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Wood Stove Pollution in the Developed World: A Case to Raise Awareness Among Pediatricians

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Abstract

Use of wood for residential heating is regaining popularity in developed countries. Currently, over 11 million US homes are heated with a wood stove. Although wood stoves reduce heating costs, wood smoke may adversely impact child health through the emission of gaseous and particulate air pollutants. Our purpose is to raise awareness of this environmental health issue among pediatricians.

To summarize the state of the science, we performed a narrative review of articles published in PubMed and Web of Science. We identified 36 studies in developed countries that reported associations of household wood stove use and/or community wood smoke exposure with pediatric health outcomes. Studies primarily investigated respiratory outcomes, with no evaluation of cardiometabolic or neurocognitive health. Studies found community wood smoke exposure to be consistently associated with adverse pediatric respiratory health. Household wood stove use was less consistently associated with respiratory outcomes. However, studies of household wood stoves always relied on participant self-report of wood stove use, while studies of community wood smoke generally assessed air pollution exposure directly and more precisely in larger study populations. In most studies, important potential confounders, such as markers of socioeconomic status, were unaccounted for and may have biased results. We conclude that studies with improved exposure assessment, that measure and account for confounding, and that consider non-respiratory outcomes are needed.

While awaiting additional data, pediatricians can refer patients to precautionary measures recommended by the US Environmental Protection Agency (EPA) to mitigate exposure. These include replacing old appliances with EPA-*certified* stoves, properly maintaining the stove, and using only dry, well-seasoned wood. In addition, several studies have shown mechanical air filters to effectively reduce wood stove pollution exposure in affected homes and communities.

Introduction

Air pollution exposure is associated with respiratory disease, and children are particularly vulnerable. As compared to adults, children's lungs are still developing, and children inhale a larger relative amount of air pollutants because of their smaller body size, higher respiratory minute volume per unit body weight, and higher activity level.[1]

In the US and other developed countries, air pollutants are primarily generated from sources outside the home, such as traffic emissions and industrial processes. However, worldwide, indoor cooking and heating appliances that burn solid fuels, such as wood, are a major source of air pollution. Indoor air pollution is estimated to have caused 2.9 million deaths globally in 2015.[2] As people in the US currently spend the majority of their time indoors,[3] sources of indoor air pollution are becoming a greater concern.

Wood was a common US home heating fuel before and through the first half of the 20th century, but as fossil fuel infrastructure expanded following World War II, utility gas and oil gained popularity, and by 1970, wood was only used as a primary source of heat in 1% of homes.[4] However, over the past 2 decades, given increasing energy prices and emphasis on renewable fuel, a rising number of households have returned to wood heating.

Over 3 million children in the US are estimated to live in homes with lower air quality from wood smoke.[5] Use of wood stoves is particularly prevalent in colder, largely rural, and forested states (Fig 1). In Maine, for example, use of wood as a primary heat source increased from 7% of households in 2005 to 13% in 2015 (Fig 2).[6] In 2009, over 2 million US households used wood as a primary heat fuel, and 8.8 million more as a supplemental fuel.[7]

In 1988, the US Environmental Protection Agency (EPA) issued New Source Performance Standards for residential wood heaters that established particulate emission limits for wood stoves on the market; these standards were updated in 2015. However, 65% of wood stoves in US homes are old, inefficient, and unregulated pre-1988 New Source Performance Standards stoves.[8]

In the sections that follow, we discuss the type and magnitude of air pollutants emitted from wood stoves commonly used in the US and other developed countries. We perform a narrative review of the literature on household and community wood smoke exposure and pediatric health. We describe EPA-recommended strategies to lower wood stove pollution and present data on the efficacy of interventions to lower wood smoke exposure. Our purpose is not to conduct a systematic review of epidemiologic studies of wood smoke exposure and pediatric health, but rather to provide a perspective of the topic that will increase awareness among pediatricians.

Wood Stoves as a Source of Air Pollution

When wood stoves burn fire-wood, combustion is incomplete, and stoves emit a mixture of gaseous and particulate air pollutants. These gases include carbon monoxide, nitrogen oxides, benzene, and aldehydes. Particulate matter in wood smoke is heterogeneous, comprised of inorganic material (e.g., salts), organic carbon, and elemental carbon with organic compounds, such as polycyclic aromatic hydrocarbons (PAHs) and acids, condensed on the surface. Particles are categorized based on size (e.g., PM_{10} is particulate matter ≤10 μm and $PM_{2.5}$ is particulate matter ≤2.5 μm in aerodynamic diameter), and wood smoke is comprised primarily of the smallest particles, which have the greatest human health effects because of their ability to reach the alveoli and distal airways.[9]

The type of wood and type, age, and condition of the wood stove impact the magnitude and composition of air pollutants. For example, burning wet as compared to dry wood leads to less complete combustion and thus higher emissions.[8] Stoves that burn pellets, a newer fuel made of compacted sawdust or wood waste, are thought to burn more efficiently and produce a less toxic emission profile than stoves using raw wood, but the efficiency of these appliances is dependent on installation and operation.[10–12] Also, pre-1988 New Source Performance Standards wood stoves have higher emissions because of poor combustion conditions, including low burning temperature, air deficiency, and poor air-to-fuel mixing.[10] $PM_{2.5}$ emissions from pre-1988 New Source Performance Standards stoves are estimated at 15–30 g/h, while $PM_{2.5}$ emissions from newer stoves are required to be ≤4.5 g/h.[8] Thus, older traditional wood stoves, particularly those burning wet wood, are likely to produce the highest levels of air pollutants.

Air Pollution Within Wood-Burning Homes

Quantifying the magnitude of indoor air pollution from wood stoves is difficult because even in households using similar stove models, pollutant concentrations can vary based on a number of factors such as outdoor pollution that filters indoors, household size and ventilation, type of wood, proper operation and maintenance of the stove, indoor temperature, and duration of wood burning, which need to be considered in these studies.

Limited data suggest higher PAHs, benzene, and PM in tobacco-free homes with versus without a wood stove.[13–17] For example, in wood-burning homes in Sweden, median concentration of benzo[a]pyrene, a PAH, was four times higher than in reference homes;[13] and median weekly indoor benzene concentration was two times higher than the referents.[14] Daily indoor PM_{10} sampling in Quebec City, Canada found that all samples >20 μg/m^3 had been collected in homes with a wood stove.[15] Average daily $PM_{2.5}$ concentration in Vermont wood-burning homes was 24 μg/m^3, while it was 18 μg/m^3 in non-wood burning homes.[16] Similarly, average weekly $PM_{2.5}$ concentration was 19 μg/m^3 in wood-burning versus 14 μg/m^3 in non-wood burning homes in Onondaga County, NY.[17] In the US and worldwide, there are currently no indoor $PM_{2.5}$ standards. However, for context, the current EPA National Ambient Air Quality Standard for outdoor air is <150 μg/m^3 daily for PM_{10} and <35 μg/m^3 daily and <12 μg/m^3 annually for $PM_{2.5}$.[18] The World Health Organization suggests a threshold of <50 μg/m^3 daily and <25 μg/m^3 annually for PM_{10} and <25 μg/m^3

daily and <10 μg/m^3 annually for $PM_{2.5}$.[19] Residential wood stove use may not only increase air pollution inside the home, but can also influence wintertime ambient air quality in wood-burning communities.

