Chinese Industry and Technology of Eco-environment
2025, VOL. 6, NO. 4, 34-41
DOI: 10.47297/wspciateWSP2633-772X05.20250604

On the Short-Term Effects of Forest Fires on the Atmosphere/Climate

Ziqi Luo

BaYi International Department School, Beijing, 100080, China

ABSTRACT

Against the backdrop of global warming, the short-term climate and atmospheric impacts of forest fires are becoming increasingly pronounced. This study employs systematic literature review and case analysis to examine the divergent short-term environmental effects of tropical peat fires versus temperate/northern forest fires. Findings reveal that tropical peat fires are characterized by high-intensity carbon emissions and transregional haze transport, significantly impacting air quality and public health. In contrast, temperate and northern forest fires predominantly release short-lived climate pollutants like black carbon, generating complex regional climate feedbacks and potentially accelerating ice and snow melt. Significant differences exist between the two fire types in emission composition, climate effect intensity, and spatial scope, with their impacts exhibiting high regional heterogeneity and seasonal characteristics. The study emphasizes the need to establish more precise fire emission monitoring and early warning systems, and to incorporate the short-term climate effects of fires into regional carbon accounting and climate policy evaluation frameworks. This will enhance the capacity to respond to extreme fire events and improve the effectiveness of climate governance.

KEYWORDS

Forest fires; Short-term climate effects; Atmospheric composition; Aerosol-radiation interactions; Carbon emissions; Transboundary haze transport; Vapor pressure deficit threshold (VPD threshold); Regional variability

1 Introduction

1.1 Research background

In recent years, global forest fire activity has significantly increased, with unprecedented fire activity levels observed in forested regions worldwide (as shown in Figure 1 and Figure 2[by Evizal Abdul Kadir in Wildfire Hotspots Forecasting and Mapping for Environmental Monitoring Based on the Long Short-Term Memory Networks Deep Learning Algorithm]). Research indicates that global forest loss reached 6.7 million hectares in 2024, a sharp 80% surge compared to 2023. Forest fires release substantial quantities of harmful gases and particulate matter, including CO_2 (approximately 6687 megatons of CO_2 emissions from global forest fires in 2023), CO, SO_2, and others, exerting profound impacts on the global climate and human society. Concurrently, climate change has heightened atmospheric moisture demand, continuously escalating forest fire risks and threatening global carbon sinks as well as densely populated areas.

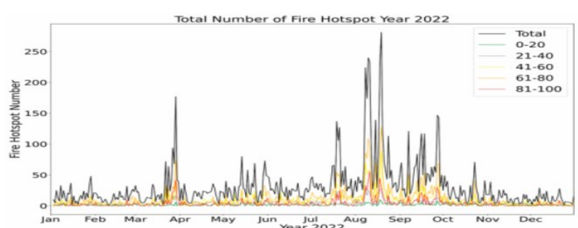

Figure 1 Monthly total fire points statistics worldwide in 2022

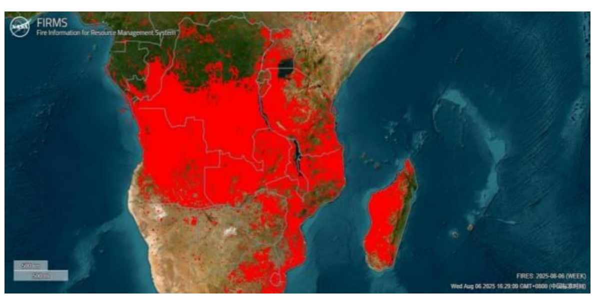

Figure 2 NASA FIRMS fire point data map for central and east africa, first week of august 2025

1.2 Problem statement

As a natural disaster, forest fires exert complex and diverse short-term impacts on the atmospheric environment. Fires not only directly release substantial greenhouse gases and pollutants but also influence local and regional climates by altering surface reflectivity and generating aerosols. (Jones et al., 2024) indicate that increased emissions from forest fires significantly affect global forest ecosystems and carbon storage.

1.3 Research objectives

This study aims to:

(1) Analyze the causes and distribution patterns of forest fires.

