

Wildfire Exposure and Respiratory Health: A Comprehensive Review of Emerging Evidence

Running Title: When Forests Burn, Lungs Suffer

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Abstract

In January 2025, a devastating wildfire in Los Angeles, California, caused massive economic damage and posed a significant threat to public respiratory health. As climate change accelerates, the frequency and intensity of wildfires have raised significant global concern due to their profound impact on respiratory health.

Wildfire smoke contains high concentrations of ambient air pollutants, particularly particulate matter (PM_{2.5}, PM₁₀), carbon monoxide (CO), nitrogen oxides (NO_x), ozone (O₃) and various toxic compounds. Among these, wildfire-related PM is particularly harmful due to its ability to penetrate deep into the lower respiratory tract and alveoli, triggering more oxidative and inflammatory response, and contribute to the onset and exacerbation of respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD).

Studies show that short-term exposure to wildfire smoke has been associated with acute exacerbations of asthma, COPD, and pneumonia, resulting in increased mortality and healthcare utilization. Long-term exposure may contribute to the development and progression of COPD and is potentially associated with an increased risk of lung cancer and mortality. These findings highlight the serious threat it poses to both individual and public health, contributing to increased morbidity, mortality, and associated socio-economic costs.

This review provides a comprehensive synthesis of recent research on the respiratory health effects associated with wildfire smoke exposure. By presenting these findings, this review aims to inform healthcare professionals and public health policymakers, facilitating evidence-based strategies for clinical care, public health education, and disaster preparedness in the light of growing threat posed by wildfires.

Keywords: wildfire, wildfire smoke, PM_{2.5}, healthcare utilization, respiratory health, asthma, COPD

Introduction

In early January 2025, a series of large-scale wildfires erupted across the greater Los Angeles region, driven by unusually strong Santa Ana winds and prolonged drought conditions(1). (Figure 1.) The initial ignition occurred around January 7, and multiple fires remained active throughout the month. Among the most destructive (16,000 structure damage, 40,000 acre burned area estimated) were the Palisades Fire, which affected areas in Pacific Palisades and Malibu, and the Eaton Fire, which burned through Altadena and Pasadena(2). These two incidents accounted for the majority of burned acreage and structural damage across the county(3).

Santa Ana winds are strong, seasonally recurring winds that predominantly occur between October and January, moving from inland high-pressure systems located in western Utah and eastern Nevada toward the coastal areas of Southern California(4, 5). As these air masses descend along the leeward slopes of the Sierra Nevada, they experience adiabatic warming and drying, leading to a marked increase in temperature and a sharp decline in relative humidity(6). This transformation results in hot, desiccating winds that significantly elevate the risk of wildfire ignition and spread, particularly in coastal regions where vegetation is already moisture-stressed⁽⁷⁾. Such meteorological phenomena are of considerable concern in environmental health, as they contribute not only to increased wildfire activity but also to subsequent air quality degradation and respiratory health risks in affected populations(8).

Multiple climatic and meteorological factors have been proposed to explain the unprecedented severity of the 2025 Los Angeles wildfires, including the compounding effects of strong seasonal winds and broader climate variability. One notable contributor is the influence of the El Niño–La Niña transition. During the 2023–2024 El Niño phase, increased rainfall led to rapid vegetation growth across California, especially in the southern regions, providing abundant fuel for future fire ignition(9). However, beginning in mid-2024, a prolonged dry period—marked as the second driest from May 2024 to January 2025 since 1877—resulted in widespread vegetation desiccation(10, 11). This was further exacerbated by the onset of a weak La Niña event in December 2024, which persisted through early

2025. This climatic shift redirected precipitation northward, intensifying drought conditions in Southern California and significantly increasing fire susceptibility(12, 13). The synergy of these climate anomalies underscores how global climatic oscillations, particularly El Niño Southern Oscillation (ENSO)-related dynamics, now play a central role in amplifying regional wildfire hazards in California.

In 2022, South Korea experienced significant wildfires, particularly in the eastern regions. A major wildfire originating in Uljin and extending to Samcheok devastated forest, while additional fires in the Gangneung and Donghae areas resulted in the total loss of 24,000 hectares, leading to substantial environmental and economic impacts(14). These wildfires produced massive plumes of smoke and particulate matter, severely affecting regional air quality. National statistics reported a 3.7% increase in annual PM2.5 emissions compared to the previous year(15), illustrating the fires' contribution to air pollution (Figure 2).

The Yeongdong region of Gangwon Province, where these fires occurred, is seasonally affected by a local wind phenomenon known as *Yangganjipung*—a hot and dry foehn wind that descends from the Taebaek Mountains during the spring(16). These winds can reach intensities comparable to typhoons, rapidly accelerating fire spread. Similar meteorological conditions have been identified as major contributing factors in past megafires along the East Sea coast, including the 1996 Goseong fire, the 2000 Donghae coastal fire, and the 2005 Yangyang fire.

Climate change is increasingly recognized as an aggravating factor for wildfire risk in South Korea. Over the past century, the country's average annual temperature has increased by approximately 1.6°C, with the most significant warming observed during spring(17, 18). Since spring is traditionally the peak wildfire season, rising temperatures accelerate evapotranspiration, leading to drier soil and vegetation(19, 20). While most wildfires are initially ignited by human activity, their escalation into large-scale catastrophes is facilitated by the synergy among elevated temperatures by climate change, intrinsic forest structural vulnerabilities, and localized wind patterns. The large-scale wildfires that erupted in Uiseong and Andong in March 2025 likewise exemplify the continuation of this climate-

driven phenomenon. These conditions not only cause extensive forest loss but also contribute to secondary environmental and public health impacts such as air pollution and particulate matter-related illness.