Air Pollution in Wood-Burning Communities

Wood stove use can be an important contributor to outdoor as well as indoor air pollution, in communities in which wood burning is prevalent.[9,20] Particles generated during residential wood burning escape the indoor environment via outside venting (i.e., chimney) and via open windows and doors, and concentrate in a community's airshed. The problem is magnified in valleys prone to wintertime temperature inversions, in which cool, polluted air is trapped near the ground under warmer air. For example, in rural Montana communities[21] and in Fairbanks, Alaska,[22] residential wood smoke has been identified as a major source of ambient pollution, contributing up to 80% of winter $PM_{2.5}$. Wood smoke also contributes, to a lesser degree, to air pollution in urban settings. Estimates from major US cities, such as San Jose, CA, Atlanta, GA, and Seattle, WA, show that wood burning contributes between 10% and 30% of winter $PM_{2.5}$.[20] As wood stove use may worsen the quality of both indoor and outdoor air, wood smoke exposure is a potential public health threat in developed countries, particularly for susceptible individuals such as children.

Other Sources of Air Pollution and Child Health

Although wood stoves worsen air quality in affected homes and communities, studies in developed countries have historically focused on other widespread sources of air pollution in relation to pediatric health. For example, traffic, which creates an air pollutant profile similar to wood burning,[23] has been consistently associated with greater childhood respiratory morbidity,[1] including respiratory infections,[24] asthma,[25,26] lower lung function,[26,27] and decreased lung growth.[26] Recent literature has additionally linked traffic pollution to childhood obesity,[28] insulin resistance,[29] and lower cognitive function.[30] Higher *in utero* exposure to traffic pollution is associated with lower birth weight.[31] Although not specific to pediatric health, the International Agency for Research on Cancer has classified outdoor PM as carcinogenic to humans.[32] Well-established associations between traffic pollution and pediatric health risk suggests the importance of investigating health effects related to other air pollution sources, such as wood stove use.

Wood Stove Pollution and Child Health: A Narrative Review of the Literature

Previous published reviews have examined the impact of wood burning in developed countries on human health.[9,10,33–36] However, these prior reviews, which concluded that wood burning negatively affects respiratory and possibly cardiovascular outcomes, did not specifically focus on pediatric health and did not target a clinical audience. Here, we summarize studies that have investigated wood smoke pollution in developed countries in relation to child health outcomes. We focus on wood smoke emissions from indoor residential wood burning, although there is also literature on outdoor wood burning emissions, for example, from forest fires and agricultural burning, in relation to child health.[9] Our aim is for pediatricians treating patients living in wood burning homes or communities to be better informed in conversations with patients.

Review Methods

To review the literature on wood smoke exposure and child health in developed countries, we searched PubMed and Web of Science databases from inception (1966 for PubMed and 1900 for Web of Science) to November 2016, by using the following search terms: ((wood stove) OR (wood smoke) OR (wood heat) OR (wood burning)) AND ((child) OR (infant)) AND ((health) OR (symptoms)). We identified 333 papers. We examined titles and abstracts to limit inclusion to English language, peer-reviewed studies assessing the health of children <19 years of age in relation to household wood stove use and/or community wood smoke from residential indoor burning. Based on these criteria, 97 papers remained for consideration. We further excluded 61 studies in developing settings where wood is typically used in conjunction with other biomass for both cooking and heating. We also excluded 9 studies that examined combined exposures (e.g., wood stove or fireplace, wood stove, or coal burning) in developed countries, as emission profiles differ between appliances and type of fuel.[10,37] Finally, we excluded one study[38] that presented preliminary findings of an included study[39] and another[40] that did not specify the study location or the sample size of the analysis. Thus, we identified 25 papers from the initial search. We identified 11 additional studies that met our review criteria from reference lists of (1) the 27 eligible papers, (2) the 9 studies that examined combined exposures in developed countries, and (3) prior reviews of wood smoke and human health.[9,10,33–36] Thus, in total, we included 36 papers in this review.

We categorized the 36 studies as pertaining to household wood stove use (26 studies; Table 1) or community wood smoke (12 studies; Table 2), with 2 studies[41,42] included in both categories. For each study, two authors (L.B.R. and A.F.F.) independently extracted data on study location, design, follow-up duration, and effect estimates for key outcomes, as well as restrictions, exclusions, and confounding variables. We summarize results below and describe limitations of this set of studies and future directions for research.

Household Wood Stove Use and Child Health

The 26 studies of household wood stove use and child health[39,41–65] (Table 1) were published in 1984–2015. In that, 24 examined respiratory outcomes and 2 examined oncologic outcomes. In total, 50% were cross-sectional, 33% cohort, and 17% case–control.

Of 24 studies that examined respiratory health, 9 observed a positive association between wood stove use and at least one respiratory outcome,[39,44–46,48,50,54,58,60] with half of these associations observed in cohorts of infants and young children (ages 2 weeks to 2 years).[44,48,54,60] One study examined lung function and showed lower spirometric measures among children living in wood-heated homes.[50] Cough[39,44,45,48,60] was the marker of respiratory health most frequently associated with wood stove use, although several studies showed no direct association between household wood stove use and cough.[41,42,52,59,61–63,65] Wheeze was also associated with wood stove use in a few studies.[39,45,58] In contrast, only one[54] of several studies of lower respiratory tract infections (bronchitis, bronchiolitis, and pneumonia),[42,52,54,57,61,63,65] one[46] of three studies of otitis media,[42,46,56] and none that examined asthma,[46,47,51,53,59,61,63,65] upper respiratory tract infections,[42,63] or allergies[61,64] showed a link with wood stove use (Table 1). Two studies observed an inverse association between wood stove use and respiratory outcomes.[62,65] Thus, current studies show inconsistent associations of household wood stove use with cough and wheeze and limited evidence for an association with other markers of respiratory health.

The two case–control studies of household wood stove use and pediatric oncologic outcomes[43,49] found inconsistent associations with prenatal and postnatal wood stove use. For example, use of a wood stove (versus no use) during pregnancy was associated with higher risk of acute lymphoblastic leukemia (ALL)[43] and brain tumors[49] in childhood. However, *frequency* of wood stove use was not associated with ALL or brain tumors, and in some cases there was a paradoxical higher risk of these outcomes with "low" versus "high" wood burning frequency. As there is limited literature, replication in larger studies is needed to draw conclusions on wood stove use and childhood oncologic outcomes.

Overall, the studies of household wood stove use had limitations that impeded our ability to draw definitive conclusions. For example, wood stove use was always assessed by self-report, and in most studies was represented only as a binary exposure (i.e., presence or absence of a wood stove in the home). A binary variable is unable to capture the spectrum of pollution as compared to continuous measurements. This raises the possibility of non-differential exposure misclassification in these studies, which may have biased results toward the null. Also, the sample size of these studies ranged from 59 to 30,593 participants, so power to detect an association was variable. Furthermore, analyses often did not account for frequency of wood stove use, stove type, or household ventilation, factors that alter indoor wood smoke exposure, and analyses did not always account for socioeconomic status, a potential confounding variable. Finally, many studies were limited by their cross-sectional design, as cross-sectional studies are less adept at showing a temporal relationship compared to longitudinal cohort studies.[66]

Community Wood Smoke and Child Health

The 12 studies of community wood smoke and child health[41,42,67–76] (Table 2) were published 1990–2014. Ten studies examined respiratory health and 2 examined birth size. Further, 33% were cohort studies, 25% time-series, 25% cross-sectional, and 17% case–control. All studies examined ambient air pollution in communities with significant wood stove use (i.e., studies did not describe prevalent forest fires or other outdoor burning). Wood smoke was typically measured using air monitoring data (e.g., average ambient winter $PM_{2.5}$) or model-estimated number of wood burning days (e.g., over participant lifetime).

