the
 267 same smoothing and trend analysis as in (a). ENF, evergreen needleleaf forest; EBF, evergreen
 268 broadleaf forest; DNF, deciduous needleleaf forest; DBF, deciduous broadleaf forest; MF, mixed
 269 forest.

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271 Considerable heterogeneity in fire activity is found across forest types. EBF
 272 accounts for the largest proportion of fire pixel counts globally, whereas ENF exhibits
 the strongest positive trend in fire occurrence (Figure 1C). By comparison, no

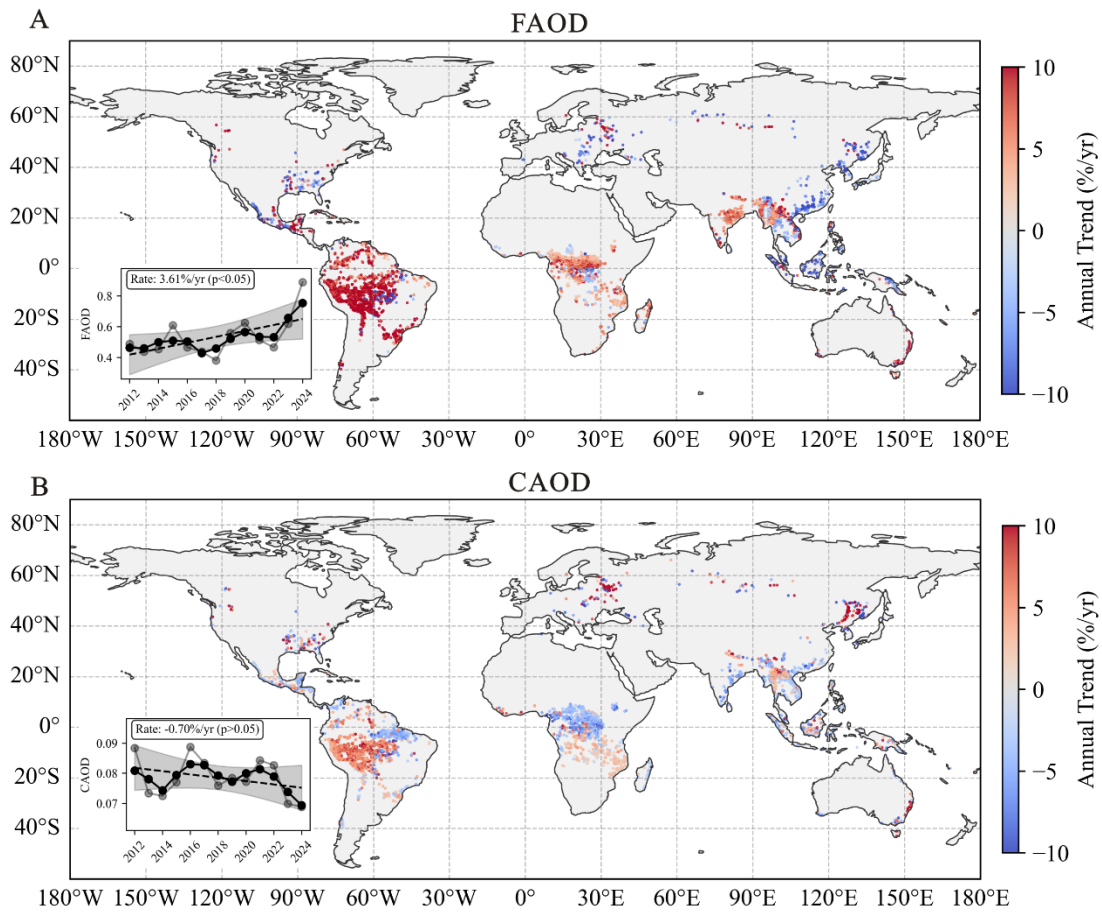
273 statistically significant changes are observed for DNF and MF. These forest types are
 274 primarily distributed across western and central Siberia (Figure 2A), regions
 275 characterized by declining fire activity (Figure 1A). Fire occurrence and severity are
 276 strongly mediated by vegetation characteristics, including forest type and fuel structure
 277 (Wang et al., 2025). High fire frequency and density are commonly associated with
 278 evergreen needleleaf forests, such as those dominated by Chir pine (*Pinus roxburghii*),
 279 which are characterized by high-intensity fire regimes (Kumar and Kumar, 2022). This
 280 elevated fire susceptibility is attributed to needle-shaped foliage, high resin content, and
 281 ladder-like branch architecture, which collectively enhance fuel flammability and
 282 vertical fire spread (Alexander and Cruz, 2011; Wang et al., 2025).