Air Pollutants Released During Wildfires

Wildfire smoke contains a complex mixture of pollutants. The composition of air pollutants in wildfire smoke is highly variable and influenced by multiple factors, including the type of materials burned, prevailing meteorological conditions at the time of the fire, and the distance from the ignition source. Among them, the major air pollutants that affect human health include particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), nitrogen oxides (NO₂ and NO), ozone (O₃), and volatile organic compounds (VOCs)(7, 17, 19, 21-23). Carcinogenic substances, such as benzene, formaldehyde, and trace metals like lead and mercury, are also present in wildfire smoke and contribute to its toxicological burden(24). Particulate matter (PM) is commonly recognized as the most significant health-impacting component in the majority of wildfire smoke exposures. PM_{2.5} levels in wildfire smoke can rapidly exceed 200 µg/m³, which is more than ten times the typical ambient levels and far surpasses the WHO's recommended exposure limits(25, 26). PM in wildfire smoke has been elucidated to contain more oxidative and proinflammatory constituents—such as oxygenated polycyclic aromatic hydrocarbons and quinones—than urban PM, potentially leading to stronger toxic effects(27). Moreover, particulate matter from wildfires tends to include smaller ultrafine particles, which can travel longer distances and exert broader health effects(28).

Inhalation and Physiological Responses to Wildfire-Related Pollutants

When wildfire smoke is inhaled, fine and ultrafine particulate matter including PM_{2.5} can reach the lower airways and alveolar spaces, where they may trigger a cascade of inflammatory and immune-

mediated responses(21). Laboratory studies using mouse models have shown that wildfire-derived particulate matter induces cell-specific oxidative stress and inflammatory responses in the lung, with PM_{2.5} in particular demonstrating greater toxicity through enhanced pulmonary injury and systemic inflammation.(29-31) Generally, inhaled PM_{2.5} promotes the generation of reactive oxygen species (ROS), which activate the NLRP3 inflammasome leading to pyroptotic cell death through proinflammatory cytokines such as IL-1 β and IL-18.(32) Especially, reactive oxygen species (ROS) from wildfire smoke can cause damage to DNA, interfere with mitochondrial activity, and impair the cell's ability to repair itself which may consequently lead to genomic instability and chronic lung injury.(33, 34) Carcinogens such as polycyclic aromatic hydrocarbons (PAHs) in wildfire smoke can induce mutagenicity and lung toxicity through direct inhalation(35). Furthermore, toxic gaseous components and PM_{2.5} impair epithelial barrier integrity by activating TRPA1 ion channels in epithelial and sensory neurons, leading to abundant calcium influx, mitochondrial stress and neurogenic inflammation.(36) Additionally, wildfire smoke alters the macrophages and disrupt human lung epithelial cells, inducing the onset or exacerbation of respiratory infections and airway diseases such as asthma and COPD(37, 38).

Health Impacts of Short-term wildfire Smoke Exposure

1. Mortality – All-Cause and Respiratory Disease Mortality

Exposure to wildfire smoke has been associated with increased mortality in the general population. Its particulate matter is smaller and contains higher levels of oxidative and proinflammatory components compared to urban sources, contributing to elevated risks of respiratory and cardiovascular mortality. Previous studies have confirmed that exposure to wildfire smoke increases mortality from respiratory diseases(7, 27, 39-45). According to a recently published systematic reviews, increased exposure to wildfire-related PM_{2.5} is associated with a corresponding rise in all-cause and respiratory

disease mortality risk(24, 46, 47). Additionally, exposure to ozone secondarily formed from wildfires has also been shown to contribute to increased respiratory disease mortality(40). Mortality caused by wildfire smoke not only poses a serious threat to public health but has also been reported to result in substantial economic losses(48).

2. Healthcare utilization – Emergency Department Visits, Physician Visits, and Hospital Admissions

A. All-cause respiratory disease healthcare utilization

Wildfires release large quantities of air pollutants over short durations, typically lasting a few weeks, resulting in elevated concentrations of particulate matter (PM) and other harmful substances. These exposures contribute to both the onset and acute exacerbation of respiratory diseases, leading to increased healthcare utilization, especially among individuals with pre-existing health conditions, through emergency department visits, outpatient consultations, and hospital admissions(7, 24, 27, 39, 46).

Emergency department visits are the most sensitive healthcare utilization indicator for capturing acute exacerbations of respiratory diseases associated with wildfire smoke exposure. Wildfire-related PM_{2.5} has been associated with an increased risk of emergency department visits for respiratory disease, particularly among individuals with a history of asthma or chronic obstructive pulmonary disease (COPD)(24, 47, 49-58). Wildfire-related PM_{2.5} also significantly increased the risk of physician visit(59) and hospital admissions for respiratory diseases(24, 25, 55, 60-63).

B. Disease specific Healthcare Utilization

Asthma

Asthma is the most strongly affected respiratory condition by wildfire smoke exposure. This is primarily due to the unique characteristics of wildfire smoke, which contains a high proportion of

ultrafine particulate matter capable of penetrating deep into the distal airways(31). Wildfire smoke, rich in oxidative and proinflammatory components, exacerbates asthma through epithelial barrier disruption and immune activation via oxidative stress and cytokine pathways, leading to heightened airway inflammation and hyperresponsiveness(31, 64). Exposure to wildfire PM_{2.5} was significantly associated with acute exacerbation of asthma. There is evidence suggesting that wildfire smoke-induced acute exacerbations of asthma can elevate asthma-related mortality by over three times(65). And wildfire smoke induced acute exacerbations of asthma can cause healthcare utilization, including emergency department visits(47, 49, 51-53, 55-58, 66), hospital admissions(52, 55, 60, 61, 67) (Table 1). According to a meta-analysis, short-term exposure to wildfire smoke PM_{2.5} is significantly associated with increased risks of asthma-related hospital admissions (RR=1.06, 95% CI: 1.02–1.09) and emergency department visits (RR=1.07, 95% CI: 1.04–1.09), with particularly pronounced effects observed among older adults and children(64). Meanwhile, among pediatric asthma patients, the use of rescue medications has been shown to be effective, supporting current recommendations for prescribing rescue therapy to children as a vulnerable group during wildfire smoke exposure(68).