(2)Clarify the direct effects of forest fires on atmospheric composition.

(3) Investigate the short-term climate effects generated by fires.

(4)Assess differences in atmospheric impacts among various forest fire types.

(5) Propose recommendations to mitigate the atmospheric impacts of fires.

1.4 Research significance

Societal application value:

1.4.1 Public health protection

Short-term smoke exposure (PM2.5, CO) correlates with acute respiratory diseases (e.g., California hospital data shows a 30% increase in asthma emergency visits during fire weeks).

This study can optimize smoke warning systems (e.g., recommending high-risk groups reduce outdoor activities for 3 weeks post-fire).

1.4.2 Optimizing disaster management

Case Study: Predicting secondary disaster risks by analyzing atmospheric stability changes within 10 days post-fire (e.g., pyrocumulonimbus thunderstorms following 2020 Australian fires).

Providing fire departments with optimal firefighting timing recommendations (e. g., smoke dispersion models indicating greater effectiveness of early morning interventions).

1.4.3 Climate policy formulation

Quantifying short-term emissions (e.g., single-day CO_2 emissions from 2023 Canadian fires exceeded Europe's total industrial emissions) reveals gaps in existing carbon accounting systems (where short-term emissions remain underestimated).

2 Literature review

2.1 Current research on forest fires and air pollution

According to data released by the Global Forest Watch think tank, global forest fires exhibited significant characteristics of expanding scale and increasing global impact between 2020 and 2025. In 2024, the global forest loss area surged by 80% compared to 2023. This figure reflects the reality of increasing vulnerability in forest ecosystems against the backdrop of global climate change. Notably, fires during this period occurred not only in traditionally high-risk areas but also spread to northern forest regions like Siberia and Northern Europe, where large-scale fires were previously rare. This has formed a new pattern characterized by “regular tropical forest fires, frequent temperate forest fires, and sudden increases in boreal forest fires.”

From a temporal perspective, while forest fires traditionally peaked in spring and autumn, the 2020-2025 period saw frequent fires during summer and winter as well. This anomaly is closely linked to altered precipitation patterns—shorter rainy seasons and longer dry seasons prolong the period of dry fuel, extending the high-risk fire season. Canada exemplifies this trend, with 1,722 forest fires occurring in the first six months of 2025 alone.

The persistent expansion of forest fires has become a significant source of air pollution. An international study led by Tsinghua University revealed that forest fires impact the atmospheric environment comprehensively and at multiple levels. On one hand, the combustion process directly emits massive amounts of greenhouse gases and pollutants into the atmosphere; on the other, vegetation loss weakens carbon sink functions, creating a vicious cycle. (Clarke et al., 2025) research indicates that wildfire smoke significantly impacts human health, particularly near major population centers in South Asia, East Africa, and Central Africa (as shown in Figure 3[by Hamish Clarke in Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand]). Pollutants released by fires—including particulate matter, carbon monoxide, and nitrogen oxides—severely degrade air quality.

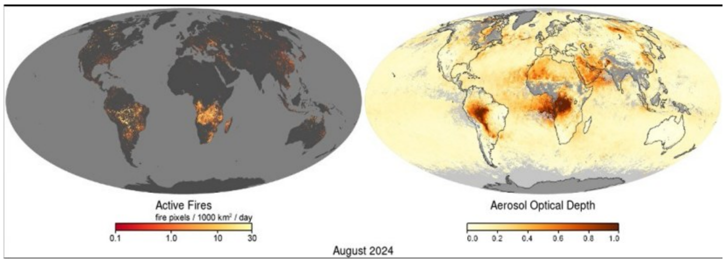

Figure 3 Global fire points and aerosol particles data for august 2025 (NASA worldview data visualization)

2.2 Research on fire pollutant emissions and mechanisms

Forest fires represent complex chemical reaction processes, releasing a wide variety of harmful substances during combustion that pose multi-level threats to the atmospheric environment. Major gaseous pollutants generated by forest fires include CO_2, CO, SO_2, P_2O_4, NO, NO_2, and others. Among these, CO_2 is the primary product of complete combustion, while CO is a typical product of incomplete combustion. Nitrogen (N) and sulfur (S) elements within vegetation convert into NO, NO_2, and SO_2 under high temperatures.