283
 284 Figure 2. Forest classification and its topographic variation. (A) Spatial patterns of the dominant
 285 forest categories. (B) Elevation-dependent distribution of forest cover, expressed as the percentage
 286 area occupied by each type within individual elevation bands. ENF, evergreen needleleaf forest;
 287 EBF, evergreen broadleaf forest; DNF, deciduous needleleaf forest; DBF, deciduous broadleaf forest;
 288 MF, mixed forest.

289 Aerosols influence the atmospheric radiation balance through the scattering and
 290 absorption of radiation (Andreae et al., 2004; Blanchard-Wrigglesworth et al., 2025).
 291 Owing to their distinct optical properties, different aerosol types exert varying climatic
 292 effects (Lin et al., 2021), particularly between fine-mode and coarse-mode particles (Li
 293 et al., 2025). To better investigate aerosol responses to forest fire activity, aerosol
 294 loading is therefore characterized using FAOD and CAOD. A consistent positive
 295 association between FAOD and fire pixel counts is observed across global forest
 296 regions from 2012 to 2024, whereas no comparable trend is detected for CAOD (Figure

297 3). It should be noted that FAOD and CAOD may also be influenced by aerosol sources
 298 unrelated to wildfire emissions; therefore, the comparison with fire activity should be
 299 treated as a first-order diagnostic of their potential linkage rather than a strict attribution
 300 of aerosol sources. The fire–FAOD relationship was quantified using linear regression
 301 of the form ($FAOD = a + k_F \times \log_{10}[\text{fires}]$) applied to each $1^\circ \times 1^\circ$ grid cell. Widespread
 302 statistically significant positive k_F values indicate that fine-mode particles dominate
 303 wildfire-related aerosol loading (Figure 4A), consistent with previous evidence that
 304 biomass burning predominantly contributes to the fine-mode portion of the aerosol
 305 population (Yan et al., 2024; Yang et al., 2021b; Kaskaoutis et al., 2014; Pei et al., 2025).

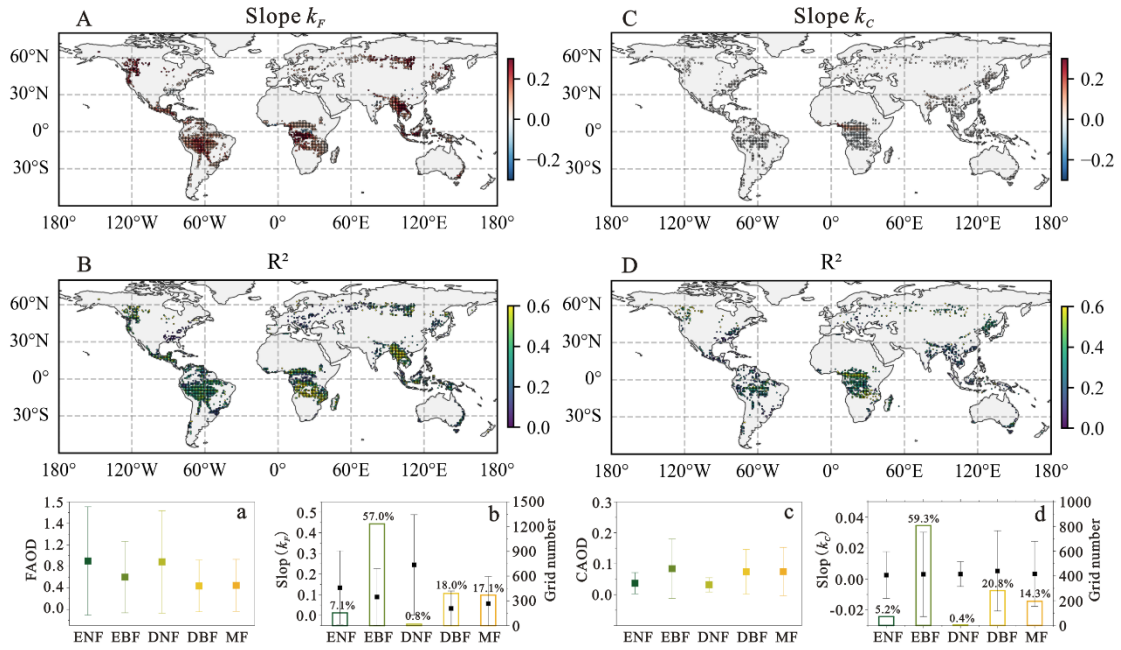


306
 307 Figure 3. Spatiotemporal trends in FAOD and CAOD during 2012–2024. (A) Spatial distribution of
 308 statistically significant trends ($p < 0.05$) in FAOD. (B) Corresponding distribution for CAOD. Insets
 309 show the annual global time series, including annual values (light circles), a 3-year centered moving
 310 average (dark circles), and the linear trend with its 95% confidence interval (dashed line with
 311 shading).