Of the 10 studies that examined respiratory health, 8 identified an association between community wood smoke and at least one respiratory outcome.[42,67,69,71,72,74–76] The associations were observed in cohorts of children of all ages. When wood smoke was higher, children had more upper respiratory tract infections,[42] bronchitis,[42] bronchiolitis,[71] otitis media,[42,74] and hospital admissions for respiratory illness.[75,76] Children with asthma had worse lung function when community wood smoke was higher,[67,69,72] but asthma prevalence was not related to wood smoke.[41,68] Cough and wheeze were associated with community wood smoke in some studies[42,69] but not others.[41,42] The literature generally shows consistent associations between higher community wood smoke and poor respiratory health in childhood.

Both studies of birth size observed an association between higher community wood smoke and lower birth size.[70,73] In a cohort of more than 700,000 births in Los Angeles, higher ambient air pollution from wood burning was associated with lower birth weight.[73] Additionally, in a cohort of more than 68,000 births in Vancouver, British Columbia, more wood burning days *in utero* was similarly associated with higher odds of small-for-gestational age, but paradoxically associated with lower odds of preterm birth <30 weeks gestation.[70] We need further data to draw conclusions regarding prenatal exposure to community wood smoke and birth outcomes.

As compared to the self-report methods used in studies of household wood stove use, community wood smoke was typically measured more objectively using ambient air monitoring. Also, many of the studies that observed associations between increased community wood smoke exposure and poor respiratory health used data from thousands or all children in a respective area and thus had more power to detect associations as compared to the studies of household wood stove use. However, as in the analyses of household wood stove use, studies of community wood smoke did not always account for socioeconomic variables, raising the possibility that observed associations may be due to residual confounding.

Literature Review Summary

Upon our review of the literature, several studies showed an association between wood smoke and childhood respiratory health. There was a paucity of studies that investigated other health outcomes. We found more consistent associations between high community wood smoke as compared to household wood stove use and adverse pediatric respiratory health. This may be due to higher quality exposure assessment and greater power in community wood smoke studies. Alternatively, families who have children with asthma or other respiratory issues may be less likely to own a wood stove or may use their wood stove less often to avoid respiratory exacerbations, diminishing the ability to observe an association between household wood stove use and respiratory health.

It is also possible that ambient wood smoke exposure may truly have a greater influence on child health as compared to household wood stove use. This idea is supported by the fact that properly installed, newer wood stoves vent air pollutants outside the home.[8] Thus, pollution emitted from a wood stove may affect community air quality more than household air quality. Also, in communities with prevalent wood stove use, outdoor air pollutants infiltrate indoors,[77] and this may also explain more consistent associations between community wood smoke and health. To better elucidate the role of household versus community wood smoke on child health, carefully designed future studies are needed.

Recommendations for Future Studies

Future studies of household wood stove use would benefit from a more detailed exposure assessment. Specifically, frequency of wood stove use should be asked on questionnaires, and cohorts should directly measure $PM_{2.5}$, PAHs, or wood smoke markers like potassium or levoglucosan,[67,76] in at least a subset of homes. Biomarkers such as urinary levoglucosan, the PAH metabolite 1-hydroxypyrene, and methoxyphenols have been tested as potential measures of wood smoke exposure, but there is not yet evidence that these can be used routinely as an exposure assessment tool. Some of these wood smoke biomarkers appear to only be a strong measure of exposure at very high exposure levels that are uncommon in the developed world.[78] Other wood smoke biomarkers that future studies may consider measuring are urinary PAH metabolites other than 1-hydroxyprene such as 1-, 2-naphthol; 2-, 3-, 9-hydroxyfluorene; and 1-, 2-, 3-hydroxyphenanthrene. A recent study found that urinary concentrations of these metabolites in adult volunteers experimentally exposed to a wood fire had moderate to strong correlations with ambient $PM_{2.5}$, levoglucosan, and PAHs.[79] Future studies would benefit from more extensive exposure assessment, including measurement of one or several of these biomarkers.

Future studies should also include more objective methods of outcome classification, as much of the current literature relies on self-report of symptoms. More objective respiratory outcomes would include physician-diagnosed illness and measurements of lung function obtained by breath test or spirometry such as fraction of exhaled nitric oxide, forced expiratory volume, or forced vital capacity. Understanding the effects of wood smoke exposure on lung function is particularly important, as failure to attain “normal” expected lung function in childhood is a risk factor for future chronic obstructive pulmonary disease in adulthood.[80,81] Improved wood smoke exposure measurement paired with objective assessment of lung function may provide further insight into specific physiologic targets of wood smoke pollution.

In addition, many of the published studies of wood smoke exposure and pediatric health present unadjusted analyses that may be prone to bias from confounding. Factors that influence indoor wood smoke exposure, such as stove type, burning practices, stove operation conditions, indoor temperature, and household ventilation, should be assessed and controlled for in analyses, particularly if exposure is not objectively measured. Also, because wood heating may be a surrogate for poverty in some communities, participant socioeconomic status as measured, for example, by household income or parental education, must be accounted for in all analyses. Future studies should also consider whether households use wood stoves for primary versus supplemental heating because in addition to producing higher emissions, use of a wood stove as a primary heat source has been associated with lower socioeconomic status. The US Census Bureau estimates that 21% of US households who use a wood stove for primary heating have a household income below the poverty line versus 7% who use a wood stove for supplemental heating and 15% overall.[7] Failing to adjust for socioeconomic indicators could lead to observing and reporting an association that is not causal.

As environmental tobacco smoke is another source of indoor air pollution exposure and is known to influence respiratory health in children,[82] future studies may also benefit from considering the extent to which environmental tobacco smoke and wood smoke may interact to lead to poor respiratory health. One study found no interaction between air pollution exposure and environmental tobacco smoke on child wheeze,[55] but additional studies are needed to further elucidate whether children in homes with both exposures are more vulnerable.

Furthermore, future studies should be designed to identify ages during which children are most susceptible to wood stove pollution. Specifically, prospective birth cohorts with follow-up through late childhood will facilitate identification of vulnerable windows of exposure (i.e., prenatal versus infancy versus early childhood) in relation to health. Also, examination of multiple exposures (i.e., household wood stove use, community wood smoke, and other sources of ambient pollution) in a single cohort will help differentiate the impact of each of these exposures. Lastly, future studies should consider examining cardiometabolic health, neurocognition, and other outcomes, in addition to respiratory health, based on emerging evidence that traffic pollution is associated with these health endpoints.[28–30]

Studies with a larger sample size and direct measures of community wood smoke may more accurately reflect health effects than smaller studies that rely on self-reported household wood stove use. However, the field will benefit from additional prospective cohort studies with improved exposure and outcome assessment and careful consideration of potential confounding factors. As wood smoke is known to contain health-damaging components, while awaiting additional data, we recommend several precautionary measures to reduce wood stove emissions.

