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Climate-Related Exposures, and the Developing Brain: Neurodevelopmental Vulnerability in Children

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Abstract

Wildfires and wildland–urban interface (WUI) events increasingly expose children to a complex mixture of environmental hazards during critical periods of brain development. Although pediatric neurodevelopmental outcomes following wildfire exposure remain incompletely characterized, emerging evidence from environmental epidemiology, neuroimaging, and toxicology raises concern regarding the potential effects of wildfire-associated fine particulate matter ($PM_{2.5}$), combustion-derived toxicants, extreme heat, systemic inflammation, and prenatal exposure on the developing nervous system. Pregnancy, infancy, childhood, and adolescence represent periods of rapid neurogenesis, synaptogenesis, myelination, vascular maturation, and circuit refinement during which environmental insults may have disproportionate and potentially lasting effects. Recent longitudinal neuroimaging research has associated high ambient temperatures during pregnancy and infancy with altered childhood brain development, including slower thalamic growth, while previous work has identified associations between early-life temperature exposure and poorer white-matter microstructure. Wildfire-related $PM_{2.5}$ may contribute additional neurobiologic risk through oxidative stress, systemic inflammation, endothelial dysfunction, placental disruption, and possible direct access to the central nervous system. This review examines current evidence regarding wildfire- and climate-associated threats to pediatric neurodevelopment, identifies important knowledge gaps, and proposes anticipatory clinical, public health, and research strategies to protect children living in increasingly fire-prone communities.

Introduction

Wildfires have become a defining pediatric environmental health challenge of a changing climate. Longer fire seasons, increasing fire intensity, prolonged smoke transport, and expansion of development into the wildland–urban interface have increased the frequency with which children encounter wildfire-associated hazards.[1] Wildfire events are no longer considered isolated regional disasters; smoke can travel hundreds to thousands of miles, producing harmful air quality far removed from the fire perimeter. During WUI fires, the combustion of homes, vehicles, plastics, electronics, and other synthetic materials further complicates exposure by generating a heterogeneous mixture of particulate matter, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), metals, and other combustion products.[1]

The neurologic implications of these exposures warrant increasing attention. The developing brain undergoes rapid and highly coordinated structural and functional maturation from fetal life through adolescence. By approximately 3 years of age, the brain has reached nearly 80% of adult size, while cortical and subcortical maturation, white-matter organization, synaptic pruning, and neural-network refinement continue throughout childhood and adolescence.[2],[3] Environmental insults during these critical periods may alter developmental trajectories in ways that are not immediately clinically apparent.

The 2025 Southern California wildfire disaster, including the Eaton and Palisades fires, illustrates the urgency of this question for children living within WUI communities. These fires occurred within densely populated regions and generated overlapping exposures to smoke, combustion products, heat, evacuation, school disruption, loss of housing, and prolonged environmental uncertainty. Although pediatric neurodevelopmental outcome data from these fires are not yet available, the events reinforce the need to move beyond a traditional organ-specific view of wildfire health effects and consider the developing nervous system as another potential target of climate-related environmental injury.

Importantly, the current evidence base is based on associations does not establish that wildfire exposure directly causes neurodevelopmental disorders. Rather, evidence from wildfire toxicology, ambient air pollution, extreme-temperature research, prenatal exposure studies, and developmental neuroimaging collectively supports biologic plausibility and identifies critical areas requiring prospective studies, both observational and of causation.

The Developing Brain as a Vulnerable Target

Pregnancy and early childhood are periods of extraordinary neurodevelopmental activity. Neurogenesis, neuronal migration, synapse formation, synaptic pruning, myelination, vascular development, and maturation of subcortical and cortical networks occur within tightly regulated developmental windows.[2] Environmental perturbation during these periods may therefore exert effects that differ substantially from those seen in mature adults.

Several characteristics may increase pediatric susceptibility to climate-related environmental exposures. Children have higher minute ventilation relative to body size than adults and consequently inhale proportionally greater quantities of airborne pollutants. Their antioxidant and detoxification systems are still developing, and the blood-brain barrier, cerebrovascular system, immune system, and neuroendocrine pathways undergo continued maturation across early life. Young children also depend on caregivers for evacuation, environmental control, hydration, temperature regulation, and avoidance of hazardous exposures.