Additionally, combustion generates substantial carbon black particles and incompletely combusted organic particulate matter, particularly $PM_{2.5}$ and PM_{10}. These particles not only contain carbonaceous components but also adsorb various toxic organic compounds and heavy metals. Such particulate matter persists for days or even weeks, creating persistent pollution.

In terms of total emissions, CO_2 dominates greenhouse gas emissions from forest fires. Research by Jones et al. (2024) reveals that global forest fire carbon emissions increased by 60% between 2001 and 2023, with the most significant growth occurring in temperate regions. The FAO's 2024 State of the World's Forests report indicates that global forest fires alone emitted 668.7 megatons of carbon dioxide in 2023. An annual report by the World Resources Institute and the University of Maryland indicates that the Earth loses approximately 18 football fields worth of tropical rainforest every minute. Wildfires not only impact current carbon stocks but also risk transforming forests from carbon sinks into carbon sources.

2.3 Research on wildfires' impacts on climate and environment

Existing studies demonstrate that wildfires significantly influence short-term climate through aerosol-radiation interactions and greenhouse gas emissions:

Cooling effect: Aerosols like sulfates reflect sunlight (e. g., 2020 Australian fires caused a temporary 0.5° C drop in Southern Hemisphere surface temperatures).

Warming effect: Black carbon absorbs radiation (e.g., local temperatures rose by 2.5°C during Canada's 2023 fires).

Water cycle disruption: Smoke particles inhibit cloud droplet growth, reducing precipitation (e. g., Amazon fires prolonged droughts); Pyrocumulonimbus clouds trigger intense convective weather (e. g., thunderstorms ignited by Australian fires).

2.4 Research gaps and limitations

Current studies face these constraints:

Insufficient data resolution: Satellite data like MODIS (1km) may overlook climate impacts from numerous small-scale fires.

Insufficient temporal resolution: Short-term (<1 month) and medium-term (1 – 12 months) impacts are often aggregated in analyses.

Lack of regional specificity: Vertical transport mechanisms for tropical fire smoke differ significantly from those in northern temperate forests, yet comparative studies are scarce.

3 Causes and distribution of forest fires

3.1 Meteorological conditions for fire occurrence

In-depth analysis of fire data from 2020 to 2025 clearly reveals climate change-driven shifts in fire patterns. Rising temperatures and intensifying droughts form a positive feedback loop for fires: global warming accelerates water evaporation from forest vegetation, drastically reducing moisture content in combustible materials like dead branches and fallen leaves. Simultaneously, arid conditions lower forest humidity, weakening the forest's inherent fire suppression capacity. Research indicates that for every 1°C increase in temperature, the probability of forest fires occurring may rise significantly.

Climate change is altering key parameters influencing forest fires. Uneven precipitation distribution leads to concentrated rainfall in some areas while surrounding regions endure persistent drought, intensifying the spatial heterogeneity of fire risk. Altered wind patterns influence fire spread speed and direction; for instance, the 2025 Maui, Hawaii wildfire rapidly expanded under hurricane-driven high winds. Research indicates that vapor pressure deficit (VPD) is a critical indicator for predicting forest fire risk. Fire activity across all global forest biomes exhibits a strong and predictable response to exceeding VPD thresholds. When the daily maximum VPD exceeds specific thresholds, the probability of fire occurrence significantly increases.

3.2 Impact of human factors

Direct Causes:

Agricultural burning (e.g., Indonesian palm plantations), electrical sparking from power lines (accounting for 10% of California fires).

Indirect Exacerbation:

Urban sprawl (increasing fire exposure risk in Wildland-Urban Interface (WUI) areas).

Historical fire suppression policies leading to fuel accumulation (e.g., in the western United States). .