Recommendations to Lower Wood Smoke Exposure

Limiting avoidable air pollution exposures in homes with wood stoves will lower indoor and community wood smoke pollution and has potential to improve community health. In the sections that follow, we review EPA recommendations related to purchasing a lower-emitting wood stove and reducing air pollution exposures from an existing wood stove. We also present data on the efficacy of two interventions, community wood stove changeout programs, and household air filter installation, that have been studied to reduce air pollution exposure from wood stoves.

Wood Stove Certifications

The US EPA provides recommendations related to purchasing a new wood stove. A white certification label on the back of the wood stove denotes that it is EPA-*certified* (i.e., meets 2015 New Source Performance Standards of ≤4.5 g of $PM_{2.5}$ mass per hour). A burn wise hang tag indicates that the stove meets the stricter 2020 EPA clean air standards of ≤2.5 g of $PM_{2.5}$ mass per hour.[8] Although particle emission rates for EPA-*certified* wood and pellet stoves have been measured and are listed at http://www.epa.gov/compliance/list-epa-certified-wood-stoves (Table 3),[83] we are unaware of evidence showing that certified wood stove use is associated with lower levels of household wood smoke pollution. However, data from wood stove changeout programs (described later) suggest that community-level adoption of EPA-*certified* stoves may improve ambient air quality.[42,84,85]

Best Burn Practices and Proper Stove Operation

The EPA also recommends several best burn practices to further reduce wood stove emissions. As dry wood results in the most complete combustion and lowest pollution, the EPA suggests drying wood for at least 6 months and storing outside, covered, and off the ground with a goal of less than 20% water content as measured by a moisture reader. In addition, burning household wastes, such as plastics, trash, cardboard, or treated wood, should be avoided, as this may produce additional smoke pollution.[8]

In addition to providing information on best burn practices, the EPA provides suggestions for proper stove installation, operation, and maintenance. For example, in addition to following the manufacturer's instructions and procedures when operating a wood stove, cleaning the ashes from a wood stove improves burning efficiency by preventing ashes from clogging the air intake vents. The EPA also recommends that a chimney sweep or similar certified professional install any indoor wood burning appliance and inspect and clean the home's chimney once in a year. Efficient and cleaner wood burning depends on proper functioning of the chimney's venting system. The EPA recommends lists of installation and maintenance professionals from Chimney Safety Institute of America, found at http://www.csia.org/, and the National Fireplace Institute, found at https://www.nficertified.org/ (Table 3).

The extent to which best burn practices and proper stove operation lowers indoor air pollution was evaluated in a small study on the Nez Perce Reservation in which old wood stoves were replaced with EPA-*certified* stoves in a small group of homes. This program provided targeted education on best burn practices and proper stove operation techniques to individuals living in 4 households that did not obtain an indoor $PM_{2.5}$ reduction with the EPA-*certified* stove. The $PM_{2.5}$ concentration was lower in all of the homes following the additional training.[86] Similarly, an intervention in New South Wales, Australia found that providing an education pack to households changed participants' wood stove operation practices and reduced wood smoke emissions.[87] These studies emphasize the importance of best burn practices and proper wood stove operation and maintenance, even in homes with an EPA-*certified* stove.

Wood Stove Changeout Interventions

Additional interventions to reduce wood stove pollution have been evaluated and published in the peer-reviewed literature. Wood stove changeout programs, for instance, provide rebates or low-interest loans to replace pre-1988 New Source Performance Standards stoves with EPA-*certified* stoves. The extent to which large-scale wood stove changeout programs improve ambient and indoor air quality has been tested in some communities.

For example, from 1989 to 1990, after 48% of old stoves in Crested Butte, CO were replaced by new stoves and an additional 33% removed entirely, ambient PM was reduced by 60%.[84] More recently, in Libby, MT, post-changeout ambient $PM_{2.5}$ concentration was 27% lower[42] and PAH concentration was 64% lower[85] compared to pre-changeout winters, which brought the community within the EPA annual $PM_{2.5}$ standard. Thus, in communities in which wood smoke contributes significantly to outdoor air pollution, wood stove changeout programs have been shown to improve ambient air quality.

The effect of wood stove changeout programs on indoor air quality is less conclusive. In the small-scale wood stove changeout within 16 homes on the Nez Perce Reservation, discussed above, there was a 36% mean reduction in indoor $PM_{2.5}$ concentration, although $PM_{2.5}$ was reduced in only 10 of the 16 homes.[86] Similarly, following a wood stove changeout in 17 homes in northern British Columbia, only half of the homes had a reduction in indoor $PM_{2.5}$ concentration.[88] In Libby, MT, after more than 1100 pre-1988 New Source Performance Standards wood stoves were replaced with newer stoves, average daily $PM_{2.5}$ decreased from 45 to 21 $\mu g/m^3$ in a sample of 21 homes.[89] However, similarly to the Nez Perce Reservation and British Columbia changeouts, there was not a measureable indoor $PM_{2.5}$ reduction for all of the Libby, MT homes following the installation of a new wood stove. As not all of these programs provided education on best burn practices and proper stove operation, the extent to which these factors may have diminished the effect of the changeouts is unclear.

Notably, in addition to formal wood stove changeout programs, several states provide financial incentives to individuals, often low-income first-time buyers, to purchase a lower-emission, EPA-*certified* wood stove (Fig 1).[90] Although EPA-*certified* stoves emit less pollution than pre-1988 New Source Performance Standards wood stoves and wood stove changeouts tend to lower levels of ambient air pollution in wood smoke-impacted communities, a changeout does not definitively improve household air quality. Alternative interventions may be more effective for indoor settings.

Household Air Cleaner Interventions

Air cleaners remove air pollutants, and several studies have shown that use of air cleaners in households with a wood stove or in a wood smoke-impacted community effectively reduces indoor $PM_{2.5}$. Air cleaners can be installed in the ductwork of a home's central heating, ventilating, and air-conditioning system to clean the air in the whole house or can be used as a portable system to clean the air in a single room or area. Mechanical air filters, such as flat filters or extended surface filters [e.g., high efficiency particulate air (HEPA) filters], are most common. Mechanical air filters remove particles by either capturing them in the fibers of the filter or by trapping them on electrostatically charged filter material.[91]

For cost and convenience, household air cleaner intervention studies to improve indoor air quality in wood smoke-impacted homes and communities typically use portable mechanical air filters, which tend to be placed in the main activity room, room with the wood stove, or bedroom. For example, portable HEPA filter units, one in the main activity room and another in the bedroom, reduced indoor $PM_{2.5}$ concentrations by 60% in both wood- and non-wood burning homes in Smithers, British Columbia, a region with frequent residential wood burning. This HEPA filter intervention reduced indoor $PM_{2.5}$ concentrations in 24 of 25 tobacco-free homes in the study.[92] A study in Vancouver, British Columbia observed a 48% reduction in indoor $PM_{2.5}$ concentrations among non-wood burning homes in wood smoke-impacted regions, after a HEPA filtration intervention in which one filter unit was placed in the living room and another in the bedroom.[93]