312 The k_F slope values exhibited variation across forest types, with the highest values

313 magnitude observed in DNF (0.25 ± 0.24), followed by ENF (0.13 ± 0.18), EBF (0.09
314 ± 0.14), MF (0.06 ± 0.13) and DBF (0.03 ± 0.08) (Figure 4b). This ranking is consistent
315 with the spatial pattern of average FAOD across these forest types (Figure 4a). Such
316 differences can be attributed to species-dependent emission strengths, as dominant taxa
317 contribute unevenly to wildfire-derived aerosols. For example, within ENF regions,
318 *Pseudotsuga* and *Picea* account for 15% and 71.1% of total FAOD contribution from
319 wildfire, respectively; among broadleaf forests, the genus *Quercus* alone contributes
320 50.6% (Chen et al., 2025). These patterns underscore that aerosol emissions from forest
321 fires depend not only on burned areas but also on fuel type and combustion efficiency
322 (Keywood et al., 2013). In contrast, no significant positive k_C values are detected for
323 CAOD (Figure 4C). The average of k_C values in different forest types was close to 0
324 with minimal variation (Figure 4d), indicating the absence of a systematic forest fire
325 influence on coarse-mode aerosol loading. In contrast to the large aerosol particles
326 associated with large fire events, such as pyroCb emissions (Li et al., 2025) or coarse
327 dust produced by post-fire dust outbreaks caused by reduced vegetation cover and soil
328 moisture (Yu and Ginoux, 2022), the results presented here mainly represent the global
329 mean response within forest fire regions. Although large fire events may generate
330 unusually high aerosol loading or coarse-mode dust, such episodic events are not fully
331 captured in the large-scale averages analyzed in this study.

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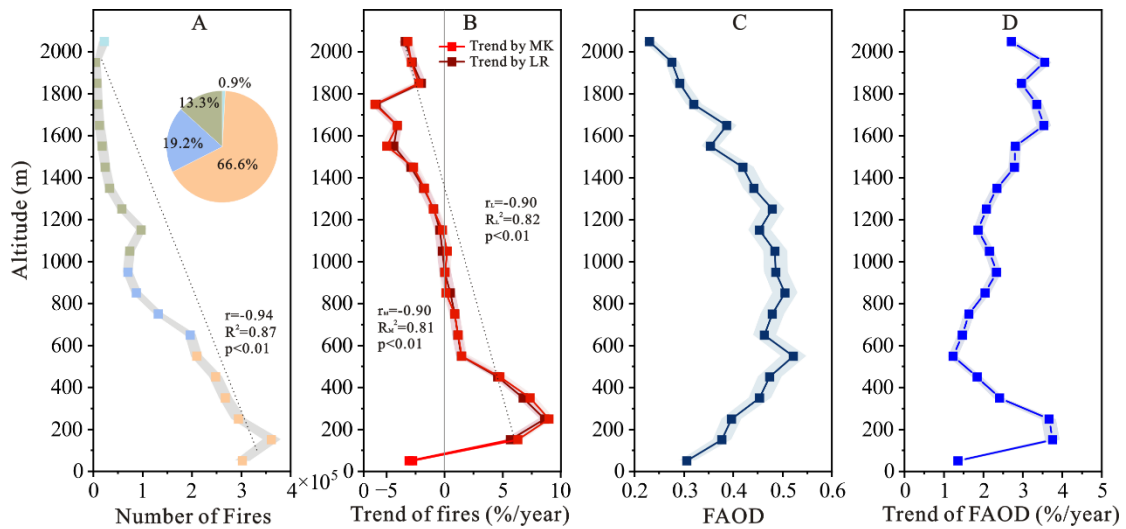
334 Figure 4. Correlation analysis between forest fires and AOD. (A, B) Regression slope k_F and R^2 for
 335 FAOD-fire relationship. (C, D) Slope k_C and R^2 for CAOD-fire relationship. (a, b) Forest-type
 336 averages of FAOD and Slope k_F . (c, d) Forest-type averages of CAOD and Slope k_C . Maps (A-D)
 337 show only locally significant relationships (linear regression, $p < 0.05$). Error bars in panels (a-d)
 338 denote standard errors. In panels (b) and (d), bar height indicates the number of grid cells per forest
 339 type, with numbers above bars showing the fractional area contribution of each forest type. ENF,
 340 evergreen needleleaf forest; EBF, evergreen broadleaf forest; DNF, deciduous needleleaf forest;
 341 DBF, deciduous broadleaf forest; MF, mixed forest.