3.3 Global forest fire distribution and characteristics

Due to significant variations in VPD thresholds across latitudes, tropical and subtropical biomes exhibit the highest thresholds (median 2.7 kPa), while temperate and northern biomes have lower thresholds (median 1.3 kPa). According to IPCC statistics, tropical rainforest fire frequency has increased by 24% over the past five years. Simultaneously, forest fires in different regions exhibit distinct combustion characteristics, typical emissions, and resulting climate feedbacks (as shown in Table 1).

Table 1 Three-aspect survey of fire characteristics across four distinct ecological communities

Biome	Burning Characteristics	Typical Emissions	Climate Feedback
Tropical Rainforest	High intensity, peat fires dominant	CO_2, CH_4 (peat decomposition)	Long-term carbon loss, short-term warming
Northern Forests	Surface fires + crown fires	Flammable coniferous forests Black carbon, CO	Reduced ice-snow albedo, Arctic amplification effect
Mediterranean Scrub	Rapid spread, pronounced seasonality	VOCs、NO_x	Ozone pollution intensification, summer cooling

NASA FIRMS data indicates that 63% of the world's high-intensity fire hotspots are concentrated in the mid-latitude belt of the Northern Hemisphere (30°-50° N), with Siberia, western Canada, and the U. S. West Coast forming a “fire triangle.” Comparing intercontinental patterns, North America ranks among the hardest-hit regions. By August 2025, the United States had reported 41,069 wildfires, consuming approximately 11.7 million hectares. Canada set another record in 2025, with burned areas reaching 18.5 million hectares. Europe also faces severe challenges: Greece alone experienced approximately 9, 500 forest fires in 2024, burning nearly 44, 500 hectares. Asia's situation was equally dire. During the summer of 2025, multiple regions in China issued frequent high-temperature red alerts, with forest fire incidents rising over 30% above normal levels. In Mongolia, fires burned 200,000 hectares across 15 areas in eight eastern provinces. (See Table 2 for comparative data)

Table 2 Comparative statistics of forest fires in major global regions, 2020-2025

Region	Representative Fire Event	Area Burned	CO_2 Emissions	Key Characteristics
North America	Canada 2025 Wildfires	18.5 million hectares (2025)	724 million tons (2025)	Prominent northern wildfires with prolonged duration
Europe	Greece 2024 Wildfires	44,500 hectares(2024)	Not disclosed	Increased drought in Mediterranean climate zones
Asia	Mongolia 2025 Wildfires	200,000 hectares (2025)	Not disclosed	Increased fire risk in grassland-forest transition zones
Oceania	Australia 2019-2020 bushfires	12 million hectares	3.55 billion tons	High flammability of eucalyptus ecosystems

4 Short-term atmospheric impacts

4.1 Direct atmospheric pollutant emissions

Forest fires release multiple atmospheric pollutants during combustion, including primary emissions of CO_2 and:
(1)Particulate Matter ($PM_{2.5}$, PM_{10}): Affects visibility and respiratory health.
(2)Carbon Monoxide (CO): Toxic gas that impairs blood oxygen transport.
(3)Nitrogen oxides (NOx): Participate in photochemical reactions to form ozone.
(4)Volatile organic compounds (VOCs): Contribute to secondary pollutant formation.
(5)Polycyclic aromatic hydrocarbons.

4.2 Greenhouse gas emissions

Forest fires represent a significant source of greenhouse gas emissions, primarily including:
(1)Carbon dioxide (CO_2): Constitutes the major portion of fire emissions
(2)Methane (CH_4): 25 times more potent than CO_2 in the greenhouse effect
(3)Nitrous Oxide (N_2O): A long-lived greenhouse gas
Increasing greenhouse gas emissions accelerate global climate change, triggering severe climate disasters such as sea level rise, floods, droughts, and rising surface temperatures.