COPD

Chronic obstructive pulmonary disease (COPD) is a highly prevalent respiratory condition that contributes significantly to healthcare utilization worldwide. Exposure to wildfire smoke recognized one of the important environmental exposures to the progression and exacerbation of COPD(69). Wildfire smoke exacerbates COPD by impairing autophagic flux and disrupting airway epithelial barrier integrity, thereby amplifying inflammation and epithelial fragility(70). Wildfire smoke exposure was associated with a significantly increased risk of COPD mortality (OR=1.14, 95% CI: 1.02–1.26) in a case-crossover study conducted in Washington State.(43) Exposure to wildfire smoke PM_{2.5} has been consistently linked to exacerbation of COPD and increased healthcare utilization, including hospitalization(60, 61, 65, 67), emergency department visit(50-53, 56, 71), and outpatient visits(59) (Table 2).

Miscellaneous diseases: Respiratory tract infectious disease (Pneumonia) and Interstitial lung disease

Exposure to wildfire smoke can lead to dysregulation of the respiratory immune system, increasing susceptibility to respiratory tract infections, such as pneumonia(7, 21). Exposure to wildfire-related PM_{2.5} can elevate the risk and severity of pneumonia by promoting lung inflammation, weakening respiratory epithelial integrity and immune function, facilitating deeper viral invasion, and intensifying pro-inflammatory cytokine activity. Through these mechanisms, short-term exposure of wildfire-related PM_{2.5} has been shown to significantly increase hospital admissions(67) and emergency department visits(53, 71) for pneumonia. Patients with interstitial lung disease (ILD) may exhibit similar clinical vulnerability to wildfire smoke such as increased ER visits and ICU admissions—epidemiological research on this association remains scarce.

Health Impacts of long-term wildfire Smoke Exposure

Long term exposure to wildfire smoke recognized one of the important environmental exposures to the development and progression of respiratory disease. Although numerous studies have elucidated the short-term effects of wildfire smoke, evidence on long-term health effect of wildfire smoke is still limited. A natural experiment based on the 1997 Indonesian wildfires revealed that lung capacity remained reduced even 10 years after exposure, particularly in men and older adults, while children showed near-complete recovery. Despite influences from age and socioeconomic status, air pollution was identified as a key determinant of long-term lung function(72).

Recently, the GOLD guidelines incorporated the classification system proposed by *The Lancet Commission on COPD*, categorizing COPD into five etiological subtypes(73, 74). Among these, a new subtype termed COPD-P (pollution-related COPD) was introduced, reflecting disease caused by environmental exposures(74). As the link between COPD pathogenesis and environmental exposures

becomes increasingly recognized, the impact of wildfire smoke exposure on COPD has garnered growing attention(69).

Lung cancer is known to be strongly influenced by exposure to environmental pollutants. In recent years, growing attention has been paid to the impact of air pollution on both the incidence and mortality of lung cancer, and wildfire smoke has emerged as an increasingly important area of investigation in this context. Several studies have suggested that exposure to wildfire-related PM_{2.5} may increase cancer mortality more than general PM_{2.5}, with a significant association observed for lung cancer mortality (HR: 1.011, 95% CI: 1.004–1.018)(75, 76). Long-term exposure to wildfire smoke has been associated with an increased risk of lung cancer. In a large population-based cohort study conducted in Canada, Korsiak et al. (2022) reported that individuals residing within 50 km of wildfire events over the past 10 years had a 4.9% higher hazard of developing lung cancer compared to unexposed populations (HR = 1.049, 95% CI: 1.028–1.071)(77). These findings support that chronic exposure to wildfire smoke contribute to the development of lung cancer over time.

Conclusion

Climate change caused by global warming is exerting adverse effects on nature and public health. By expanding arid regions and extreme wind conditions, global warming is directly associated with increasing frequency of large-scale wildfire. These large-scale wildfires are expected to make significant threats to public health, particularly respiratory diseases.

Wildfire smoke contains a variety of harmful air pollutants, among which fine particulate matter (PM_{2.5}) is considered the most crucial to respiratory health. Wildfire PM_{2.5} contains higher oxidative and proinflammatory potential, making it more harmful when inhaled. Short-term exposure has been linked to acute exacerbations of respiratory conditions such as asthma, chronic obstructive pulmonary disease (COPD), and pneumonia, contributing to increased emergency department visits and hospital

admissions. Furthermore, there is growing evidence of long-term consequences, including the development or progression of COPD and lung cancer, underscoring the sustained public health burden of wildfire smoke exposure.

As the frequency and intensity of wildfires continue to rise, the role of healthcare professionals will become increasingly critical. A solid, evidence-based understanding of wildfire smoke's impact on various respiratory diseases is essential. Physicians should also proactively educate and prepare vulnerable patient populations for wildfire events. In addition, there remains a significant paucity of evidences on the effects of wildfire smoke in rare diseases such as interstitial lung disease (ILD), despite the presumed heightened vulnerability of these populations. Therefore, it would be critical to further conduct targeted epidemiological studies to better understand the consequences of wildfire smoke exposure in individuals with ILD and other rare diseases. Ultimately, enhancing our understanding of wildfire-related health impacts will not only improve individual patient care but also contribute to public health strategies and policymaking in response to climate change. Wildfires are no longer distant events affecting others, they are a pressing concern that we must all address.