342 3.2 Elevation-Dependent Patterns of Forest Fire Occurrence and FAOD

343 To evaluate how topography shapes forest fire activity globally, we examined the
 344 elevational dependence of fire occurrence from 2012 to 2024. A clear and statistically
 345 significant decline in mean annual fire pixel counts with increasing elevation was
 346 identified (Figure 5A). Forest fires were predominantly concentrated at low elevations,
 347 with 66.6% of total fire detections occurring below 600 m, followed by 19.2% between
 348 601 and 1000 m and 13.3% between 1001 and 2000 m. Only 0.9% of fires were detected
 349 above 2000 m (Figure 5A). This inverse relationship between elevation and fire activity
 350 agrees with previous regional studies conducted in the Canadian Rocky Mountains
 351 (Rogean and Armstrong, 2017) and across forested regions of China (Tian et al., 2013;
 352 Ma et al., 2020). Similar elevational dependence is also evident in the interannual trends.
 353 Both the multiyear mean fire pixel counts, and the corresponding annual trends exhibit

354 a pronounced decrease from low to high elevations (Figure 5A, B). However, Xu and
 355 You (2022) reported increasing burned areas in global high-mountain regions above
 356 3000 m, primarily focusing on high-mountain ecosystems that include alpine and other
 357 non-forest environments. In contrast, the present study examines wildfire activity
 358 within global forest regions, where most fires occur at low and mid elevations.
 359 Differences in vegetation type, fuel availability, and fire regimes between forested
 360 landscapes and alpine environments may partly explain these contrasting patterns.

361 Notably, while the largest absolute number of fires were observed between 100
 362 and 200 m, the strongest positive trend in fire activity occurred near ~300 m before
 363 declining at higher elevations. This discrepancy suggests that recent fire activity has
 364 increasingly concentrated around the ~300 m elevation range, potentially reflecting the
 365 combined influence of climate variability and fire management practices. In contrast, a
 366 weak negative trend in fire occurrence was observed below 100 m, which may be
 367 associated with more effective control of ignition sources in densely managed lowland
 368 regions (Wang et al., 2022b).



369
 370 Figure 5. Elevational variations in multiyear mean fire pixel counts, FAOD, and their temporal
 371 trends. (A, B) Multiyear mean (A) and significant annual trend (B) in fire pixel counts as a function
 372 of elevation. (C, D) Corresponding multiyear average (C) and trend (D) in FAOD. Dashed lines
 373 indicate overall elevation-dependent tendencies in (A) and (B). Colors denote elevation classes: 0–
 374 600 m (light orange), 600–1000 m (light blue), 1000–2000 m (gray-green), and >2000 m (light
 375 cyan). Shaded areas represent the 95% confidence intervals.

376 In contrast to the monotonic decline in fire occurrence, FAOD exhibits a distinct
377 elevational pattern. While FAOD trends below 600 m broadly track those of fire activity,
378 its multiyear mean values peak at mid-elevations (600–1400 m) rather than at low
379 elevations (Figure 5C, D). This divergence indicates that FAOD is not solely controlled
380 by local fire occurrence but is also influenced by forest composition and
381 topographically modulated by smoke transport processes. Around 600 m elevation,
382 forest composition shifts toward a higher fraction of ENF (Figure 2B), which exhibits
383 stronger FAOD sensitivity to fire activity ($k_F = 0.14 \pm 0.18$) than EBF ($k_F = 0.09 \pm 0.14$).
384 In addition, smoke particles released by low-elevation fires may be carried to higher
385 levels of the atmosphere via aerosol self-lifting processes associated with radiative
386 heating and convective motions (De Laat et al., 2012; Ohneiser et al., 2023; Xu et al.,
387 2025), thus elevating FAOD levels at mid-elevations. Above 600 m, the strengthening
388 FAOD trends with elevation diverge from the concurrent decline in fire occurrence,
389 implying the involvement of additional processes beyond local fire emissions. In
390 addition, with fewer than 50 grid cells above 1500 m exhibiting statistically significant
391 trends, the representativeness and accuracy of the computed global FAOD trend may
392 be compromised. Collectively, these results suggest that mid-elevation regions (600–
393 1400 m) are disproportionately influenced by smoke aerosols from forest fires at a
394 global scale.