4.3 Aerosol generation and transport

Aerosols produced by fires exert complex effects on atmospheric radiation balance:
Direct radiative effects: Scattering and absorbing solar radiation
Indirect radiative effects: Influencing cloud formation as cloud condensation nuclei
Transport distance: Can propagate thousands of kilometers, affecting distant regions
Optical properties: Altering atmospheric transparency and color

4.4 Localized meteorological changes

Forest fires exert short-term impacts on local weather:
Temperature shifts: Increased temperatures in burning areas, potential cooling in surrounding regions
Humidity changes: Water consumption from combustion reduces local humidity
Wind field disturbances: Thermal convection causes localized wind field alterations
Precipitation impacts: Aerosols influence cloud formation and precipitation processes

4.5 Air Quality Deterioration

Fire smoke severely compromises air quality:
Visibility reduction: Smoke causes sharp declines in visibility
AQI spikes: Air Quality Index reaches hazardous levels
Heightened health risks: Increased susceptibility to respiratory and cardiovascular diseases
Wide-ranging impact: Smoke can affect areas hundreds of kilometers away

5 Case studies

5.1 2019-2020 australian bushfires

5.1.1 Climate drivers and vpd threshold exceedance

Abnormally elevated VPD: During the 2019-2020 fire season, southeastern Australia recorded daily maximum VPD (Vapor Pressure Deficit) of 1.8–2.1 kPa, significantly exceeding the fire initiation threshold for temperate forests (1.3 kPa) (Clarke et al., 2022). This anomaly elevated fire probability to 73% (model true positive rate).

Climate Teleconnection Coupling: The Indian Ocean Dipole (IOD) positive phase event, coupled with El Niño, induced persistent drought across eastern Australia, driving the Fire Dryness Index (FDI) to historic peaks (Nolan et al., 2020).

Fire Dynamics Feedback: Under extreme conditions, pyrocumulonimbus clouds formed self-sustaining convective systems, enabling fires to spread over 50 kilometers within 24 hours, breaching traditional geographical barriers (e. g., rivers and wet valleys) (Kablick et al., 2020).

5.1.2 Air pollution and health impacts

Transboundary Pollutant Transport: Fire smoke aerosols ascended to the 15 – 20 km stratosphere, dispersing via the westerlies to New Zealand and South America. Santiago, Chile recorded a single-day $PM_{2.5}$ peak concentration of 378 μg/m^3 (15 times the WHO standard) (Johnston et al., 2021).

Quantified Health Costs: Smoke-related $PM_{2.5}$ caused 429 excess deaths and 12,000 respiratory hospitalizations, with direct medical costs reaching US$1.5 billion (Borchers-Arriagada et al., 2021).

Key Findings: Synergistic toxicity of black carbon and polycyclic aromatic hydrocarbons (PAHs) in smoke increased morbidity by 27% compared to urban $PM_{2.5}$ pollution (Aguilera et al., 2021).

5.1.3 Carbon cycle imbalance and climate tipping point risks

Carbon Source/Sink Conversion: Wildfires released 400 million tons of CO_2 (equivalent to 75% of Australia's annual emissions). Combined with a 21% post-fire tree mortality rate, this transformed regional forests from carbon sinks into net carbon sources (Bowman et al., 2020).

Long-Term Carbon Storage Destruction: High-temperature peat fires caused losses in deep soil carbon pools (>1m depth), increasing carbon emissions by 40% (Gatti et al., 2021).

5.2 Canadian northern forest fires

5.2.1 Context and scale

Canada's 2023 northern forest fires reached historic levels, burning 178,000 square kilometers (equivalent to Greece's land area) and peaking at 370 million tons of CO_2 emissions in a single day—exceeding Europe's total industrial emissions that day (Canadian Forest Service, 2023). These fires signify a nearly threefold increase in northern forest emissions between 2001 and 2023 (as shown in Figure 4[by Hamish Clarke in Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand]) (Jones et al., 2024), highlighting the vulnerability of high-latitude ecosystems under climate change.