Tables

Table 1. Research Assessing the Impact of Wildfire Smoke Exposure on Asthma-Related Healthcare Utilization (Emergency Department Visits and Hospital Admissions)

Author	Year	Wildfire Location	Study Participants	Main Result (OR/RR, 95%CI) for each outcome
Asthma related Emergency Department Visit (EDV)				
Rappold et al.	2011	North Carolina, USA	Records of 111 of 114 civilian North Carolina EDs	1.65 (1.25–2.10) (RR)
Resnick et al.	2015	New Mexico, USA	0.55 million population	1.08 (0.91–1.29) (RR)
Haikerwal et al.	2015	Victoria, Australia	5.1 million population	1.02 (1.00–1.04) (RR)
Alman et al.	2016	Colorado, USA	10,699 ED records	1.04 (1.02–1.06) (OR)
Reid et al.	2016	California, USA	12.7 million population	1.06 (1.05–1.07) (RR)

Parthum et al.	2017	Virginia, USA	2 million population	1.65 (1.25–2.17) (RR)
Hutchinson et al.	2018	California, USA	176,851 healthcare utilized population	2.12 (1.57–2.86) (RR)
Borchers Arriagada et al.	2019	Meta-analysis	20 Studies (Meta-analysis)	1.07 (1.04–1.09) (RR)
Malig et al.	2021	California, USA	Bay Area population	1.56 (1.49–1.64) (RR)
Tornevi et al.	2021	Jämtland Härjedalen Region, Sweden	130,000 population	1.68 (1.09–2.57) (RR)
Heaney et al.	2022	California, USA	Total population of California	1.10 (1.02–1.19) (RR)
Duncan et al.	2023	North Carolina, USA	12,483 ED records	1.10 (1.06–1.14) (OR)
Chen et al.	2023	California, USA	17,847,917 population	1.57 (1.45–1.71) (RR)
Schweizer et al.	2023	California, USA	Total population of California	1.38 (1.21–1.57) (OR)
Doubleday et al.	2023	Washington, USA	1,864,470 non-traumatic ED visits	1.13 (1.10–1.17) (OR)
Asthma related Hospital admission				
Morgan et al.	2010	Sydney, Australia	3.5 million population of Sydney	1.05 (1.02–1.08) (RR)
Kollanus et al.	2016	Helsinki, Finland	1 million population of Helsinki	1.16 (0.98–1.37) (RR)
Reid et al.	2016	California, USA	12.7 million population of California	1.07 (1.05–1.10) (RR)
Gan et al.	2017	Washington, USA	26,835 admissions	1.07 (1.02–1.14) (OR)
Borchers Arriagada et al.	2019	Meta-analysis	20 Studies (Meta-analysis)	1.06 (1.02–1.09) (RR)
Malig et al.	2021	California, USA	Bay Area population of San Francisco	1.22 (1.06–1.40) (RR)
Magzamen et al.	2021	Colorado, USA	46,585 admissions of Colorado	1.46 (1.09–1.94) (OR)

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240 **Table 2. Research Assessing the Impact of Wildfire Smoke Exposure on COPD-Related**
241 **Healthcare Utilization (Emergency Department Visits and Hospital Admissions)**

Author	Year	Wildfire Location	Study Participants	Main Result (OR/RR, 95%CI) for each outcome
COPD related Emergency Department Visit (EDV)				
Rappold et al.	2011	North Carolina, USA	Records of 111 of 114 civilian North Carolina EDs	1.73 (1.06–2.83) (RR)
Alman et al.	2016	Colorado, USA	10,699 ED records	1.05 (1.02–1.08) (OR)
Reid et al.	2016	California, USA	12.7 million population	1.02 (1.01–1.04) (RR)
Parthum et al.	2017	Virginia, USA	2 million population	1.73 (1.06–2.83) (RR)
Duncan et al.	2023	North Carolina, USA	12,483 ED records	2.93 (1.59–5.41) (OR)
COPD related Hospital admission				
Morgan et al.	2010	Sydney, Australia	3.5 million population	1.04 (1.01–1.06) (RR)

Gan et al.	2017	Washington, USA	26,835 cardiopulmonary hospital admissions	1.08 (1.03–1.15) (OR)
Magzamen et al.	2021	Colorado, USA	46,585 hospital admissions	1.15 (1.00–1.31) (OR)