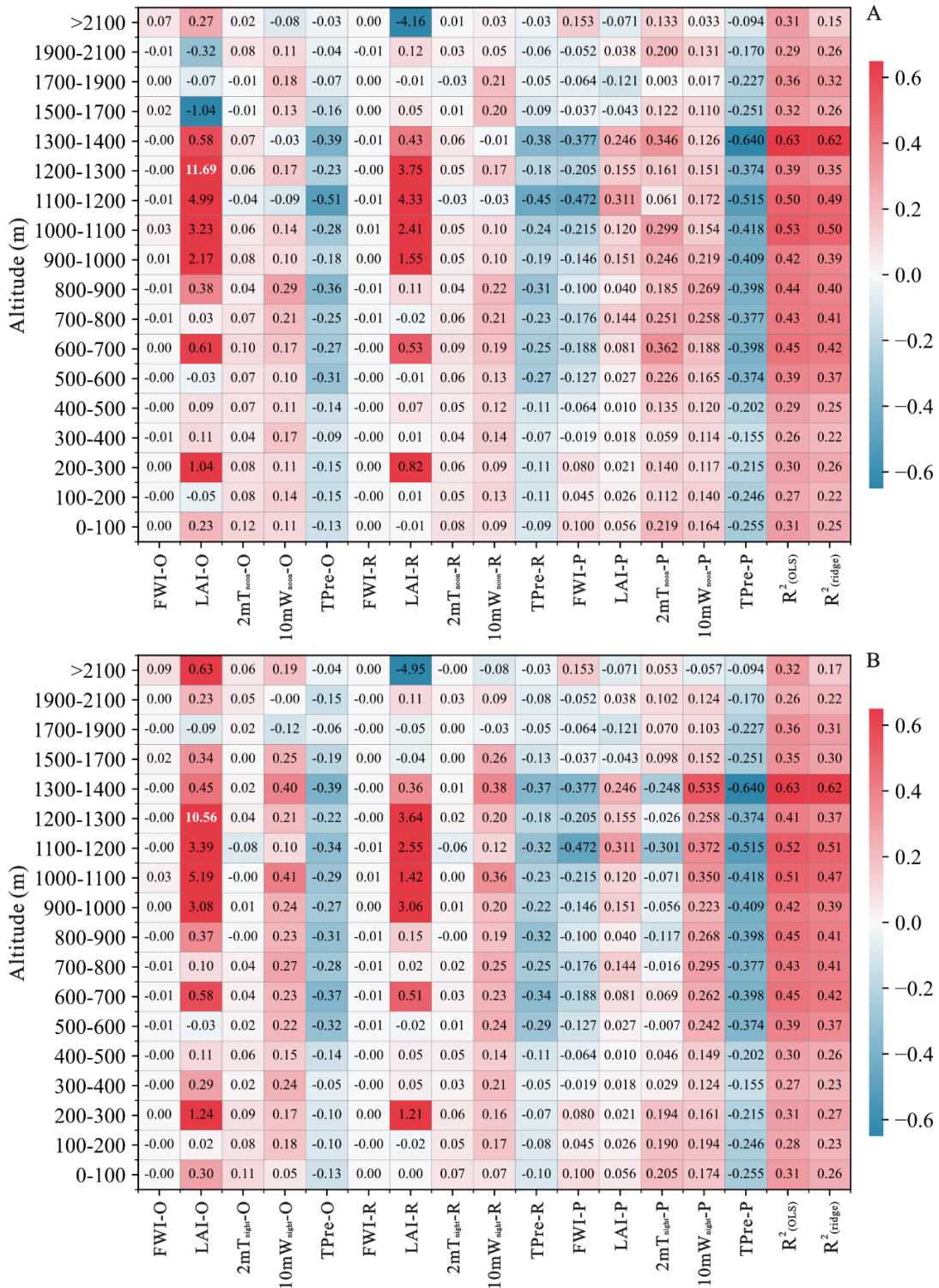
395 **3.3 Drivers of Elevational-Dependent Variations in Fire Activity**

396 To explain the contrasting elevational patterns of forest fire occurrence identified
397 in Section 3.2, we next examine the meteorological and ecological drivers governing
398 fire activity along with the elevation gradient. Vegetation fire activity is governed by
399 multiple interacting factors, including ignition sources, fuel supply and moisture, fire-
400 conducive weather, and forest management practices (Wang et al., 2022a; Clarke et al.,
401 2025). However, the relative contributions of these drivers change with elevation.
402 Notably, the FWI—often used to characterize the meteorological fire danger—exerts
403 little explanatory power, with regression coefficients near zero at all heights (Figure 6).
404 Partial correlation coefficients were negative between 300 and 2100 m, indicating a