Additionally, some studies have tested portable units with a flat filter made of electrostatically charged material rather than HEPA filters. In a study of wood-burning homes in rural areas of Idaho, Montana, and Alaska, those with portable air filter units placed in the same room as the wood stove and in the bedroom had an overall $PM_{2.5}$ reduction of 63% relative to homes with a sham filter.[94] Another study of 29 wood-burning homes in Nova Scotia observed a 52% reduction in median indoor $PM_{2.5}$ with use of a portable air filter versus sham filter typically placed in the living room.[95]

In addition to having strong efficacy data, air filters are a fairly cost-effective mechanism to reduce wood stove pollution. A portable mechanical air filter typically costs about $200 with an annual fee of $100 for filter replacement and energy fees of $100–$200 per year.[94] Even considering these potential extra costs, the use of a wood stove may still be a less expensive option than other residential heating systems because wood fuel tends to be more cost effective than oil, propane, and electric heat. Holding efficiency of the heating systems constant, the Maine Governor's Energy Office estimated that wood fuel costs $11 per million British thermal unit (MMBTU) and wood pellet fuel costs $16 per MMBTU, while oil is $17 per MMBTU, propane is $28 per MMBTU, and electricity costs up to $53 per MMBTU.

The EPA provides further basic information on residential air filters (https://www.epa.gov/indoor-air-quality-iaq/guide-air-cleaners-home)[91] and recommends the Association of Home Appliance Manufacturers' clean air delivery rating (http://ahamverifide.org/search-for-products/room-air-cleaners/)[96] as a tool to compare the efficacy of several air cleaning device options. Pediatricians may recommend these resources, along with others referenced in this section (Table 3), to patients and their families residing in wood burning communities.

Conclusions

An increasing number of US households, particularly in northern, rural areas, use wood stoves for residential heating, which lowers air quality. Children living in wood-burning communities, regardless of whether there is a wood stove in the home may be at higher risk for adverse respiratory health. Additional prospective epidemiologic studies with improved characterization of exposure and outcome and careful consideration of potential confounding variables are needed to fully elucidate this relationship and to investigate associations between wood smoke and other child health outcomes. While awaiting additional data, pediatricians may refer families using a wood stove to EPA recommendations regarding certified, lower-emitting stoves, and best burn practices. In addition, mechanical air filters have been shown to improve indoor air quality in wood-burning and non-wood burning homes located in communities with a high wood smoke burden.

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Abbreviations

ALL	acute lymphoblastic leukemia
EPA	Environmental Protection Agency
HEPA	high efficiency particulate air
MMBTU	million British thermal units
PAH	polycyclic aromatic hydrocarbon
PM	particulate matter

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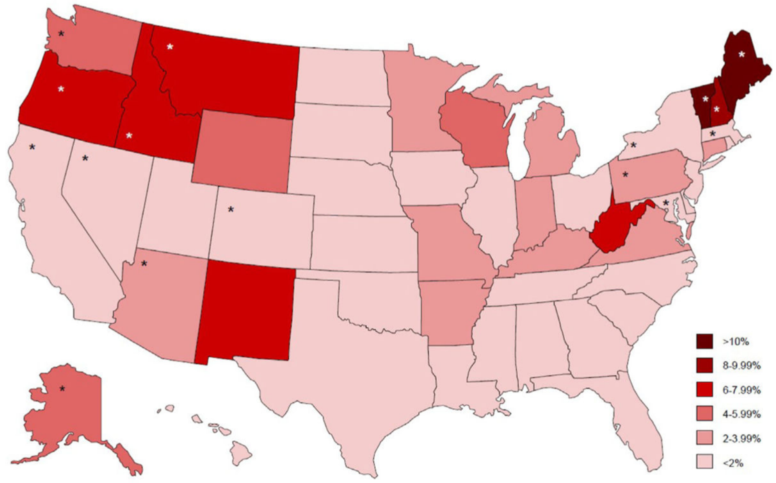

* Wood stove changeout or incentive programs as of November 2016. Refer to the Hearth, Patio & Barbecue Association's Wood Stove Changeout website for an updated list of state programs.[90]

FIG 1.

Prevalence of households estimated to use wood as primary heating fuel in 2015. (Original figure using data obtained from *2015 American Community Survey 1-Year Estimates* in Ref.[6]) (Color version of figure is available online.)

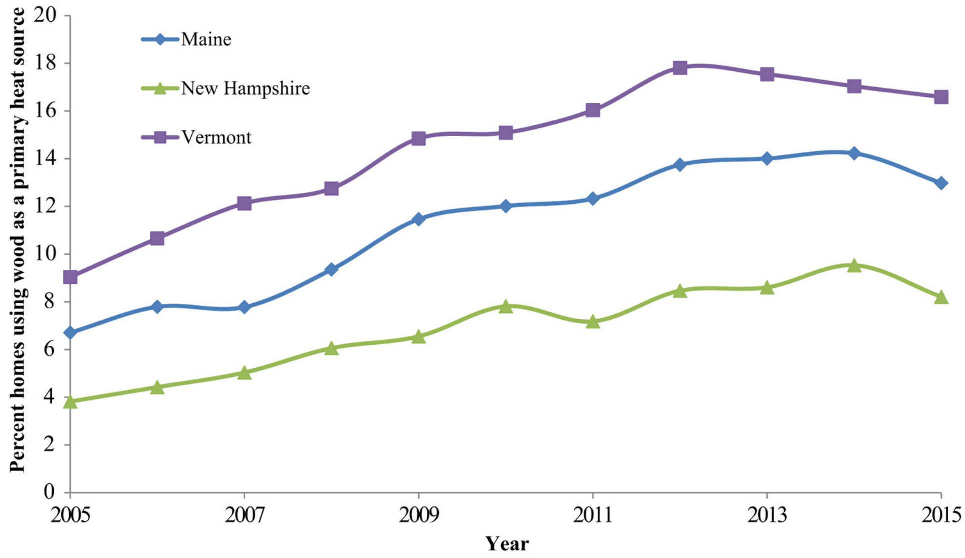

FIG 2.

From 2005 to 2015, the percent of homes estimated to use wood as a primary heat source increased in New England. (Original figure using data obtained from Ref.[6]) (Color version of figure is available online.)