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Figure legends

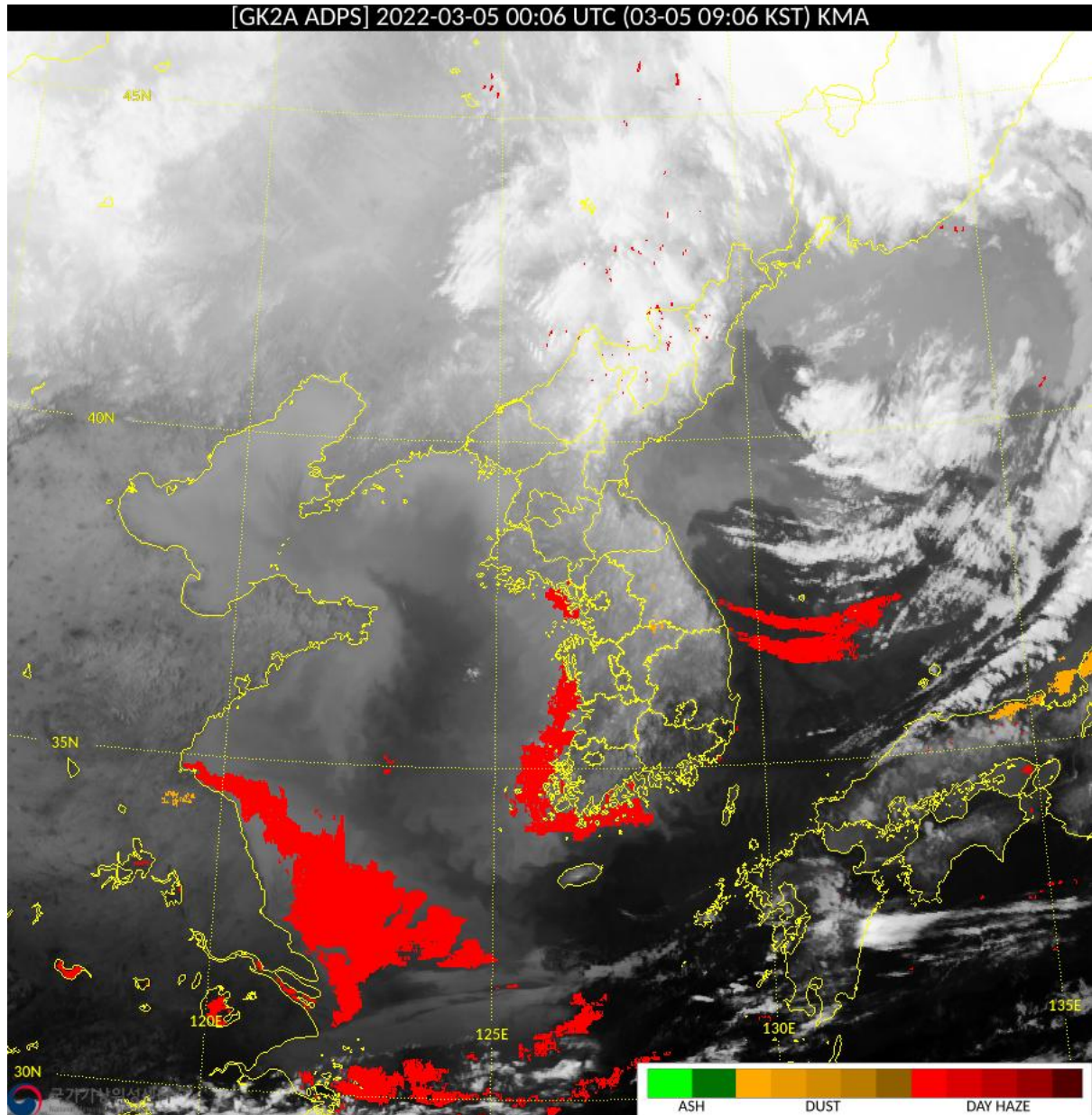
Figure 1. Satellite Image of Wildfire Smoke Dispersion in Southern California (January 2025)

Image was captured by the [Copernicus Sentinel-3 mission](#) on 9 January 2025, shows the Palisades fire at lower left and the Eaton fire at upper right, with smoke seen reaching Catalina Island and the Santa Barbara reserve to the south of the fires. ©ESA(78)



Figure 2. Satellite Imagery of Wildfire-Associated Air Pollution in Korea (March 2022)"

2022 March, GEO-KOMPSAT-2A Detection of Yellow Dust, Aerosols, and Volcanic Ash(79)



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267 Software: all authors. Validation: all authors. Investigation: all authors. Writing - original draft

268 preparation: KM Gu, T Lee. Writing - review and editing: all authors. Approval of final

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Reference

1. Lindsey R. The weather and climate influences on the January 2025 fires around Los Angeles.: Climate.gov; 2025 February 19th.
2. Wikipedia contributors. January 2025 Southern California wildfires: Wikipedia; 2025 [Available from: https://en.wikipedia.org/wiki/January_2025_Southern_California_wildfires.
3. Los Angeles Economic Development Corporation. LAEDC 2025 LA Wildfires Study. Los Angeles Economic Development Corporation (LAEDC); 2025.
4. Raphael M. The santa ana winds of california. *Earth Interactions*. 2003;7(8):1–13.
5. National Weather Service. Santa Ana Winds: National Oceanic and Atmospheric Administration 2025 [Available from: <https://www.weather.gov/glossary>.
6. Keeley JE, Syphard AD. Climate Change and Future Fire Regimes: Examples from California. *Geosciences*. 2016;6(3):37.
7. Reid CE, Brauer M, Johnston FH, Jerrett M, Balmes JR, Elliott CT. Critical review of health impacts of wildfire smoke exposure. *Environmental health perspectives*. 2016;124(9):1334–43.
8. NOAA Climate.gov. El Niño & La Niña (El Niño–Southern Oscillation): National Oceanic and Atmospheric Administration 2025 [Available from: <https://www.climate.gov/enso>.
9. NASA Earth Observatory. Fuel for California Fires: NASA Earth Observatory 2025 [Available from: <https://earthobservatory.nasa.gov/images/152174/fuel-for-california-fires>.
10. NOAA Climate.gov. January 2025 update: La Niña is here: National Oceanic and Atmospheric Administration 2025 [Available from: <https://www.climate.gov/news-features/blogs/enso/january-2025-update-la-niña-here>.
11. NASA Earth Observatory. Fuel for California Fires: NASA Earth Observatory; 2025 [Available from: <https://earthobservatory.nasa.gov/images/152174/fuel-for-california-fires>.
12. Namu Wiki. March 2022 Uljin-Samcheok Wildfire: Namu Wiki; 2025 [Available from: <https://en.namu.wiki/w/2022%EB%85%84%20%EC%9B%94%20%EC%9A%B8%EC%A7%84-%EC%82%BC%EC%B2%99%20%EC%82%B0%EB%B6%88?from=2022%EB%85%84%20%EC%9A%B8%EC%A7%84-%EC%82%BC%EC%B2%99%20%EC%82%B0%EB%B6%88#fn-reference>.
13. NOAA Climate.gov. January 2025 update: La Niña is here: National Oceanic and Atmospheric Administration; 2025 [Available from: <https://www.climate.gov/news-features/blogs/enso/january-2025-update-la-niña-here>.