Prenatal development may be particularly vulnerable. The placenta acts not only as a conduit for oxygen and nutrients but also as an endocrine and immunologic organ that helps regulate fetal brain development. Environmental stressors capable of altering placental perfusion,

inflammatory signaling, oxidative balance, or hormone regulation may therefore affect the fetal nervous system indirectly even when the toxicant itself does not cross the placenta.

Wildfire Smoke and Potential Neurobiologic Injury

Wildfire smoke is composed of $PM_{2.5}$ and ultrafine particles together with carbon monoxide, nitrogen oxides, ozone precursors, VOCs, PAHs, and other compounds whose composition varies with fuel source, combustion temperature, atmospheric aging, and distance from the fire.[1] WUI fires introduce additional concern because smoke may contain products generated from the combustion of manufactured materials rather than vegetation alone.

Fine particles are of particular interest because of their ability to penetrate deeply into the respiratory tract and initiate oxidative and inflammatory responses. Wildfire-derived particulate matter has been associated experimentally with increased reactive oxygen species, inflammatory cytokine production, antioxidant depletion, cellular injury, and DNA damage.[1] These effects provide several potential pathways through which inhaled wildfire pollutants could influence the nervous system.

Systemic Inflammation and Oxidative Stress

Pulmonary exposure to $PM_{2.5}$ can generate inflammatory and oxidative responses that extend beyond the respiratory system. Proinflammatory mediators released into the circulation may affect vascular endothelium, alter blood-brain barrier integrity, and promote neuroinflammation. Oxidative stress may additionally affect mitochondrial function, lipid membranes, proteins, and DNA—processes of particular concern during periods of rapid neural growth.

Direct Particle or Chemical Translocation

Very small particles and particle-associated chemicals may reach the systemic circulation after inhalation. Experimental and observational literature has also raised the possibility of access to the central nervous system across the blood-brain barrier or through olfactory pathways. Although direct evidence specific to children exposed to wildfire smoke remains limited, these mechanisms provide biologic plausibility for neurologic effects.

Cerebrovascular Effects

Wildfire-associated $PM_{2.5}$ has been linked with cerebrovascular events in adult populations. During California's 2015 wildfire season, emergency department visits for cerebrovascular disease increased on smoke-exposure days.[4] Although stroke represents a different clinical outcome than neurodevelopment, this literature demonstrates that wildfire-derived particulate

exposure can affect cerebral vascular physiology and reinforces concern regarding the developing neurovascular unit.

Extreme Heat as a Co-Exposure Affecting Brain Development

Wildfires often occur during periods of high ambient temperature, drought, and extreme heat. Heat therefore represents a clinically important co-exposure rather than an unrelated environmental hazard.

Recent longitudinal neuroimaging findings provide some of the strongest emerging evidence that climate-associated environmental exposures may influence childhood brain development. Granés and colleagues examined temperature exposure from conception through 8.5 years of age in 3251 children participating in the Generation R Study.[5] Brain magnetic resonance imaging was subsequently performed during later childhood and adolescence.

Exposure to high ambient temperature during pregnancy and the first months of life was associated with slower thalamic growth between approximately 9 and 15 years of age.[5] The association was observed across all three trimesters and during early infancy. The investigators did not identify comparable associations for the other evaluated brain structures or for cold exposure.

The thalamus is an especially compelling structure from a developmental perspective. It is among the earliest recognizable regions of the fetal brain, participates in sensory integration and cortical signaling, and undergoes highly regulated thalamocortical development beginning early in gestation. The investigators proposed several potential mechanisms, including altered placental perfusion, disruption of the placental glucocorticoid barrier, changes in serotonin signaling, and oxidative stress.[5]

These findings build upon earlier research from the same group demonstrating associations between early-life heat and cold exposure and poorer white-matter microstructure at approximately 10 years of age.[6] Together, these studies suggest that environmental temperature during early developmental windows may influence both macrostructural and microstructural brain maturation.

They should not, however, be interpreted as evidence that wildfire exposure causes altered thalamic development. Instead, they demonstrate that one major exposure accompanying contemporary wildfire risk is extreme heat which may independently influence neurodevelopment, reinforcing the importance of studying wildfire events as compound environmental exposures rather than $PM^{2.5}$ exposure alone.

Prenatal Exposure, the Placenta, and Early Neurodevelopment

Wildfire exposure during pregnancy may warrant particular concern because several pathways converge at the maternal–placental–fetal interface.