TABLE 1

Characteristics of the studies of household wood stove use for heating and child health, 1980–2016

Reference, location	Design	Sample size; study population[a]	Follow-up duration	Wood stove exposure	Key outcome(s) OR (95% CI) or p value[b]	Key exclusions; matching	Key covariates
Tuthill,[61] Massachusetts	Cross-sectional	399 children (K-6th grade); 65% used wood stove	N/A	Self-report (Y/N)	Cough: $p > 0.05$ Wheeze: $p > 0.05$ Asthma: $p > 0.05$ Bronchitis: $p > 0.05$ Allergies: $p > 0.05$	None	Unadjusted; collected information on parental education, occupation, smoking, child age, sex, and time outdoors but did not adjust when effect estimate was not significant
Butterfield et al.,[45] Idaho	Cohort	59 children (1–5.5 years); 49% used wood stove	6 weeks	Self-report (h/week)	***Cough: $p < 0.05$*** ***Wheeze: $p < 0.05$***	Excluded if outside home >8 h/week, or if chronic respiratory disease	Unadjusted
Browning et al.,[41] Washington	Cross-sectional	164 children (1–14 years)	N/A	Self-report (Y/N)	Cough: 3.6 (0.3–51.4) Wheeze: 1.0 (0.3–2.8) for 1–5 years old[c]	None	Unadjusted; collected information on smoking but did not adjust when effect estimate was not significant
Morris et al.,[54] Arizona	Case–control	58 Navajo and Hopi children with respiratory infection and 58 controls (2 weeks–2 years); 70% used wood stove	N/A	Self-report (Y/N)	***Pneumonia/bronchiolitis: 4.9 (1.7–12.9)***	Excluded if asthma, preterm birth, congenital heart disease; matched for age and sex	Respiratory illness exposure; collected information on humidifier use, crowding, smoking and family history of asthma but did not adjust when effect estimate was not significant
Daigler et al.,[46] New York	Case–control	137 children with asthma, 125 children with otitis, and 246	N/A	Self-report (Y/N)	Asthma: $p > 0.05$ ***Otitis media: 1.7 (1.0–2.9)***	None	Age, sex, preterm birth, family history of respiratory illness, pets,

Reference, location	Design	Sample size; study population[a]	Follow-up duration	Wood stove exposure	Key outcome(s) OR (95% CI) or *p* value[b]	Key exclusions; matching	Key covariates
		controls (mean: 4 years); 29% used wood stove					humidifier use, and maternal smoking
Dekker et al.,[47] Canada	Cross-sectional	10,819 children (5–8 years); 10% used wood stove	N/A	Self-report (Y/N)	Wheeze: 0.9 (0.7–1.1) Asthma: 0.8 (0.6–1.1)	Excluded if cystic fibrosis or living in temporary home	Child sex, age, race, parental education, sex of respondent, region of residence, crowding, home dampness, gas cooking, and environmental tobacco smoke
Honicky and Osborne,[39] Michigan	Cohort	62 children (1–7 years); 50% used wood stove	3 winters	Self-report (Y/N)	***Cough:*** $p < 0.05$ ***Wheeze:*** $p < 0.05$	Participants living in homes with versus without a wood stove matched for age, sex, and town	Unadjusted; collected information on parental education, smoking, medical history, use of foam insulation, or humidifier use but did not adjust when effect estimate was not significant; homes with a wood stove more frequently used gas versus electric cooking and more frequently used an air filter
Infante-Rivard,[51] Canada	Case–control	457 children with asthma and 457 controls (3–4 years); 17% used wood stove	N/A	Self-report (Y/N)	Asthma: 0.9 (0.6–1.3)	Matched for age and census tract	Allergies, eczema, family history of asthma, maternal education, breastfeeding duration,

Reference, location	Design	Sample size; study population[a]	Follow-up duration	Wood stove exposure	Key outcome(s) OR (95% CI) or *p* value[b]	Key exclusions; matching	Key covariates
							household smoking, humidifier use, electric heat, and air conditioning
Guneser et al.,[50] Turkey	Cross-sectional	617 children (9–12 years)	N/A	Self-report (Y/N)	***FEV_1: $p < 0.05$; FVC: $p < 0.05$***	None	Unadjusted
Spengler et al.,[59] US/ Canada	Cross-sectional	12,842 children (9–11 years); 29% used wood stove	N/A	Self-report (Y/N)	Wheeze/cough/bronchitis: 1.0 (0.9–1.1) Asthma: 1.0 (0.9–1.1)	Excluded if non-white race/ethnicity or if prior lung or heart disease	City, sex, parental COPD, parental asthma, and parental education
Volkmer et al.,[62] South Australia	Cross-sectional	14,124 children (4–5 years); 22% used wood stove as primary heat source	N/A	Self-report (Y/N)	***Cough: 0.9 (0.8–1.0) Wheeze: 0.8 (0.7–0.9)***; ***Asthma: 0.8 (0.8–0.9)***; ***Bronchitis: 0.8 (0.7–1.0) URTI: 0.8 (0.7–0.9)***	Excluded households with no heating, kerosene heating, or multiple heating sources	Cook fuel, household cooling system, parental smoking, and postcode percent below poverty threshold
Robin et al.,[57] Arizona	Case–control	45 Navajo children with respiratory illness and 45 controls (<2 years); 19% used wood stove	N/A	Self-report (Y/N)	Pneumonia/bronchiolitis: 1.3 (0.5–3.8)[d]	Matched for age and sex	Unadjusted; collected information on access to care, household crowding, running water, electricity, and smoking but did not adjust when effect estimate was not significant
Maier et al.,[53] Washington	Cross-sectional	925 children (5–9 years); 10% used wood stove	N/A	Self-report (Y/N)	Wheeze: 1.0 (0.5–2.1); Asthma: 0.9 (0.5–1.7)[c]	None	Sex, race/ ethnicity, allergy history, socioeconomic status, and paternal asthma
Zacharasiewicz et al.,[64] Austria	Cross-sectional	18,606 children (6–9 years); 19%	N/A	Self-report (Y/N)	Allergies: 1.3 (0.8–2.2)	Excluded participants who reported changes in the	Age, sex, family history of allergies,

Reference, location	Design	Sample size; study population[a]	Follow-up duration	Wood stove exposure	Key outcome(s) OR (95% CI) or *p* value[b]	Key exclusions; matching	Key covariates
		used wood stove				indoor environment due to allergies	parental education, household smoking, cooking fuel, household pets, mold, and bedding
Triche et al.,[60] Connecticut/Virginia	Cohort	890 infants (3–5 months); 17% used wood stove	2 week intervals over 1 year	Self-report (h/day)	***Cough: 1.1 (1.0–1.2)*** *per 8 h wood stove use* Wheeze: 1.1 (0.9–18.4) *per 8 h wood stove use*[e]	Excluded smoking households, mother <19 years, non-English language, multiple gestations	Household kerosene heater, space heater, fireplace, dwelling type, maternal allergies/ asthma, education, breastfeeding, infant sex, season of birth, and daycare
Etiler et al.,[48] Turkey	Cohort	204 infants (<1 year old); 57% used wood stove	2 month intervals over 4–12 months	Self-report (Y/N)	***Cough: 1.8 (1.3–2.5)***	None	Unadjusted
Belanger et al.,[44] Connecticut/ Massachusetts	Cohort	593 infants (2–4 months) who have sibling with asthma and mother without asthma; 6% used wood stove	1 year	Self-report (Y/N)	***Cough: 2.1 (1.1–3.9)***[f] Wheeze: 1.0 (0.5–2.0)	None	Maternal education, ethnicity, child sex, and home exposures (smoking, dust mites, cockroaches, pets, gas stove, and mold/ mildew)
Sotir et al.,[58] North Carolina	Cross-sectional	30,593 children (7th–8th grade)	N/A	Self-report (never, <1 time/month, 1–3 times/month, 1 time/ week, every day)	***Wheeze: 1.4 (1.2–1.6)*** *for every day versus never users*	Restricted to participants with at least one episode of wheeze in the prior year	Sex, race/ ethnicity, socioeconomic status, urban/ rural residence, and household smoking
Pettigrew et al.,[56] Connecticut/Virginia	Cohort	904 infants (2–5 months); 17% used wood stove	2 week intervals over 1 year	Self-report (h/day)	Otitis media: 1.0 (0.5–1.2) *per 8 h wood stove use*	Excluded smoking households, infants admitted to newborn intensive-care units, mother <18 years, non-	Household kerosene heater, fireplace, air conditioning,