405 weak association between FWI and fire occurrence after accounting for elevation. The
406 weak agreement observed here aligns with earlier reports (Su et al., 2025; Wang et al.,
407 2025) and arises primarily from mismatches in spatial and temporal resolution. FWI
408 primarily represents short-term surface meteorological conditions conducive to wildfire
409 occurrence, but it does not explicitly account for atmospheric instability, which can play
410 an important role in the development of large fires (Pinto et al., 2020). In addition, our
411 analysis focuses on the influence of topographic effects. The complex regional
412 topography may strongly modulate atmospheric instability (Santos et al., 2023), which
413 is closely associated with lightning activity and has been shown to be an important
414 factor in fire growth at the local scale (Haines, 1988).

415 To further disentangle elevational controls on fire activity, we examined individual
416 climatic and ecological variables associated with fuel aridity, ignition potential, and fuel
417 availability. Observed declines in LAI and wind speed with increasing elevation (Figure
418 7) are consistent with a reduced probability of fire occurrence at higher altitudes. LAI
419 was selected as a proxy for fuel availability (Yu et al. 2020). Multiple linear regression
420 analyses reveal pronounced elevation-dependent relationships (Figure 6). At high
421 elevations (>1500 m), fire occurrence shows no significant relationship with LAI. In
422 contrast, fire activity shows clear positive correlations with LAI at both low (200–300
423 m) and mid-elevations (600–1400 m), highlighting the importance of vegetation density
424 as a proxy for available fuels. While relatively strong regression coefficients are
425 observed in the low-elevation band (200–300 m), the corresponding R^2 values are
426 comparatively low, indicating that LAI explains only a limited fraction of the variability
427 in fire occurrence at these elevations. Consequently, the relationship between
428 vegetation and fire activity is more robust at mid-elevations. Although ridge regression
429 produced smaller coefficients than OLS, the coefficient for LAI remained significantly
430 higher than those of the other predictors. These observations support earlier studies
431 showing that vegetation structure and forest composition strongly regulate fire
432 dynamics (Parks et al., 2018; Wang et al., 2022c). In particular, evergreen needleleaf
433 species such as *Pinus densiflora* and *Pinus roxburghii* possess resin-rich needles that

434 enhance flammability and promote high-intensity fire behavior (Baek et al., 2022;
 435 Kumar and Kumar, 2022).



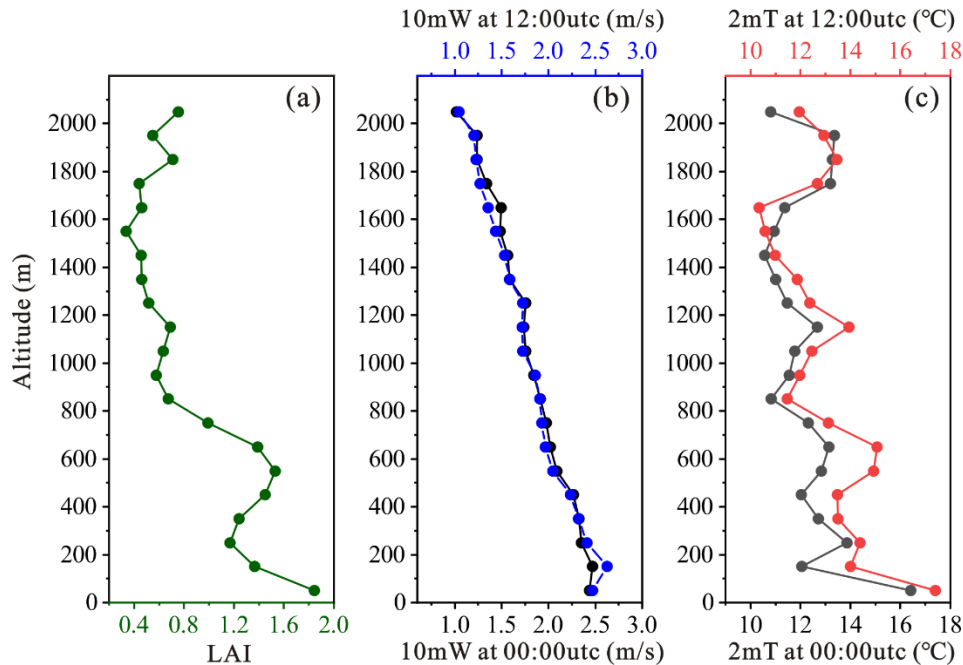
436
 437 Figure 6. Elevational variations in the key drivers of fire activity derived from multiple linear
 438 regression. Fire pixel counts were related to the FWI, LAI, 2mT, 10mW, and maximum total
 439 precipitation (TPre) ($p < 0.05$). Panels (A) and (B) represent nighttime and midday conditions,
 440 respectively. For each predictor, “-O” denotes the OLS standardized coefficient, “-R” the ridge

441 regression coefficient, and “-P” the partial correlation coefficient. Model skill was evaluated using
442 the coefficients of determination derived from both OLS ($R^2_{(OLS)}$) and ridge regression ($R^2_{(ridge)}$).