- 304 14. Air Korea. 2022 National Air Pollutant Emissions Disclosure (Press Release)
305 (National Fine Dust 12.17). Sejong, Republic of Korea: Department of Environment,; 2024.
- 306 15. Yum N, Kim Y, Im A, Lee E. Spatiotemporal Patterns and Climatological Processes
307 of Large Spring Wildfire in Yeongdong, Gangwon-do, Korea. *Journal of the Korean*
308 *Geographical Society*. 2024;59(3):401–16.
- 309 16. Bae M, Chae H. Regional Characteristics of Forest Fire Occurrences in Korea from
310 1990 to 2018. *J Korean Soc Hazard Mitig*. 2019;19(7):305–13.
- 311 17. Urbanski SP, Hao WM, Baker S. Chemical composition of wildland fire emissions.
312 *Developments in environmental science*. 2008;8:79–107.
- 313 18. Climate Change Monitoring Division CSB. Climate Change Analysis Report of Korea:
314 109 Years (1912–2020). Seoul: Korea Meteorological Administration,; 2021.
- 315 19. Stone SL, Anderko L, Berger M, Butler CR, Cascio WE, Clune A, et al. Wildfire smoke:
316 a guide for public health officials. US Environmental Protection Agency. 2019.
- 317 20. Sung M-K, Lim G-H, Choi E-H, Lee Y-Y, Won M-S, Koo K-S. Climate change over
318 Korea and its relation to the forest fire occurrence. *Atmosphere*. 2010;20(1):27–35.
- 319 21. Xu R, Yu P, Abramson Michael J, Johnston Fay H, Samet Jonathan M, Bell Michelle
320 L, et al. Wildfires, Global Climate Change, and Human Health. *New England Journal of*
321 *Medicine*. 2020;383(22):2173–81.
- 322 22. dos SANTOS LR, Alves-Correia M, Câmara M, Lélis M, Caldeira C, da Luz Brazão M,
323 et al. Multiple victims of carbon monoxide poisoning in the aftermath of a wildfire: a case
324 series. *Acta medica portuguesa*. 2018;31(3):146–51.
- 325 23. Reid CE, Considine EM, Watson GL, Telesca D, Pfister GG, Jerrett M. Associations
326 between respiratory health and ozone and fine particulate matter during a wildfire event.
327 *Environment international*. 2019;129:291–8.
- 328 24. Gould CF, Heft-Neal S, Johnson M, Aguilera J, Burke M, Nadeau K. Health Effects
329 of Wildfire Smoke Exposure. *Annu Rev Med*. 2024;75:277–92.
- 330 25. Aguilera R, Corringham T, Gershunov A, Benmarhnia T. Wildfire smoke impacts
331 respiratory health more than fine particles from other sources: observational evidence from
332 Southern California. *Nature Communications*. 2021;12(1):1493.
- 333 26. Ketcherside DT, Miller DD, Kenerson DR, Scott PS, Andrew JP, Bakker MAY, et al.
334 Effects of Wildfire Smoke on Volatile Organic Compound (VOC) and PM2.5 Composition
335 in a United States Intermountain Western Valley and Estimation of Human Health Risk.
336 *Atmosphere*. 2024;15(10):1172.
- 337 27. Cascio WE. Wildland fire smoke and human health. *Science of the total*

environment. 2018;624:586–95.

28. Dong TT, Hinwood AL, Callan AC, Zosky G, Stock WD. In vitro assessment of the toxicity of bushfire emissions: A review. *Science of the total environment*. 2017;603:268–78.

29. Williams KM, Franzi LM, Last JA. Cell-specific oxidative stress and cytotoxicity after wildfire coarse particulate matter instillation into mouse lung. *Toxicol Appl Pharmacol*. 2013;266(1):48–55.

30. Wegesser TC, Pinkerton KE, Last JA. California wildfires of 2008: coarse and fine particulate matter toxicity. *Environ Health Perspect*. 2009;117(6):893–7.

31. Verma V, Polidori A, Schauer JJ, Shafer MM, Cassee FR, Sioutas C. Physicochemical and toxicological profiles of particulate matter in Los Angeles during the October 2007 southern California wildfires. *Environ Sci Technol*. 2009;43(3):954–60.

32. Ren F, Xu J, Zhang J, Xu X, Huang L, Sun W, et al. PM(2.5) induced lung injury through upregulating ROS-dependent NLRP3 Inflammasome-Mediated Pyroptosis. *Immunobiology*. 2022;227(3):152207.

33. Liu X, Chen Z. The pathophysiological role of mitochondrial oxidative stress in lung diseases. *J Transl Med*. 2017;15(1):207.

34. Wong JPS, Tsagkaraki M, Tsiodra I, Mihalopoulos N, Violaki K, Kanakidou M, et al. Effects of Atmospheric Processing on the Oxidative Potential of Biomass Burning Organic Aerosols. *Environ Sci Technol*. 2019;53(12):6747–56.

35. Kim YH, Warren SH, Krantz QT, King C, Jaskot R, Preston WT, et al. Mutagenicity and Lung Toxicity of Smoldering vs. Flaming Emissions from Various Biomass Fuels: Implications for Health Effects from Wildland Fires. *Environ Health Perspect*. 2018;126(1):017011.