Reference, location	Design	Sample size; study population[a]	Follow-up duration	Wood stove exposure	Key outcome(s) OR (95% CI) or *p* value[b]	Key exclusions; matching	Key covariates
						English language, multiple gestations	daycare, heating season, gas appliance(s), infant sex, race, season of birth, maternal education, additional children in home, breastfeeding, mother's allergy and asthma, mold, and pets
Li et al.,[52] Ohio/Kansas Massachusetts/ Tennessee/Missouri/ Wisconsin	Cross-sectional	1754 children (7–11 years); 20% used wood stove	N/A	Self-report (Y/N)[g]	Wheeze/cough/bronchitis: 1.1 (0.9–1.3)[h]	None	City, parental factors (marital status, education, history of bronchitis, or emphysema, asthma), child factors (sex and age), household smoking
Noonan and Ward,[55] Montana	Cross-sectional	397 children (1st–8th grade); 36% used wood stove	N/A	Self-report (Y/N)	Wheeze: 1.1 (0.5–2.4)	None	Household smoking, school grade
Bailey et al.,[43] Australia	Case–control	389 children with acute lymphoblastic leukemia (ALL) and 876 controls (<15 years); 17% used wood stove prenatally	N/A	Self-report (Y/N)	***ALL: 1.4 (1.0–1.9)***[i]	Matched for age at diagnosis, sex, and state of residence; excluded if non-English language, non-citizen, biological mother unavailable, or did not reach remission	Age, sex, state of residence, parental education, ethnicity, birth order; collected information on household income, maternal age, birth defects, and paternal smoking but did not adjust when effect estimate was not significant

Reference, location	Design	Sample size; study population[a]	Follow-up duration	Wood stove exposure	Key outcome(s) OR (95% CI) or *p* value[b]	Key exclusions; matching	Key covariates
Noonan et al.,[42] Montana	Cohort	920 children (1st–12th grade); 43% used wood stove	4 winters	Self-report (Y/N)	Cough: 1.1 (0.8–1.3) Wheeze: 1.0 (0.7–1.5) Bronchitis: 1.6 (0.9–3.0) URTI: 0.9 (0.7–1.2) Otitis media: 1.3 (0.8–2.1)	None	School grade, community influenza rate
Zhou et al.,[65] France	Cohort	1765 children (1 year); 4% used wood stove	N/A	Self-report (Y/N)	Wheeze: 0.5 (0.3–1.0) Asthma: 1.0 (0.4–2.5) Bronchiolitis: 0.6 (0.4–1.1)	Excluded if known prepregnancy diabetes, non-French language	Study center, maternal occupation, maternal age, pre-pregnancy BMI, birth weight, cesarean delivery, preterm birth, breastfeeding, siblings, sex, and family history of asthma, eczema, allergic rhinitis, or food allergy
Ware et al.,[63] Alaska	Cross-sectional	475 children (<18 years); 28% used wood stove	N/A	Self-report (Y/N)	Cough: 1.5 (0.7–3.2) Wheeze: 0.8 (0.3–2.0) Asthma: 1.8 (0.6–5.2) Pneumonia: 2.1 (0.6–7.2) for <5 year olds Bronchitis: 2.0 (0.7–6.3) for <5 year olds URTI: 1.8 (0.5–6.3) for <5 years old Otitis media: 1.7 (0.7–4.4) for <5 years old	None	Unadjusted; collected information on household smoking but did not adjust when effect estimate was not significant
Greenop et al.,[49] Australia	Case–control	306 children with brain tumors and 950 controls (<15 years); 17% used wood stove prenatally	N/A	Self-report (Y/N)	***Brain tumors: 1.5 (1.1–2.2)***[j]	Matched for age at diagnosis, sex, state of residence, excluded if non-English language, non-citizen	Adjusted for year of birth, maternal age, ethnicity, and index of socioeconomic disadvantage

ALL, acute lymphoblastic leukemia; OR, odds ratio; URTI, upper respiratory tract infections.

[a] Included the percent of the cohort who used a wood stove when this value was reported in the article.

[b] *p* Value listed when OR is not reported in article.

[c] Estimates reported as prevalence ratios.

[d]Homes with wood stoves had higher levels of PM_{10} assessed by indoor air monitoring. For homes with PM_{10} ≥65 μg/m^3 (versus <65 μg/m^3), odds of pneumonia/bronchiolitis was 7 times higher (95% CI: 0.9–56.9) in unadjusted analyses with <20% change in effect estimate after accounting for access to care, household crowding, running water, electricity, and smoking.

[e]Estimates reported as risk ratios.

[f]For 256 children whose mothers had asthma, odds (95% CI) of persistent cough was 1.22 (0.34–4.37).

[g]Reported presence of a wood stove in the home, rather than use of a wood stove.

[h]In this sample, presence of a wood stove in the home was paradoxically linked to lower nitrogen dioxide levels in a subset of 1137 homes.

[i]Odds (95% CI) of ALL following postnatal wood stove use was 1.3 (0.9–1.7). When participants were categorized as high versus low wood stove users, associations between prenatal and postnatal wood stove use and ALL were non-monotonic [e.g., odds (95% CI) of ALL following high prenatal wood stove use versus none were 1.25 (0.84–1.86) and odds (95% CI) of low prenatal wood stove use versus none were 1.7 (1.0–2.7)].

[j]Odds (95% CI) of brain tumor following postnatal wood stove use was 1.4 (1.0–2.0). When participants were categorized as high versus low wood stove users, associations between prenatal wood stove use and brain tumor were monotonic [odds (95% CI) of brain tumor following high prenatal wood stove use versus none were 1.6 (1.0–2.5) and odds (95% CI) of low prenatal wood stove use vs. none were 1.4 (0.9–2.3)], whereas odds of postnatal wood stove use and brain tumor were non-monotonic [odds (95% CI) of brain tumor following high postnatal wood stove use versus none were 1.3 (0.8–2.0) and odds (95% CI) of low postnatal wood stove use versus none were 1.6 (1.0–2.4)].

TABLE 2

Characteristics of the studies of community wood smoke from wood stove use and child health, 1980–2016.