443 Air temperature, closely linked to climate change, influences fire activity by
444 modulating fuel drying and convective processes (Dastour et al., 2024; Duane et al.,
445 2021). However, temperature exhibited negligible effects, with both OLS and ridge
446 coefficients remaining close to zero across all elevations under both nighttime and
447 midday conditions. The weak elevational dependence of 2 m air temperature (Figure 7)
448 suggests that temperature alone cannot explain the observed decline in fire occurrence.
449 At mid-elevations, nighttime temperature exhibits a weak negative partial correlation
450 with fire occurrence, while daytime temperature shows a positive association,
451 highlighting the complex and diurnally dependent influence of temperature under
452 topographic constraints. In contrast, precipitation emerges as a robust suppressor of fire
453 activity across all elevation bands, with the strongest effects observed at mid-elevations.
454 The consistently negative regression coefficients indicate that precipitation deficits are
455 a primary determinant of fire occurrence and spatial distribution, consistent with
456 previous findings linking fire activity to precipitation amount and rainy-day frequency
457 (Kim et al., 2025). Relative humidity likely reinforces this effect by further modulating
458 fuel moisture, particularly in boreal forest systems (Veraverbeke et al., 2017; Dastour
459 et al., 2024).

460 Wind speed also exhibits strong elevational dependence. Nighttime wind speed
461 shows a positive association with fire occurrence below 1800 m in both OLS and ridge
462 models, with the strongest influence at mid-elevations (Figure 6). Daytime wind speed
463 is positively related to fire activity at low elevations but shows no significant
464 relationship at mid-elevations, likely reflecting differences between daytime up-valley
465 winds and nighttime downslope flows. In mountainous terrain, downslope flows may
466 advect warm and dry air toward lower elevations, creating fire-favorable conditions
467 when fuels are sufficiently dry (Abatzoglou et al., 2023; Abatzoglou et al., 2021).
468 Partial correlation analyses indicate that, when isolated from other factors, wind speed
469 remains positively associated with fire activity across elevations below 2000 m,

470 particularly at mid-elevations. Elevated wind speeds enhance fire activity by increasing
 471 evaporative drying, promoting sustained combustion, and facilitating ember transport
 472 (Ma et al., 2020; Jones et al., 2022).



473
 474 Figure 7. Elevation patterns of multiyear mean variables. (a) Leaf area index (LAI). (b) 10 m wind
 475 speed (10mW) at 00:00 and 12:00 utc. (c) 2 m air temperature (2mT) at 00:00 utc and 12:00 utc.

476 Together, these results identify precipitation, wind speed, and vegetation
 477 abundance as primary drivers of the elevation-dependent distribution of forest fires. At
 478 mid-elevations, fire activity is jointly controlled by sufficient fuel availability and
 479 aridity, the latter mediated by reduced precipitation and elevation-specific wind regimes.
 480 In addition, enhanced FAOD associated with fire-emitted smoke aerosols—dominated
 481 by light-absorbing black carbon (Yu et al., 2019)—may further contribute to
 482 atmospheric heating and fuel drying at seasonal to interannual timescales (Pei et al.,
 483 2025), potentially reinforcing fire-favorable conditions. Several potentially important
 484 drivers, including anthropogenic ignitions, lightning frequency, soil moisture, and
 485 regional fire management practices, were not explicitly considered in this analysis. In
 486 addition, the limited number of grid cells (< 10) between 1300 and 2100 m reduces
 487 statistical robustness, suggesting that fire controls at these elevations may be more
 488 complex at the global scale. This threshold differs from that used in the FAOD trend
 489 analysis because the two analyses are conducted at different spatial resolutions.

490 Specifically, the FAOD trend analysis is based on a 0.1° grid with a large number of
491 global grid cells, for which a threshold of 50 grid cells is applied to ensure statistical
492 representativeness. In contrast, the elevation-dependent regression analysis is
493 performed on a coarser 1° grid, where the number of available grid cells is substantially
494 smaller; therefore, a lower threshold of 10 grid cells is adopted to maintain sufficient
495 statistical robustness. These unaccounted factors likely contribute to the residual
496 variability in fire occurrence and warrant further investigation.