36. Xu M, Zhang Y, Wang M, Zhang H, Chen Y, Adcock I, et al. TRPV1 and TRPA1 in Lung Inflammation and Airway Hyperresponsiveness Induced by Fine Particulate Matter (PM 2.5). *Oxidative Medicine and Cellular Longevity*. 2019;2019:1–15.

37. Roscioli E, Hamon R, Lester SE, Jersmann HPA, Reynolds PN, Hodge S. Airway epithelial cells exposed to wildfire smoke extract exhibit dysregulated autophagy and barrier dysfunction consistent with COPD. *Respiratory Research*. 2018;19(1):234.

38. Nakayama Wong LS, Aung HH, Lamé MW, Wegesser TC, Wilson DW. Fine particulate matter from urban ambient and wildfire sources from California's San Joaquin Valley initiate differential inflammatory, oxidative stress, and xenobiotic responses in human bronchial epithelial cells. *Toxicol In Vitro*. 2011;25(8):1895–905.

39. Black C, Tesfaigzi Y, Bassein JA, Miller LA. Wildfire smoke exposure and human health: Significant gaps in research for a growing public health issue. *Environ Toxicol Pharmacol*. 2017;55:186–95.
40. Chen G, Guo Y, Yue X, Xu R, Yu W, Ye T, et al. All-cause, cardiovascular, and respiratory mortality and wildfire-related ozone: a multicountry two-stage time series analysis. *The Lancet Planetary Health*. 2024;8(7):e452–e62.
41. Ye T, Xu R, Yue X, Chen G, Yu P, Coêlho M, et al. Short-term exposure to wildfire-related PM(2.5) increases mortality risks and burdens in Brazil. *Nat Commun*. 2022;13(1):7651.
42. Jegasothy E, Hanigan IC, Van Buskirk J, Morgan GG, Jalaludin B, Johnston FH, et al. Acute health effects of bushfire smoke on mortality in Sydney, Australia. *Environment International*. 2023;171:107684.
43. Doubleday A, Schulte J, Sheppard L, Kadlec M, Dhammapala R, Fox J, et al. Mortality associated with wildfire smoke exposure in Washington state, 2006–2017: a case-crossover study. *Environmental Health*. 2020;19(1):4.
44. Chen G, Guo Y, Yue X, Tong S, Gasparri A, Bell ML, et al. Mortality risk attributable to wildfire-related PM_{2.5} pollution: a global time series study in 749 locations. *The Lancet Planetary Health*. 2021;5(9):e579–e87.
45. Ye T, Xu R, Yue X, Chen G, Yu P, Coêlho MSZS, et al. Short-term exposure to wildfire-related PM_{2.5} increases mortality risks and burdens in Brazil. *Nature Communications*. 2022;13(1):7651.
46. Wang Y, Chen J, Huang Y, Wang J, Xiong Y, Xue T, et al. Associations of wildfire-derived particulate matter with hospitalization, emergency department visits and mortality: A systematic review and meta-analysis. *Environ Res*. 2025;273:121221.
47. Resnick A, Woods B, Krapfl H, Toth B. Health outcomes associated with smoke exposure in Albuquerque, New Mexico, during the 2011 Wallow fire. *J Public Health Manag Pract*. 2015;21 Suppl 2:S55–61.
48. Wu Y, Li S, Xu R, Chen G, Yue X, Yu P, et al. Wildfire-related PM(2.5) and health economic loss of mortality in Brazil. *Environ Int*. 2023;174:107906.
49. Hutchinson JA, Vargo J, Milet M, French NH, Billmire M, Johnson J, et al. The San Diego 2007 wildfires and Medi-Cal emergency department presentations, inpatient hospitalizations, and outpatient visits: An observational study of smoke exposure periods and a bidirectional case-crossover analysis. *PLoS medicine*. 2018;15(7):e1002601.
50. Tinling MA, West JJ, Cascio WE, Kilaru V, Rappold AG. Repeating cardiopulmonary

health effects in rural North Carolina population during a second large peat wildfire. *Environmental Health*. 2016;15(1):12.

51. Alman BL, Pfister G, Hao H, Stowell J, Hu X, Liu Y, et al. The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: a case crossover study. *Environmental Health*. 2016;15(1):64.

52. Reid CE, Jerrett M, Tager IB, Petersen ML, Mann JK, Balme JR. Differential respiratory health effects from the 2008 northern California wildfires: A spatiotemporal approach. *Environmental research*. 2016;150:227–35.

53. Parthum B, Pindilli E, Hogan D. Benefits of the fire mitigation ecosystem service in The Great Dismal Swamp National Wildlife Refuge, Virginia, USA. *Journal of Environmental Management*. 2017;203:375–82.

54. Casey JA, Kioumourtzoglou MA, Elser H, Walker D, Taylor S, Adams S, et al. Wildfire particulate matter in Shasta County, California and respiratory and circulatory disease-related emergency department visits and mortality, 2013–2018. *Environ Epidemiol*. 2021;5(1):e124.

55. Malig BJ, Fairley D, Pearson D, Wu X, Ebisu K, Basu R. Examining fine particulate matter and cause-specific morbidity during the 2017 North San Francisco Bay wildfires. *Sci Total Environ*. 2021;787:147507.

56. Duncan S, Reed C, Spurlock T, Sugg MM, Runkle JD. Acute Health Effects of Wildfire Smoke Exposure During a Compound Event: A Case-Crossover Study of the 2016 Great Smoky Mountain Wildfires. *Geohealth*. 2023;7(10):e2023GH000860.