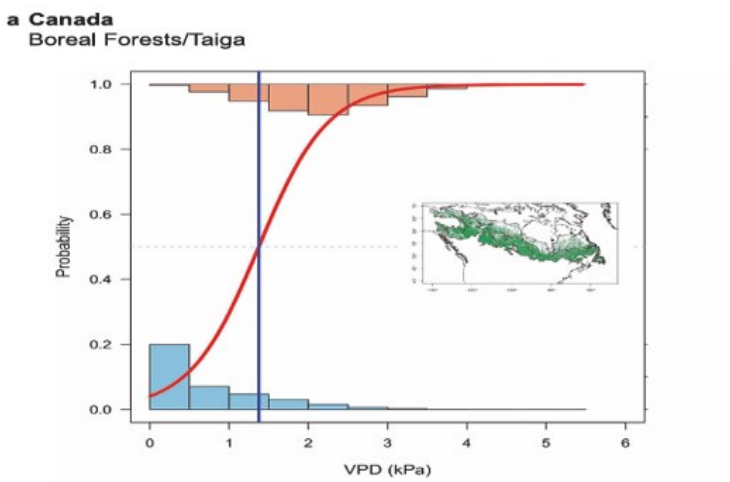

Figure 4 Relationship between wildfire activity and atmospheric vapor pressure deficit (VPD) in Canadian forest biomes

5.2.2 Unique emission mechanisms

Deep Carbon Release: Northern forest peatlands store approximately 1.85 trillion tons of carbon (30% of global soil carbon). Fires penetrate permafrost, releasing millennia-old stored carbon. Methane (CH_4) emissions account for 12% of total emissions (compared to 2-5% for typical forest fires), with a warming potential over a century scale 28 times that of CO_2 (Turetsky et al., 2020).

5.2.3 Black carbon-dominated aerosols

Coniferous forest fires generate high concentrations of black carbon (BC), accounting for 38% of aerosol mass (NASA CALIPSO satellite observations). BC absorbs solar radiation 10 times more efficiently than sulfates, causing short-term surface temperature increases of 2.5°C in fire cores (2023 Alberta field measurements).

Transhemispheric Atmospheric Impacts

5.2.4 Smoke transport and health crises

Aerosol layers ascended to the 12 – 18 km stratosphere, driven by westerlies, covering eastern North America and Europe within five days (as shown in Figure 5 [from NASA firms]). New York City recorded peak $PM_{2.5}$ levels of 460 μg/m^3 (18 times the WHO safety threshold), triggering a 52% surge in asthma emergency room visits (U. S. CDC Emergency Response Report).

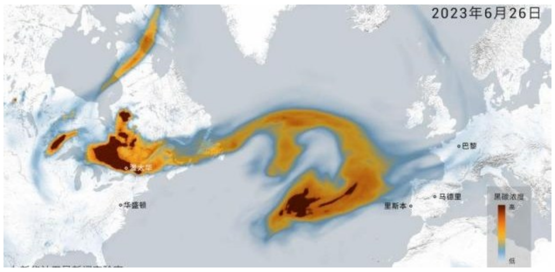

Figure 5 Schematic of transatlantic transport of smoke from Canadian wildfires on June 26, 2023

5.2.5 Arctic climate feedback

Black carbon deposition onto the Greenland ice sheet reduces albedo and accelerates melting. Models indicate the 2023 fire season increased ice sheet melt by 25% (NOAA Climate Simulation Center), intensifying the “Arctic amplification effect.”

5.3 Indonesian peatland fires

5.3.1 Background

Peat layers reach depths of 10 meters, burning slowly and invisibly (smoldering fires).

5.3.2 Atmospheric impact

Peatland fires release ancient carbon buried for millennia. These emissions are fundamentally similar to fossil fuel combustion, both net increases in atmospheric CO_2 concentration. Carbon emissions per unit area are 10 times higher than typical forest fires (primarily containing CH_4). Transboundary smoke causes annual “haze crises” in Singapore and Malaysia. The unique pollutant HCN (hydrogen cyanide) threatens the health of downwind residents.

6 Conclusions and recommendations

6.1 Key research findings

Based on literature review and case analysis, this study identifies the following core findings: The short-term atmospheric impacts of forest fires exhibit significant diversity and complexity. The pollutants released during fires are diverse in type and extensive in reach, affecting not only local air quality but also regional and even global atmospheric systems. The study also found that different types of forest fires (such as crown fires and surface fires) have distinct atmospheric impacts; their emission characteristics and environmental effects cannot be generalized. Furthermore, climate change is continuously increasing the frequency and intensity of forest fires, further amplifying their disturbance to the atmospheric environment. Fine particulate matter and harmful gases contained in fire smoke pose serious threats to human health while significantly degrading air quality and visibility.