High ambient temperature has been associated with changes in placental perfusion and placental molecular function.[5],[7] Heat stress may alter maternal glucocorticoids and disrupt placental regulation of fetal corticosteroid exposure. Experimental studies further suggest that heat can affect placental serotonin signaling, a pathway relevant to early thalamocortical development.[5]

Wildfire smoke may add a second biologic stressor through maternal pulmonary and systemic inflammation. Wildfire exposure has also been associated with adverse birth outcomes, including lower birth weight in pregnancies affected by Southern California wildfires.[1],[8] Because prematurity, fetal growth restriction, and placental dysfunction themselves increase neurodevelopmental risk, prenatal wildfire exposure may operate through both direct and indirect developmental pathways.

These overlapping mechanisms make pregnancy an important target for anticipatory guidance and future wildfire-neurodevelopment research.

Neurodevelopmental and Cognitive Outcomes: What Do We Know?

Direct pediatric evidence linking wildfire smoke exposure with long-term neurodevelopmental outcomes remains sparse. This limitation should be explicitly acknowledged.

Existing wildfire research has focused predominantly on respiratory morbidity, mortality, cardiovascular disease, and acute healthcare utilization.[1] Neurodevelopment has historically received far less attention.

Nevertheless, several adjacent evidence streams justify concern.

Air pollution and particulate matter exposure have been associated more broadly with neuroinflammation, cognitive effects, and altered brain development. During acute wildfire smoke episodes, investigators and clinicians have reported short-term attention changes, while adult literature has increasingly identified associations between long-term $PM^{2.5}$ exposure and cognitive decline.[9] These findings cannot be directly extrapolated to pediatric neurodevelopment, but they provide important mechanistic and epidemiologic context.

Temperature-related developmental research is more specific. In addition to structural neuroimaging findings, higher ambient temperatures have been associated with poorer learning and academic performance, and early-life temperature exposure has been associated with later cognitive and behavioral outcomes.[5],[6]

The central question is therefore not whether wildfire smoke has already been proven to cause a particular pediatric neurologic disorder; it has not. The question is whether a rapidly developing nervous system repeatedly exposed to $PM^{2.5}$, combustion toxicants, extreme heat, systemic inflammation, and displacement during critical developmental periods warrants prospective investigation. The answer is increasingly yes.

Compound Exposures in the Wildland–Urban Interface

Unlike traditional ambient air pollution events, wildland–urban interface (WUI) fires expose children to a complex and overlapping combination of environmental, physiologic, and psychosocial stressors. Acute and prolonged exposure to fine particulate matter ($PM_{2.5}$), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), metals, and other structural combustion byproducts may coincide with extreme heat, disrupted sleep, and altered circadian rhythms. These exposures frequently occur alongside substantial disruptions to daily life, including evacuation, displacement, housing instability, and interruptions in schooling, developmental therapies, and access to essential healthcare services.

The cumulative burden may be particularly consequential during critical periods of neurodevelopment, when children depend on stable environments, consistent routines, adequate nutrition, restorative sleep, and uninterrupted access to medical and developmental support. Caregiver stress, reduced access to medications and healthcare, and prolonged uncertainty surrounding displacement and recovery may further compound these challenges. Moreover, children living in fire-prone communities may experience repeated exposures across successive wildfire seasons, raising additional concerns about cumulative environmental and developmental vulnerability.

Importantly, these stressors are unlikely to operate independently. Rather, their overlapping effects may influence neurodevelopment through interconnected biologic and psychosocial pathways, including systemic inflammation, oxidative stress, sleep disruption, and interruption of developmental supports. Although the extent to which these combined exposures contribute to long-term neurodevelopmental outcomes remains uncertain, their convergence underscores the importance of examining WUI fires as complex environmental events rather than isolated episodes of smoke exposure.

This cumulative-exposure model is especially important for children with existing neurologic or developmental conditions.