57. Chen AI, Ebisu K, Benmarhnia T, Basu R. Emergency department visits associated with wildfire smoke events in California, 2016–2019. *Environ Res*. 2023;238(Pt 1):117154.

58. Doubleday A, Sheppard L, Austin E, Busch Isaksen T. Wildfire smoke exposure and emergency department visits in Washington State. *Environ Res Health*. 2023;1(2):025006.

59. Mahsin M, Cabaj J, Saini V. Respiratory and cardiovascular condition-related physician visits associated with wildfire smoke exposure in Calgary, Canada, in 2015: a population-based study. *International Journal of Epidemiology*. 2022;51(1):166–78.

60. Morgan G, Sheppard V, Khalaj B, Ayyar A, Lincoln D, Jalaludin B, et al. Effects of bushfire smoke on daily mortality and hospital admissions in Sydney, Australia. *Epidemiology*. 2010;21(1):47–55.

61. Kollanus V, Tiittanen P, Niemi JV, Lanki T. Effects of long-range transported air pollution from vegetation fires on daily mortality and hospital admissions in the Helsinki metropolitan area, Finland. *Environ Res*. 2016;151:351–8.

62. Ye T, Guo Y, Chen G, Yue X, Xu R, Coêlho M, et al. Risk and burden of hospital admissions associated with wildfire-related PM_{2.5} in Brazil, 2000-15: a nationwide time-series study. *Lancet Planet Health*. 2021;5(9):e599–e607.
63. Heaney A, Stowell JD, Liu JC, Basu R, Marlier M, Kinney P. Impacts of Fine Particulate Matter From Wildfire Smoke on Respiratory and Cardiovascular Health in California. *Geohealth*. 2022;6(6):e2021GH000578.
64. Borchers Arriagada N, Horsley JA, Palmer AJ, Morgan GG, Tham R, Johnston FH. Association between fire smoke fine particulate matter and asthma-related outcomes: Systematic review and meta-analysis. *Environ Res*. 2019;179(Pt A):108777.
65. Magzamen S, Gan RW, Liu J, O'Dell K, Ford B, Berg K, et al. Differential Cardiopulmonary Health Impacts of Local and Long-Range Transport of Wildfire Smoke. *Geohealth*. 2021;5(3):e2020GH000330.
66. Haikerwal A, Akram M, Sim MR, Meyer M, Abramson MJ, Dennekamp M. Fine particulate matter (PM_{2.5}) exposure during a prolonged wildfire period and emergency department visits for asthma. *Respirology*. 2016;21(1):88–94.
67. Gan RW, Ford B, Lassman W, Pfister G, Vaidyanathan A, Fischer E, et al. Comparison of wildfire smoke estimation methods and associations with cardiopulmonary-related hospital admissions. *Geohealth*. 2017;1(3):122–36.
68. Lipner EM, O'Dell K, Brey SJ, Ford B, Pierce JR, Fischer EV, et al. The Associations Between Clinical Respiratory Outcomes and Ambient Wildfire Smoke Exposure Among Pediatric Asthma Patients at National Jewish Health, 2012-2015. *Geohealth*. 2019;3(6):146–59.
69. Joo H, Yoon HK, Hwang YI, Kim SH, Um S-J, Lee W-Y, et al. Application of the Lancet Commission COPD classification to COPD Cohort Population in South Korea. *Respiratory Medicine*. 2024;230:107679.
70. Roscioli E, Hamon R, Lester SE, Jersmann HPA, Reynolds PN, Hodge S. Airway epithelial cells exposed to wildfire smoke extract exhibit dysregulated autophagy and barrier dysfunction consistent with COPD. *Respir Res*. 2018;19(1):234.
71. Rappold AG, Stone SL, Cascio WE, Neas LM, Kilaru VJ, Carraway MS, et al. Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. *Environ Health Perspect*. 2011;119(10):1415–20.
72. Kim Y, Knowles S, Manley J, Radoias V. Long-run health consequences of air pollution: Evidence from Indonesia's forest fires of 1997. *Econ Hum Biol*. 2017;26:186–98.

73. Stolz D, Mkorombindo T, Schumann DM, Agusti A, Ash SY, Bafadhel M, et al. Towards the elimination of chronic obstructive pulmonary disease: a Lancet Commission. *The Lancet*. 2022;400(10356):921–72.
74. Agustí A, Celli BR, Criner GJ, Halpin D, Anzueto A, Barnes P, et al. Global Initiative for Chronic Obstructive Lung Disease 2023 Report: GOLD Executive Summary. *Eur Respir J*. 2023;61(4).
75. Yu P, Xu R, Li S, Yue X, Chen G, Ye T, et al. Exposure to wildfire-related PM_{2.5} and site-specific cancer mortality in Brazil from 2010 to 2016: A retrospective study. *PLoS Med*. 2022;19(9):e1004103.
76. Gao Y, Huang W, Xu Z, Xu R, Gasevic D, Liu Y, et al. Wildfire-related PM_{2.5} and cause-specific cancer mortality. *Ecotoxicol Environ Saf*. 2024;285:117023.
77. Korsiak J, Pinault L, Christidis T, Burnett RT, Abrahamowicz M, Weichenthal S. Long-term exposure to wildfires and cancer incidence in Canada: a population-based observational cohort study. *The Lancet Planetary Health*. 2022;6(5):e400–e9.
78. European Space Agency. Los Angeles struggles to contain wildfires. European Space Agency,; 2025.
79. National Meteorological Satellite Center. GK-2A Satellite Imagery: Dust/Aerosol/Volcanic Ash, Korean Peninsula, March 5, 2022, 09:00 KST. Seoul,; Korea Meteorological Administration,; 2022.