497 **4. Conclusion**

498 Across global forested regions from 2012 to 2024, we analyze spatiotemporal
499 variability in forest fire activity and its associated AOD, together with their elevation-
500 dependent drivers, across global forested regions during 2012–2024. Satellite
501 observations reveal a modest but statistically significant increase in forest fire
502 occurrence, with a global mean linear trend of $+2.89\% \text{ yr}^{-1}$. Fire trends vary
503 substantially among forest types, with ENF exhibiting the strongest positive trends,
504 while DNF and MF show no significant changes. Fire-associated aerosol loading is
505 dominated by fine-mode particles. The consistent positive trends and statistically
506 significant relationships between FAOD and fire pixel counts, together with the absence
507 of a corresponding response in CAOD, indicate that forest fire emissions primarily
508 enhance the fine aerosol fraction. Both the multiyear mean fire pixel counts and its
509 temporal trend decline systematically with increasing elevation, from lowlands to
510 elevations above 2000 m, highlighting a pronounced elevational control on global forest
511 fire activity. In contrast, FAOD exhibits a more complex elevational structure. Below
512 600 m, FAOD trends broadly track fire occurrence, whereas at mid-elevations (600–
513 1400 m) FAOD displays elevated mean values and increasing trends despite declining
514 fire occurrence. This divergence suggests that mid-elevation aerosol burdens are
515 influenced not only by local fire activity but also by shifts in forest-type composition
516 and by topographically modulated smoke transport, including aerosol self-lifting driven
517 by radiative absorption and atmospheric convection.

518 Elevation-stratified multiple linear regression analyses further indicate that forest

519 fire activity is primarily controlled by the combined effects of fuel availability and
520 aridity. Fuel load, represented by leaf area index, plays a critical role at mid-elevations,
521 while precipitation consistently exerts a suppressive influence on fire occurrence across
522 all elevation bands. Wind speed emerges as an important contributor to fuel drying and
523 fire spread, especially in mid-elevation regions. In contrast, temperature and the FWI
524 show limited independent explanatory power once elevation and other covarying
525 factors are considered. Overall, these results highlight elevation as an important
526 organizing dimension linking forest fire activity, aerosol emissions, and their
527 underlying drivers at the global scale. By elucidating how fuel characteristics,
528 meteorological conditions, and topography jointly regulate fire–aerosol interactions
529 across elevation gradients, this study provides a physically grounded framework for
530 improving wildfire risk assessment, interpreting fire-driven aerosol impacts, and
531 refining fire management strategies under a changing climate. Continued investigation
532 incorporating anthropogenic ignitions, lightning activity, and region-specific
533 management practices will be essential for further constraining elevation-dependent
534 fire regimes.

535

536 **Data availability**

537 Active fire detections at 375 m resolution were obtained from the NASA Land-SIPS
538 VIIRS product, provided through the Fire Information for Resource Management
539 System (FIRMS) (<https://earthdata.nasa.gov/firms>). Elevation information was derived
540 from the 2024 General Bathymetric Chart of the Oceans (GEBCO) global gridded
541 dataset (doi:10.5285/1c44ce99-0a0d-5f4f-e063-7086abc0ea0f), available at
542 <https://www.gebco.net/>. Land cover classifications were taken from the MODIS Land
543 Cover Type Yearly Climate Modeling Grid (CMG; MCD12Q1), distributed via the
544 Level-1 and Atmosphere Archive & Distribution System (LAADS DAAC)
545 (<https://ladsweb.modaps.eosdis.nasa.gov/search/order/1>). Historical Fire Weather
546 Index (FWI) data were sourced from the Copernicus Emergency Management Service
547 (<https://doi.org/10.24381/cds.0e89c522>). Meteorological variables and leaf area index
548 (LAI) were extracted from the ECMWF Reanalysis v5 (ERA5) archive
549 (<https://cds.climate.copernicus.eu/datasets>). The daily global FAOD and CAOD
550 datasets at 500 nm are available from the authors upon request.

551

552 **Author contributions**

553 CZ initiated and supervised the study. QP carried out the data analysis and drafted the
554 initial manuscript. XY contributed the daily global FAOD and CAOD datasets. All
555 authors (CZ, QP, XY, XY, AC, and XW) participated in improving the manuscript.

556

557 **Competing interests**

558 The authors declare that they have no conflict of interest.

559

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565

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