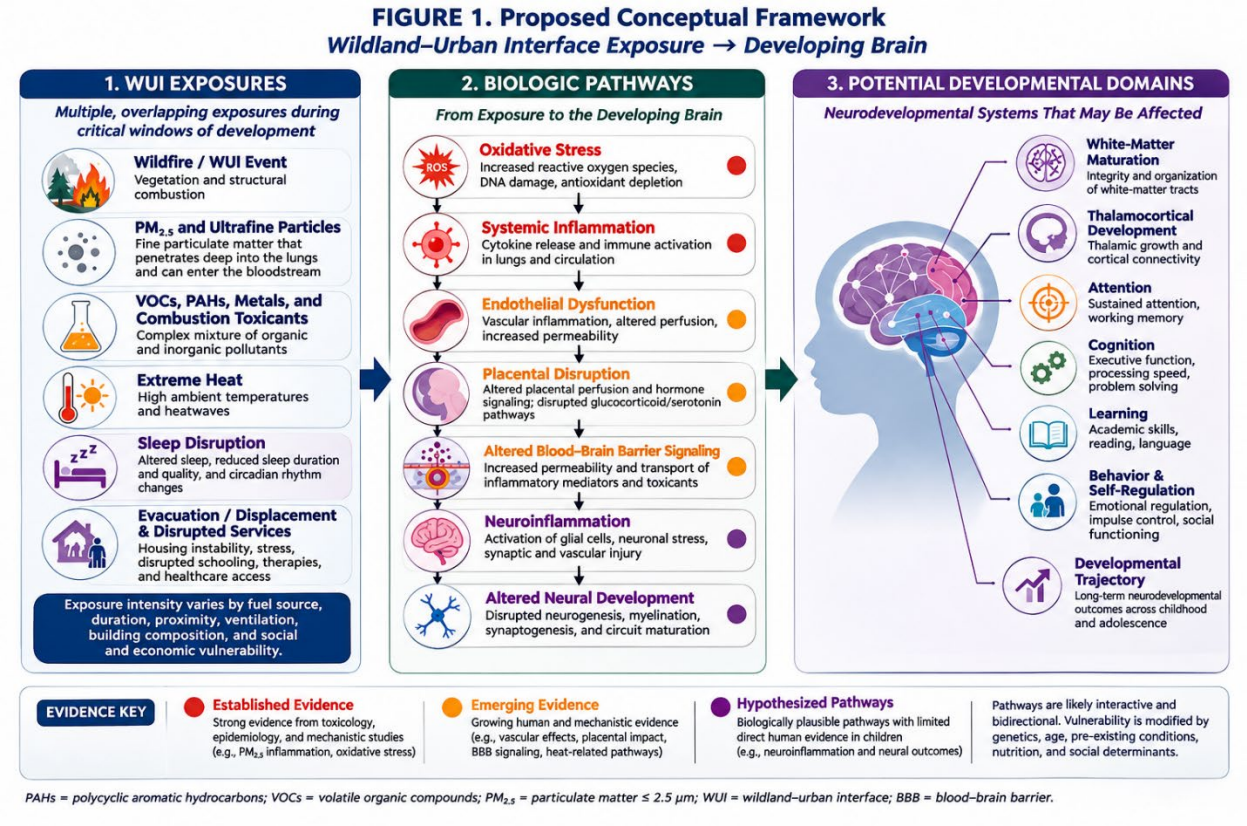


Figure 1 illustrates a proposed conceptual framework linking WUI-associated environmental exposures with potential biologic pathways and neurodevelopmental domains of concern. The framework emphasizes overlapping exposures during critical developmental windows while distinguishing established evidence from emerging and hypothesized mechanisms.

Children at Potentially Increased Risk

Although definitive neurodevelopmental risk stratification following wildfire exposure is not yet available, several pediatric populations warrant particular consideration because of developmental vulnerability, preexisting medical or neurologic conditions, dependence on essential services, or environmental and socioeconomic barriers. Figure 2 summarizes these potentially overlapping populations and highlights the importance of individualized preparedness.