Reference, location	Design	Sample size; study population	Follow-up duration	Ambient wood smoke exposure	Key outcome(s) OR (95% CI) or *p* value[a]	Key exclusions; matching	Key covariates
Browning et al.,[41] Washington	Cross-sectional	164 children (1–14 years)	N/A	Household in high versus low wood smoke area	Wheeze: 2.0 (0.2–17.9) for 1–5 years old, 1.1 (0.3–3.7) for 6–14 years old Cough: 1.1 (0.4–3.0) for 6–14 years old Asthma: 0.5 (0.2–1.5) for 6–14 years old[b]	None	Unadjusted; collected information on smoking but did not adjust when effect estimate was not significant
Koenig et al.,[72] Washington	Cross-sectional	30 children with asthma (3rd–6th grade)	2 winters	Previous night's 12 h ambient light-scattering coefficient[c]	***FEV_1*: *$p < 0.01$*** ***FVC*: *$p < 0.01$***[d]	None	Height; collected information on temperature, relative humidity, recent illness, type of spirometer, parental education, household use of wood heat but did not adjust when effect estimate was not significant
McGowan et al.,[75] New Zealand	Time-series	All children (≤14 years) in Christchurch, New Zealand	7 months	Two-day lag average ambient PM_{10}	***Hospital respiratory admissions: 3.6% (2.3–4.9)*** *increase per interquartile increase in PM_{10}*	None	Weather conditions
Allen et al.,[67] Washington	Cross-sectional	9 children with asthma (6–13 years) not using inhaled corticosteroids	N/A	Previous day ambient levoglucosan	***FEV_1*: *1.7 L (1.2–2.0)*** Lower per 0.3 μg/m^3 of levoglucosan[e]	Excluded households with smokers	Temperature, relative humidity, BMI, and age
Epton et al.,[69] New Zealand	Time-series	93 male adolescents (12–18 years) in boarding school; 28% with asthma	1 winter	Previous day maximum ambient PM_{10}	***Cough*: *$p < 0.05$*** ***FEV_1***: *$p > 0.05$ for all participants;* ***$p < 0.05$ for participants with asthma***	Excluded participants who smoked or were taking oral corticosteroids for asthma	Reliever inhaler use and climate-related measures
Karr et al.,[71] Canada	Case–control	10,485 infants with bronchiolitis (2–12 months) and 57,127 controls	N/A	Lifetime number of wood burning days[f]	***Bronchiolitis: 1.1 (1.0–1.1)*** *per interquartile increase in wood burning days*	Matched on date of birth	Sex, first nations status, parity, maternal age, maternal smoking during pregnancy, breastfeeding, income, and maternal education
Ostro et al.,[76] California	Time-series	All children in 6 California counties (<19 years)	4 winters	Previous day ambient potassium	Hospital admissions for: Asthma: $p > 0.05$; ***Pneumonia*: *$p < 0.05$;*** ***Bronchitis*: *$p < 0.05$***;	None	Time, day of week, temperature, and relative humidity

Reference, location	Design	Sample size; study population	Follow-up duration	Ambient wood smoke exposure	Key outcome(s) OR (95% CI) or *p* value[a]	Key exclusions; matching	Key covariates
Clark et al.,[68] Canada	Case–control	2873 children with asthma (3–5 years) and 14,365 controls	N/A	Number of wood burning days *in utero* and during the first year of life[f]	Asthma: 1.0 (1.0–1.0) *per 10 burn days in utero or during 1st year of life*[g]	None; matched for age and sex	Maternal smoking, maternal age, breastfeeding, first nations status, birth weight, gestational age, census tract income, and maternal education
MacIntyre et al.,[74] Canada	Cohort	39,283 children (0–2 years)	2 years	Lifetime number of wood burning days[f]	***Otitis media: 1.3 (1.3–1.4)*** *per interquartile increase in wood burning days*	None	Otitis media season, sex, aboriginal, older siblings, maternal smoking during pregnancy, maternal age, neighborhood income, and female education
Noonan et al.,[42] Montana	Cohort	920 children (1st–12th grade)	4 winters	Ambient average winter $PM_{2.5}$ following wood stove changeout	Cough: 0.9 (0.8–1.8) ***Wheeze: 0.7 (0.6–1.0)*** ***Bronchitis: 0.5 (0.3–0.8)*** ***URTI: 0.8 (0.6–0.9)*** Otitis media: 0.7 (0.5–1.0) *per 5* µg/m³ *decrease in* $PM_{2.5}$	None	School grade and community influenza rate
Gehring et al.,[70] Canada	Cohort	68,326 births	Pregnancy	Number of wood burning days *in utero*[f]	***Small-for-gestational age: 1.2 (1.1–1.3)*** ***Very preterm birth: 0.3 (0.2–0.4)*** *per 40 wood burning days*[h]	Excluded participants without any exposure to wood burning	Maternal smoking, parity, age, ethnicity, education, income, child sex, year, and month of birth
Laurent et al.,[73] California	Cohort	704,148 births	Pregnancy	Ambient average $PM_{2.5}$ fraction from wood burning	***Low birth weight: 1.0 (1.0–1.0)*** *per interquartile range increment (0.46* mg/m³*) in* $PM_{2.5}$	Excluded multiple births and infants with birth defects or missing gestational age	Maternal age, race/ethnicity, education, parity, prenatal care, neighborhood income, child sex, and gestational age; collected information on population density, diabetes, chronic hypertension, preeclampsia, and day of conception but did not adjust when effect estimate was not significant

FEV_1, forced expiratory volume in the first second; FVC, forced vital capacity; OR, odds ratio; URTI, upper respiratory tract infections.

[a] p Value listed when OR not reported in article.

[b] Estimates reported as prevalence ratios.

[c] Strongly correlated with $PM_{2.5}$. Source apportionment studies have shown 80% of overnight $PM_{2.5}$ in this region is produced by wood burning appliances.

[d] For 283 children without asthma, estimates for FEV_1 and FVC were not significant.

[e]Mean (25–75 percentile) reported, 36 total respiratory health measures.

[f]Monitored levels of $PM_{2.5}$ and levoglucosan as well as spatial covariates were included in land use regression models of wood smoke, then postal codes in top tertile were classified as being in a wood burning area. The number of wood burning days was identified by a model including temperature and measured levoglucosan on each day.

[g]Although asthma was not associated with the number of wood burning days, it was associated with ambient black carbon, NO, NO_2, CO, and PM_{10} exposure (e.g., OR = 1.1, 95% CI: 1.0–1.3 per 10^{-5} increase in filter absorbance during the first year of life).

[h]Very preterm birth defined as gestational age <30 weeks. Any wood smoke exposure during pregnancy (Y/N) was associated with small-for-gestational age [OR (95% CI): 1.1 (1.0–1.1)] but not with very preterm birth [OR (95% CI): 1.2 (0.9–1.6)].

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TABLE 3

Publicly available resources available for individuals living in communities with prevalent wood stove use

Resource	Website	Information
US EPA-certified wood heaters list	https://www.epa.gov/compliance/list-epa-certified-wood-stoves	EPA-*certified* wood and pellet stoves
US EPA burn wise	https://www.epa.gov/burnwise https://www.epa.gov/sites/production/files/documents/burnwisetips.pdf	Best burn practices, wood stove installation, and maintenance
Chimney Safety Institute of America	http://www.csia.org/	Wood stove installation, chimney cleaning, and maintenance
The National Fireplace Institute	https://www.nficertified.org/	
Heath, Patio and Barbecue Association's wood stove changeout	http://www.woodstovechangeout.org/index.php	Ongoing wood stove changeout and incentive programs in the US and Canada
US EPA Guide to air cleaners in the home	https://www.epa.gov/indoor-air-quality-iaq/guide-air-cleaners-home	Air cleaners
Association of home appliance manufacturers room air cleaners	http://ahamverifide.org/search-for-products/room-air-cleaners/	Air cleaners