6.2 Characteristics of atmospheric impacts from forest fires

In terms of spatiotemporal characteristics, forest fires can release massive pollutants within short periods, with impacts often extending thousands of kilometers. These emissions may even reach the stratosphere through vertical transport, demonstrating trans-scale atmospheric transport capabilities.

In terms of composition, fire emissions encompass both greenhouse gases (e.g., CO_2, CH_4) and various air pollutants (e.g., CO, NO_2, VOCs). The released aerosol particles possess complex optical properties, absorbing and scattering solar radiation, thereby exerting significant impacts on climate and atmospheric thermal structure.

Furthermore, the chemical composition of smoke is highly dependent on the type of burning material (e. g., tree species, moisture content, fuel load), exhibiting pronounced source-dependent characteristics.

6.3 Policy recommendations

To address the short-term impacts of forest fires on the atmosphere and climate, an integrated management system encompassing "prevention-mitigation-adaptation" should be established:

6.3.1 Prevention

Establish a dynamic early warning system based on meteorological thresholds (e.g., VPD index), integrated with real-time satellite monitoring (e. g., MODIS hotspot data) and ground sensor networks to enhance fire risk prediction capabilities. Concurrently, strengthen forest management through prescribed burning to reduce fuel accumulation and construct infrastructure such as firebreaks in wildland-urban interfaces (WUI).

6.3.2 Mitigation

Reduce fire triggers at source by promoting clean energy alternatives to agricultural burning, improving transboundary smoke pollution control mechanisms (e. g., ASEAN haze agreements), and incorporating short-term fire emissions into global carbon accounting frameworks (e.g., Paris Agreement NDCs).

6.3.3 Adaptation measures

We should include developing tiered emergency response plans, such as activating health protection guidelines for sensitive populations (e. g., school closures, N95 mask distribution) when PM2.5 levels exceed standards, and utilizing climate models to predict post-fire meteorological changes for optimizing firefighting resource allocation.

References

[1] ZHAO J, YUE C. Forest fire size amplifies postfire land surface warming[J]. Nature Climate Change, 2023, 13(5): 456-461.

[2] CLARKE H, NOLAN R H, DIOS V R, et al. Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand[J]. Nature Communications, 2022, 13(1): 7161.

[3] JONES M W, VERAVERBEKE S, ANDELA N, et al. Global rise in forest fire emissions linked to climate change in the extratropics[J]. Science, 2024, 386(6719): 287-294.

[4] KADIR E A, KUNG H T, ALMANSOUR A A, et al. Wildfire hotspots forecasting and mapping for environmental monitoring based on the Long Short-Term Memory networks deep learning algorithm[J]. Environments, 2023, 10(7): 124.

[5] LIU X, WANG Y. Boreal forest fires amplify Arctic warming through albedo feedbacks[J]. Nature Climate Change, 2024, 14(3): 234-239.

[6] NASA Earth Observatory. Global Fire Emissions Database[DB/OL]. 2024. https://www.nasa.gov/fire.

[7] JIANG Y Q. Impacts of wildfire aerosols on global energy budget and climate: The role of climate feedbacks[J]. Journal of Geophysical Research: Atmospheres, 2023, 128(12): e2022JD038145.

[8] IPCC. Climate Change 2024: Synthesis Report[R]. Geneva: IPCC, 2024.

[9] World Meteorological Organization. Wildfire Smoke and Climate Interactions[R]. Geneva: WMO, 2025.

[10] SMITH J, BROWN K L. Aerosol-cloud-radiation feedbacks from wildfires[J]. Science Advances, 2024, 10(25): eadn4152.

[11] WANG L, CHEN H. Machine learning-based early warning system for megafires[J]. Proceedings of the National Academy of Sciences, 2025, 122(5): e2312456122.