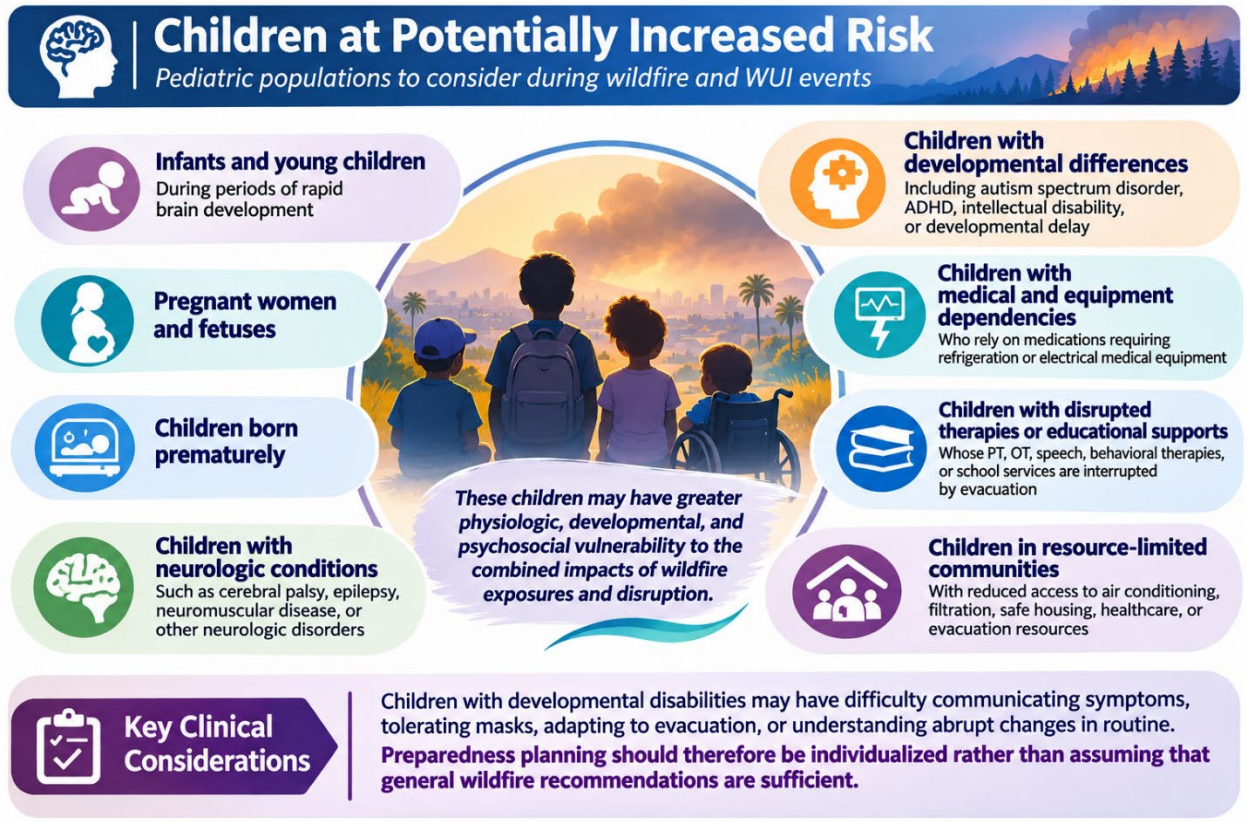


Figure 2. Pediatric Populations at Potentially Increased Risk During Wildfire and WUI Events. Developed by the authors based on the evidence and clinical recommendations presented in this manuscript.

Children with developmental disabilities may face additional challenges communicating symptoms, tolerating protective measures, adapting to evacuation, or navigating abrupt disruptions in routine. Preparedness strategies should therefore be individualized to the child's developmental, medical, behavioral, and family circumstances rather than relying exclusively on general wildfire recommendations.

Health Equity and Environmental Justice

Neurodevelopment cannot be separated from the social environment in which children experience disaster.

Families with greater financial resources may be able to purchase HEPA filtration, relocate temporarily, access air-conditioned spaces, replace contaminated belongings, continue therapy through telehealth, or recover more rapidly after evacuation. Families with fewer resources may face prolonged exposure, housing instability, lost educational services, transportation barriers, and delayed access to developmental or medical care.

Children with disabilities may be disproportionately affected when evacuation shelters, transportation systems, or recovery services are not designed for sensory, mobility, behavioral, communication, or medical needs.

These inequities may become biologically embedded throughout childhood. For neurodevelopmental research, socioeconomic context should therefore be treated not simply as a confounder but as a potential determinant of exposure intensity, mitigation capacity, recovery, and developmental outcome.

Clinical Implications for Pediatric Providers

The available evidence does not currently support routine neurologic testing or neuroimaging solely because a child has experienced wildfire smoke exposure. It does, however, support incorporating environmental preparedness into pediatric care.

Clinicians should consider wildfire and extreme-heat exposure during pregnancy, developmental surveillance, and care of children with neurologic conditions. Families can be counseled to reduce smoke exposure, maintain cooler indoor environments during extreme heat, preserve hydration, and use properly sized high-efficiency particulate air filtration when feasible.

For children with established developmental or neurologic conditions, emergency plans should address continuity of medications, backup power, feeding supplies, communication devices, mobility equipment, seizure rescue medication, and therapy or school accommodations.

After significant wildfire exposure or displacement, clinicians should pay attention to changes in mood, sleep, attention, school performance, developmental functioning, headaches, seizures, behavior, or previously acquired skills. Such symptoms are nonspecific and should not be attributed automatically to smoke exposure, but longitudinal observation may be particularly important in children who already have developmental vulnerability.

TABLE 1. Proposed Clinical Considerations for Protecting Neurodevelopment
During Wildfire and Extreme-Heat Events

CLINICAL DOMAIN	RECOMMENDED CONSIDERATIONS
Prenatal care	Discuss smoke and extreme-heat avoidance; hydration; indoor cooling; filtration; exposure reduction during critical pregnancy periods.
Infants and young children	Prioritize clean indoor air, thermal safety, hydration, and continued developmental surveillance.
Neurologic conditions	Ensure uninterrupted antiseizure and other neurologic medications; maintain emergency rescue plans.
Technology-dependent children	Verify backup power, chargers, batteries, communication devices, feeding equipment, and mobility support.
Developmental disabilities	Create individualized evacuation plans that address sensory needs, communication, behavior, and routine.
Therapy and education	Plan continuity of PT, OT, speech therapy, ABA/developmental therapy, IEP/504 supports, and school services when displacement occurs.
Post-event follow-up	Assess sleep, attention, school performance, developmental regression, headaches, seizures, or other neurologic changes when clinically indicated.
Equity	Identify barriers to filtration, cooling, transportation, housing, therapies, and healthcare access before wildfire season.

Key Takeaway: Proactive, individualized planning and equitable access to resources are essential to protect the developing brain before, during, and after wildland–urban interface (WUI) events.

Table 1. Protecting Pediatric Neurodevelopment During Wildfire and Extreme-Heat Events: A Clinical Action Framework. Developed by the authors based on the evidence and clinical recommendations presented in this manuscript.

Research Priorities

Major evidence gaps remain in understanding the neurodevelopmental impacts of wildfire smoke exposure in children. Future research should prioritize prospective longitudinal cohort studies beginning during pregnancy and early infancy, as well as the integration of satellite-derived wildfire smoke and $PM^{2.5}$ exposure estimates with electronic health records and developmental outcome data. Additional priorities include neuroimaging studies examining white matter integrity, cortical maturation, and subcortical brain structures; measurement of placental, inflammatory, oxidative stress, and vascular biomarkers; identification of critical windows of developmental vulnerability; and evaluation of the cumulative effects of repeated wildfire smoke exposure across multiple fire seasons. Studies should also distinguish wildfire-specific $PM^{2.5}$ from background particulate pollution whenever possible and characterize structural-fire exposures separately from vegetation-only wildfire smoke.

The 2025 Eaton and Palisades fires offer an important opportunity to develop such approaches in Southern California. Integrating geospatial exposure assessment with pediatric clinical outcomes, developmental surveillance, school data, and longitudinal follow-up could substantially advance understanding of pediatric WUI health effects.

Conclusions

The developing brain may represent an important and underrecognized target of wildfire- and climate-associated environmental exposures. Current evidence does not establish a direct causal relationship between wildfire smoke and pediatric neurodevelopmental disorders; however, emerging neuroimaging, temperature, air pollution, and toxicologic research provide substantial biologic plausibility.

Early-life exposure to high ambient temperatures has now been associated with altered white-matter microstructure and slower later thalamic growth, while wildfire-derived particulate matter can produce oxidative stress, systemic inflammation, cellular injury, and vascular effects. WUI events combine these environmental hazards with displacement, disrupted developmental services, and social inequities.

As wildfire events increase in frequency and intensity, pediatric care must evolve from acute smoke-response strategies toward a broader developmental-health framework. Protecting children will require coordinated research, anticipatory clinical guidance, environmental mitigation, longitudinal surveillance, and policies that recognize pregnancy, infancy, childhood, and adolescence as critical windows of vulnerability.

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Tables and Figures:

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